Geosphere

Introduction: Origin and Evolution of the Sierra Nevada and Walker Lane

Keith D. Putirka and Cathy J. Busby

Geosphere 2011;7;1269-1272
doi: 10.1130/GES00761.1

Notes

Introduction: Origin and Evolution of the Sierra Nevada and Walker Lane

Keith D. Putirka[1,*] and Cathy J. Busby[2,*]
[1]*California State University, Fresno, Department of Earth and Environmental Sciences, 2345 E. San Ramon Ave., MS/MH24, Fresno, California 93720, USA*
[2]*Department of Earth Science, University of California, Santa Barbara, California 93106, USA*

BACKGROUND AND HISTORY

This *Geosphere* themed issue is an outgrowth of our Penrose Conference: *Origin and Uplift of the Sierra Nevada, California*, which was held in Bridgeport, California, August 16–20, 2010. The theme is here expanded to include the Walker Lane (Fig. 1), since a large number of our Penrose abstracts were oriented to that topic, and because that region is no less a part of the Sierran story than the high peaks themselves. A fundamental question for the conference and themed issue is "How did the Sierra Nevada form?" The question can mean many things to disparate disciplines. One might refer to the age and origin of the rocks that form the Sierra Nevada batholith, or instead to the time at which such rocks were uplifted to form the topographic crest of the eastern Sierra. One might also speak to the origin of canyons and peaks formed by erosion as much as uplift, or to the time at which the Sierra's varied present-day ecological zones were established. The answers to these questions can be quite different, but are not necessarily independent, as insights from one may lend insight to another. Finally, the complete story of the Sierra also cannot be told without the tectonic forces that act on the Sierran crust, which involves the evolution of the San Andreas Fault system and the opening of the Gulf of California.

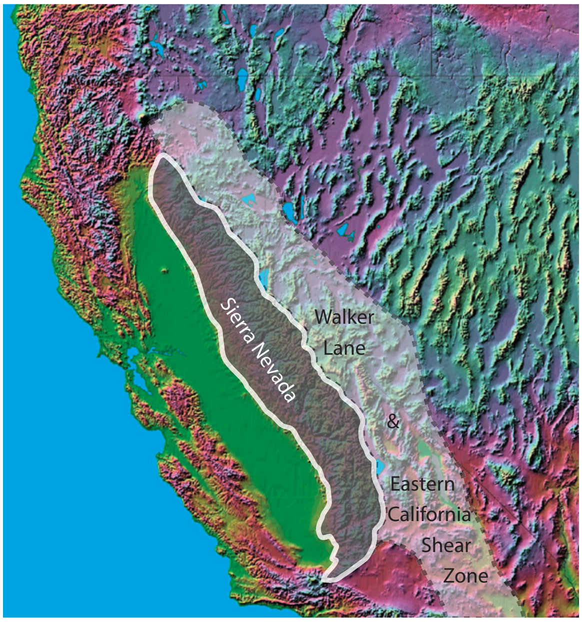

Figure 1. A map showing an outline of the Sierra Nevada and approximate boundaries of the Walker Lane belt. The outline of the Walker Lane (and its southern extension into the Eastern California Shear Zone) is modified from Faulds et al. (2005) and Oldow and Cashman (2009); we draw the western boundary to coincide with the Sierra Nevada range front; the Walker Lane belt is then drawn to include the region of the Basin and Range province where basins and ranges trend more N–S, rather than NE–SW. Our outline for the Sierra Nevada includes the topographically contiguous part of the range, and so includes the Lassen Volcanic Center, which is the geologically southern terminus of the modern Cascades province. The base map is from Andrew Birrell (http://birrell.org/andrew/reliefMaps/image.php?zone = west&type = jpg&scale = 50).

What makes the Sierra Nevada mountain range of particular interest is the rich history of geologic studies. Pioneers of Sierran geology have provided a well-constructed platform on which later scientists could build, with the Range of Light illuminating processes as diverse as glaciation, structural geology, petrology, and tectonics. Some aspects of this storied history are well known, such as John Muir's early work on Sierran glaciers and glacial erosion (Muir, 1871, 1911; followed by Matthes, 1929, and Blackwelder, 1931), which initiated our current understanding of the forces that carve Sierran peaks and canyons. Perhaps less well known are 19th-century speculations on the nature of range uplift. Ransome (1898, p. 71), for example, mapped lava flows in the west-central Sierra Nevada; noting contrasts in Neogene and modern canyon slopes, he suggested that "the elevation of the crest of the Sierra Nevada…has been…produced by a simple block-tilting without perceptible warping"—a view that has been subsequently accepted and quantified (Huber, 1981; Wakabayashi and Sawyer, 2001). Early workers also recognized that Eocene and younger strata in the Sierra Nevada were largely preserved in "paleochannels" that transported material from east to west (parallel to modern rivers), although their headwaters were inferred to lie at the present-day crest (Lindgren, 1911), which we now know did not form until 10 Ma or later (Busby and Putirka, 2009). Also of note are the early tectonic speculations on the origin of what we now refer to as the "Sierran block" and the adjacent Walker Lane structural belt. The Walker Lane belt has been in the geologic literature since Locke et al. (1940) used the term to describe a region of the western Great Basin where extensional faults have a significant dextral shear component. But, six years earlier, Gianella and Callaghan (1934) not only drew the outlines of the Walker Lane, but also noted the similarity of horizontal components of strain between the western Great Basin and what was then referred to as the San Andreas "rift." Gianella and Callaghan (1934, p. 22) speculated "that the underlying causes of movement in at least the western part of the Great Basin may be related to those in California" (referring to the San Andreas), and suggested that the Walker Lane may represent "a tectonic line" that separates the San Andreas and Great Basin structural

*Emails: Putirka: kputirka@csufresno.edu; Busby: busby@geol.ucsb.edu.

Geosphere; December 2011; v. 7; no. 6; p. 1269–1272; doi: 10.1130/GES00761.1; 1 figure.

regimes. This view of a connection between Walker Lane motion and stress and strain along the San Andreas Fault system has survived the plate tectonic view of the San Andreas (Atwater, 1970), and has been verified by Global Positioning Studies, which show that the Walker Lane takes up 20%–22% of Pacific–North American displacement (Bennett et al., 1999; Dixon et al., 1995, 2000). Perhaps even more impressive is that a structural geologist today could use nearly the precise same language as Gianella and Callaghan did in 1934, some three decades prior to the plate tectonic revolution.

Since these early works, the Sierra Nevada and adjacent Walker Lane regions have played center stage in studies of batholith construction (Kistler and Peterman, 1973), the origin of low-angle normal faults (Proffett, 1977) and associated "chaos" formed by huge gravitational slides (e.g., Troxel and Wright, 1987), the evolution of pull-apart basins (Burchfiel and Stewart, 1966), the tectonic significance of ophiolites and ultramafic rocks (Moores, 1970), the origin of metamorphic core complexes (Wright et al., 1974), and volcanic processes such as bimodal volcanism and magma mixing (Bacon, 1982; Bacon and Metz, 1984). It may be fair to say that the Sierra Nevada is a type example of many such processes, including range uplift and microplate formation, and the crustal extension processes that yield continental rift basins and mountain ranges.

CURRENT ISSUES IN SIERRA NEVADA–WALKER LANE GEOLOGY

In the past few decades, the Sierra Nevada has entered center stage again, this time on the issue of lithosphere removal. Careful geologic and geophysical studies (Ducea and Saleeby, 1996, 1998; Fliedner et al., 1996; Wernicke et al., 1996) suggest that cold continental mantle lithosphere beneath the eastern part of the range, being denser than underlying asthenosphere, drips back into the mantle (e.g., Zandt et al., 2004). The driving force for such a buoyancy shift within the thermal lithosphere may be generated by the accumulation of dense pyroxene- and garnet-rich lithologies, which may in turn represent the crystalline residues of parent magmas that fractionate to form the Sierra Nevada batholith (Ducea and Saleeby, 1996). Such a removal of lithosphere leads to an upward flow of asthenosphere, which provides (a) a source of buoyancy to support high elevations (Ducea and Saleeby, 1996), and (b) mantle partial melts, which supply volcanic eruptions within and adjacent to the range (Farmer et al., 2002).

Our attempts to determine how this story unfolds lead to a great number of unresolved but important questions. For example, the current standard model clearly implies that the petrologic nature of batholith development determines the rates and timing of future uplift. Earlier views of Sierra Nevada uplift posited an isostatic model, whereby the high elevations in the eastern Sierra are supported by great thicknesses of crust (>60 km; Bateman and Eaton, 1967). The discovery by seismologists that the crust is ≤40 km in thickness, and is of greater thickness in the lower-elevation western part of the range (Fliedner and Ruppert, 1996), shows that Airy isostasy cannot apply to the Sierra. Warm mantle asthenosphere is thus posited to provide buoyancy to support its high elevations (Wernicke et al., 1996). If this view is correct, the "high Sierra" exists only because of the formation, and removal, of dense crystalline residues of magmas parental to the batholith. Absent the formation of dense residues, the lithosphere "drip" could not have formed, and asthenosphere upwelling would not occur, providing no source of buoyancy.

Not unrelated are potentially competing models for Sierra Nevada uplift; some argue that the range has mostly been high since the late Cretaceous (House et al., 1999), while others argue that range uplift has occurred mostly since 10 or 5 Ma (Huber, 1981; Wakabayashi and Sawyer, 2001). These models might not be mutually exclusive: Clark et al. (2005) suggest at least three pulses of uplift, occurring in the late Cretaceous, again at 32 Ma, and another at 3.5–0 Ma. These varied works lead to a range of questions:

- Does granitoid batholith formation necessarily portend a later emergence of a high mountain range, through the loss of dense residual crystalline phases? If so, what time scales are required for lithosphere removal?
- If lithosphere can only be removed once, should asthenosphere upwelling support only one phase of uplift? If so, and if uplift does occur in pulses over a protracted period of time, which phase of uplift is driven by asthenosphere upwelling, and what forces drive other uplift phases?
- Alternatively, DeCelles et al. (2009) suggest that delamination can be repeated on a 25–50 Ma time scale. Can episodes of uplift operate on a similar time scale, as is implied by the results of Clark et al. (2005)? Might other cyclic processes be at work?

Yet another set of issues arises from the compositions and temporal distributions of volcanic rocks. Farmer et al. (2002) argue that mantle delamination occurred in the Pliocene, as signaled by high K_2O Pliocene volcanism, which was supposedly triggered by asthenosphere upwelling. Age determinations across the Sierra, including the southern Sierra, however, indicate a distinct pulse of volcanism at 10 Ma throughout the range. More perplexingly, as even Farmer et al. (2002) note, Pliocene lavas in the southern Sierra still carry the geochemical signature of enriched mantle lithosphere, so an enriched mantle lithosphere must have existed below the Sierra at the time of the Pliocene eruptions.

- Did delamination of ancient lithosphere occur in the Pliocene or the Miocene, or earlier? If delamination (and asthenosphere upwelling) is a Pliocene event, what is the driving force of mantle melting so as to yield volcanism at 15–10 Ma, which occurs throughout the range? If asthenosphere upwelling predated the Pliocene, what structural controls led to volcanism from the Pliocene to the present?

Much new research is now focused on the spatial scope and temporal extent of what has been termed the "Ancestral Cascades." Christiansen and Yeats (1992) outlined a region of Miocene-age andesitic volcanism that extends from central California into the Basin and Range province south to Las Vegas (Colgan et al., 2011). Based on space-time distributions of volcanic rocks using NAVDAT, Glazner and Farmer (2008) indicate that what has been referred to as Ancestral Cascades are rocks that may instead be related to larger Cordilleran spatial patterns of volcanic migration and so have little connection to the modern Cascades; they thus suggest that the term "Ancestral Cascades" has no meaning. In contrast, others have noted that the field characteristics and geochemical signals of Miocene and some Pliocene volcanic rocks support remarkably well the Christiansen and Yeats (1992) model (Cousens et al., 2008; Busby et al., 2008; Busby and Putirka, 2009), especially for subduction-related volcanism formed prior to arrival of the Mendocino Triple Junction (MTJ). These subduction-related volcanic rocks include the type section of the volcanic rock termed "latite" (by Ransome, 1898), which is distinguished by its high K_2O, a geochemical signal that Manley et al. (2000) suggest is related to delamination. Meanwhile, Frasetto et al. (2011) see a "delamination" Moho extending from the southern Sierra north to the Lake Tahoe region, beneath the putative Miocene arc. We thus obtain another set of key questions related to volcanic activity.

- If there was indeed an Ancestral Cascade arc, what is its areal and temporal extent?
- What is the meaning of the term "Ancestral Cascades" if such volcanism is limited in temporal extent, or if such volcanics fall into other, broader Cordilleran space-time patterns? Or, might *all* early- and mid-Tertiary volcanism in the interior (e.g., in Nevada, Arizona, and Utah)

of the Cordillera (pre-passage of the MTJ) be "Ancestral Cascades"?

• If the term "Ancestral Cascades" is discontinued, then what processes controlled Miocene-age volcanism, especially those rocks erupted north of the MTJ? If such rocks are ascribed to Basin and Range extension, what explains their geochemical contrasts (lower alkalis, lower Sm/Yb) compared to Basin and Range volcanics?

• If high K_2O is a signal of delamination, might the latites of the central Sierra mark an earlier episode of delamination, which could still be visible in the seismic signal?

• Might high K_2O have nothing to do at all with lithosphere degradation events (see Putirka and Busby, 2007)?

Finally, the importance of the Sierra Nevada–Walker Lane region cannot be overemphasized for understanding the processes involved in the rupturing of continental lithosphere. This region has been described as the northernmost extension of the Gulf of California rift where it has not yet completed the process of continental rupture (Faulds and Henry, 2008; Jayko and Bursik, 2012). Similarly to the Gulf of California, the Walker Lane started to develop during Miocene time, and both form an oblique-divergent plate boundary (Wilson, 1965; Larson et al., 1968; Lonsdale, 1989; Wesnousky, 2005; Lizarralde et al., 2007; Umhoefer et al., 2007; Putirka and Busby, 2007; Surpless, 2008). Many questions remain regarding the formation of oblique rift margins because they have not been studied in as much detail as orthogonal rift margins

Data generated from the Gulf of California MARGINS Rift Initiation focus site are now being supplemented by on-land studies in the Walker Lane transtensional rift, which has not yet completed the process of continental rupture. Extensive Cenozoic volcanic and sedimentary rocks, excellent exposure, and abundant previous geological mapping in the Walker Lane make it an excellent region in which to study rifting processes (e.g., Henry and Perkins, 2001; Trexler et al., 2000; Henry et al., 2007; Busby et al., 2008; Busby and Putirka, 2009; Cashman et al., 2009; Jayko, 2009; Hagan et al., 2009; Norton, 2011). Furthermore, the region is important for geothermal and mineral resources and has a population living on active faults (e.g., Reno–Carson City population corridor and the North Tahoe basin). However, the processes involved in oblique continental rifting, as well as the uplift history of the Sierra Nevada, cannot be understood without reference to the broader context, including Laramide flat-slab subduction, whose effects reached far inboard of the Sierra; these effects include thickening of the crust to form a high broad plateau referred to as the "Nevadaplano" (DeCelles, 2004). Another tectonic context involves ensuing slab rollback, resulting in ignimbrite flare-up on the thickest "Nevadaplano" crust, and dispersal of ash flows down ~200-km-long paleochannels across the western shoulder of the Nevadaplano, now the Sierra Nevada. This flare-up resulted in burning of the lithospheric land bridge across what is now the Great Basin (Dickinson, 2002, 2006, 2011; Henry, 2008; Best et al., 2009).

The papers of this themed issue touch on these key topics and others. This themed issue brings together the results connected not so much by approach or technique, but rather by their authors' interest in fundamental problems of tectonics, volcanism and range uplift, and the use of the Sierra Nevada as a case study for how mountain ranges form and evolve. Our hope is that the cumulative geologic, geochemical, and geophysical data may point toward a single coherent tectonic model that explains all observations—volcanic, structural, stratigraphic, paleobotanical, and geochemical, etc. But if nothing else, these papers perhaps attest to the usefulness of collaborative research for addressing fundamental questions of the origin of the Sierra Nevada, microplate formation, and rift initiation.

ACKNOWLEDGEMENTS

We would like to thank the participants of the 2010 Penrose Conference for their interest in and enthusiasm for the conference itself, and the high level of discussion at that meeting, both of which helped to launch this themed issue. We also thank Science Editor Carol Frost and Managing Editor Bridgette Moore for their tireless efforts in bringing this themed issue to fruition.

REFERENCES CITED

Atwater, T., 1970, Implications of plate tectonics for the Cenozoic tectonic evolution of western North America: Geological Society of America Bulletin, v. 81, p. 3513–3536, doi: 10.1130/0016-7606(1970)81[3513:IOPTFT]2.0.CO;2.

Bacon, C.R., 1982, Time-predictable bimodal volcanism in the Coso Range, California: Geology, v. 10, p. 65–69, doi: 10.1130/0091-7613(1982)10<65:TBVITC>2.0.CO;2.

Bacon, C.R., and Metz, J., 1984, Magmatic inclusions in rhyolites, contaminated basalts and compositional zonation beneath the Coso volcanic field, California: Contributions to Mineralogy and Petrology, v. 85, p. 346–365, doi: 10.1007/BF01150292.

Bateman, P.C., and Eaton, J.P., 1967, Sierra Nevada Batholith: Science, v. 158, p. 1407–1417, doi: 10.1126/science.158.3807.1407.

Bennett, R.A., Davis, J.L., and Wernicke, B.P., 1999, Present-day pattern of Cordilleran deformation in the western United States: Geology, v. 31, p. 327–330.

Best, M.G., Barr, D.L., Christiansen, E.H., Gromme, S., Deino, A., and Tingey, D.G., 2009, The Great Basin Altiplano during the middle Cenozoic ignimbrite flareup: Insights from volcanic rocks: International Geology Review, v. 51, p. 589–633, doi: 10.1080/00206810902867690.

Blackwelder, E., 1931, Pleistocene glaciations in the Sierra Nevada and Basin Ranges: Geological Society of America Bulletin, v. 42, p. 865–922.

Burchfiel, B.C., and Stewart, J.H., 1966, Pull-apart origin of the central segment of Death Valley, California: Geological Society of America Bulletin, v. 77, p. 439–442, doi: 10.1130/0016-7606(1966)77[439:POOTCS]2.0.CO;2.

Busby, C.J., and Putirka, K., 2009, Cretaceous-Cenozoic landscape evolution of the SW USA: Evidence from Cenozoic paleocanyon fill in the central Sierra Nevada: International Geology Review, v. 51, p. 670–701, doi: 10.1080/00206810902978265.

Busby, C.J., Hagan, J., Putirka, K., Pluhar, C., Gans, P., Rood, D., DeOeo, S., Skilling, I., and Wagner, D., 2008, The ancestral Cascades arc: Implications for the development of the Sierran microplate and tectonic significance of high K_2O volcanism, *in* Wright, J., and Shervais, J., eds, Ophiolites, Arcs and Batholiths: Geological Society of America Special Paper 438, p. 331–378.

Cashman, P.H., Trexler, J.H., Muntean, T.W., Faulds, J.E., Louie, J.N., and Oppliger, G.L., 2009, Neogene tectonic evolution of the Sierra Nevada–Basin and Range transition zone at the latitude of Carson City, Nevada, *in* Oldow, J.S., and Cashman, P.H., eds., Late Cenozoic Structure and Evolution of the Great Basin–Sierra Nevada Transition: Geological Society of America Special Paper 447, p. 171–188.

Christiansen, R.L., and Yeats, R.S., 1992, Post-Laramide geology of the U.S. Cordilleran region, *in* Burchfiel, B.C., Lipman, P.W., and Zoback, M.L., eds., The Cordilleran Orogen: Conterminous U.S.: Boulder, Colorado, Geological Society of America, Geology of North America, v. G-3, p. 261–406.

Clark, M.K., Maheo, G., Saleeby, J., and Farley, K., 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.

Colgan, J.P., Egger, A.E., John, D.A., Cousens, B., Fleck, R.J., and Henry, C.D., 2011, Oligocene and Miocene arc volcanism in northeastern California: Evidence for post-Eocene segmentation of the subducting Farallon plate: Geosphere, v. 7, no. 3, p. 733–755, doi: 10.1130/GES00650.1.

Cousens, B., Prytulak, J., Henry, C., Alcazar, A., and Brownrigg, T., 2008, Geology, geochronology, and geochemistry of the Miocene-Pliocene ancestral Cascades arc, northern Sierra Nevada, California and Nevada: The roles of the upper mantle, subducting slab and the Sierra Nevada lithosphere: Geosphere, v. 4, p. 829–853, doi: 10.1130/GES00166.1.

DeCelles, P.G., 2004, Late Jurassic to Eocene evolution of the Cordilleran thrust belt and foreland basin system, western USA: American Journal of Science, v. 304, p. 105–168, doi: 10.2475/ajs.304.2.105.

DeCelles, P.G., Ducea, M.N., Kapp, P., and Zandt, G., 2009, Cyclicity in Cordilleran orogenic systems: Nature Geoscience, doi:10.1038/NGE0469.

Dickinson, W.R., 2002, The Basin and Range Province as a composite extensional domain: International Geology Review, v. 44, p. 1–38, doi: 10.2747/0020-6814.44.1.1.

Dickinson, W.R., 2006, Geotectonic evolution of the Great Basin: Geosphere, v. 2, p. 353–368, doi: 10.1130/GES00054.1.

Dickinson, W.R., 2011, The place of the Great Basin in the Cordilleran orogeny, *in* Steininger, R., and Pennell, B., eds., Great Basin Evolution and Metallogeny: Reno, Geological Society of Nevada 2010 Symposium, p. 419–436.

Dixon, T.H., Robaudo, S., Lee, J., and Reheis, M.C., 1995, Constraints on present-day Basin and Range deformation from space geodesy: Tectonics, v. 14, p. 755–772, doi: 10.1029/95TC00931.

Dixon, T., Farina, F., DeMets, C., Suarez-Vidal, F., Fletcher, J., Marquez-Azua, B., Miller, M., Sanchez, O., and Umhoefer, P., 2000, New kinematic models for Pacific-North America motion from 3 Ma to present, II: Tectonic implications for Baja and Alta California: Geophysical Research Letters, v. 27, p. 3961–3964, doi: 10.1029/2000GL008529.

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, p. 8229–8244, doi: 10.1029/95JB03452.

Ducea, M., and Saleeby, J., 1998, A case for delamination of the deep batholithic crust beneath the Sierra Nevada, California: International Geology Review, v. 40, p. 78–93, doi: 10.1080/00206819809465199.

Farmer, G.L., Glazner, A.F., and Manley, C.R., 2002, Did lithospheric delamination trigger late Cenozoic potassic volcanism in the southern Sierra Nevada, California: Geological Society of America Bulletin, v. 114, p. 754–768, doi: 10.1130/0016-7606(2002)114<0754:DLDTLC>2.0.CO;2.

Faulds, J.E., and Henry, C.D., 2008, Tectonic influences and temporal evolution of the Walker Lane: An incipient transform along the evolving Pacific-North American plate boundary, *in* Spencer, J.E., and Titley, S.R., eds., Ores and Orogenesis: Circum-Pacific Tectonics, Geologic Evolution, and Ore Deposits: Arizona Geological Society Digest 22, p. 437–470.

Faulds, J.E., Henry, C.D., and Hinz, N.H., 2005, Kinematics of the northern Walker Lane: An incipient transform fault along the Pacific-North American plate boundary: Geology, v. 33, p. 505–508, doi: 10.1130/G21274.1.

Fliedner, M.M., Ruppert, S., and Southern Sierra Nevada Continental Dynamics Working Group, 1996, Three dimensional crustal structure of the southern Sierra Nevada from seismic fan profiles and gravity modeling: Geology, v. 24, p. 367–370.

Frassetto, A., Zandt, G., Gilbert, H., Owens, T.J., and Jones, C.H., 2011, Structure of the Sierra Nevada from receiver functions and implications for lithospheric foundering: Geosphere, v. 7, no. 4, p. 898–921, doi: 10.1130/GES00570.1.

Gianella, V.P., and Callaghan, E., 1934, The Earthquake of December 20, 1932, at Cedar Mountain, Nevada, and its bearing on the genesis of Basin Range structure: Journal of Geology, v. 42, p. 1–22.

Glazner, A.F., and Farmer, G.L., 2008, Ancestral Cascades = Modern Cascades, Geological Society of America, 104th annual meeting: Geological Society of America, Abstracts with Programs, v. 40, no. 1, p. 98.

Hagan, J., Busby, C., Renne, P., and Putirka, K., 2009, Cenozoic evolution of paleochannels, Ancestral Cascades magmas, and range-front faults in the Kirkwood–Carson Pass–Markleeville region (Central Sierra Nevada), *in* Ernst, G., ed., The Rise and Fall of the Nevadaplano: International Geology Reviews, v. 51, nos. 9–11, p. 777–823.

Henry, C.D., 2008, Ash-flow tuffs and paleovalleys in northeastern Nevada: Implications for Eocene paleogeography and extension in the Sevier hinterland, northern Great Basin: Geosphere, v. 4, p. 1–35, doi: 10.1130/GES00122.1.

Henry, C.D., and Perkins, M.E., 2001, Sierra Nevada–Basin and Range transition near Reno, Nevada; Two stage development at ~12 and 3 Ma: Geology, v. 29, p. 719–722, doi: 10.1130/0091-7613(2001)029<0719:SNBART>2.0.CO;2.

Henry, C.D., Faulds, J.E., and dePolo, C.M., 2007, Geometry and timing of strike-slip and normal faults in the northern Walker Lane, northwestern Nevada and northeastern California: Strain partitioning or sequential extension and strike-slip deformation? *in* Till, A.B., Roeske, S.M., Sample, J.C., and Foster, D.A., eds., Exhumation Associated with Continental Strike-Slip Fault Systems: Geological Society of America Special Paper 434, p. 59–79, doi: 10.1130/2007.2434(04).

House, M.A., Wernicke, B.P., and Farley, K.A., 1999, Dating topography of the Sierra Nevada, California, using apatite (U-Th)/He ages: Nature, v. 396, doi: 10.1038/23926.

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 1197, 28 p.

Jayko, A.S., 2009, The Mono Arch, eastern Sierra Region, California: Dynamic topography associated with mantle upwelling? *in* Ernst, G., ed., The Sierra Nevada Plano: International Geology Review, v. 51, p. 702–722, doi: 10.1080/00206810902880271.

Jayko, A.S., and Bursik, M., 2012, Active transtensional intracontinental basins, Walker Lane, western Great Basin, *in* Busby, C., and Azor, A., eds., Tectonics of Sedimentary Basins: Recent Advances: Hoboken, New Jersey, Wiley-Blackwell (in press).

Kistler, R.W., and Peterman, Z.E., 1973, Variations in Sr, Rb, K, Na, and Initial Sr^{87}/Sr^{86} in Mesozoic granitic wall rocks and intruded wall rocks in central California: Geological Society of America Bulletin, v. 84, p. 3489–3512, doi: 10.1130/0016-7606(1973)84<3489:VISRKN>2.0.CO;2.

Larson, R.L., Menard, H.W., and Smith, S.M., 1968, Gulf of California: A result of ocean floor spreading and transform faulting: Science, v. 161, p. 781–784, doi: 10.1126/science.161.3843.781.

Lindgren, W., 1911, The Tertiary Gravels of the Sierra Nevada of California: Washington, DC, United States Geological Survey, 222 p.

Lizarralde, D., Axen, G.J., Brown, H.E., Fletcher, J.M., Gonzalez-Fernandez, A., Harding, A.J., Holbrook, W.S., Kent, G.M., Paramo, P., Sutherland, F., and Umhoefer, P., 2007, Variation in styles of rifting in the Gulf of California: Nature, v. 448, p. 466–469, doi: 10.1038/nature06035.

Locke, A., Billingsley, P., and Mayo, E.B., 1940, Sierra Nevada tectonic patterns: Geological Society of America Bulletin, v. 51, p. 513–540.

Lonsdale, P., 1989, Segmentation of the Pacific-Nazca spreading center, 1°N-20°S: Journal of Geophysical Research, v. 94, p. 12,197–12,225, doi: 10.1029/JB094iB09p12197.

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

Matthes, F., 1929, Multiple glaciations in the Sierra Nevada: Science, v. 70, p. 75–76, doi: 10.1126/science.70.1803.75.

Moores, E., 1970, Ultramafics and orogeny, with models of the US Cordillera and the Tethys: Nature, v. 228, p. 837–842, doi: 10.1038/228837a0.

Muir, J., 1871, Yosemite Glaciers: New York Tribune, December 5.

Muir, J., 1911, My First Summer in the Sierra: Boston, New York, Houghton-Mifflin Co., 353 p.

Norton, I., 2011, Two-stage formation of Death Valley: Geosphere, v. 7, p. 171–182, doi:10.1130/GES00588.1.

Oldow, J.S., and Cashman, P.H., 2009, Introduction, *in* Oldow, J.S., and Cashman, P.H., eds., Late Cenozoic Structure and Evolution of the Great Basin–Sierra Nevada Transition: Geological Society of America Special Paper 447, p. v–viii.

Proffett, J.M., Jr., 1977, Cenozoic geology for the Yerington district, Nevada, and implications for the nature and origin of Basin and Range faulting: Geological Society of America Bulletin, v. 88, p. 247–266, doi: 10.1130/0016-7606(1977)88<247:CGOTYD>2.0.CO;2.

Putirka, K., and Busby, C.J., 2007, The tectonic significance of high K_2O volcanism in the Sierra Nevada, California: Geology, v. 35, p. 923–926, doi: 10.1130/G23914A.1.

Ransome, F.L., 1898, Some lava flows of the western slope of the Sierra Nevada, California: U.S.G.S. Bulletin no. 89, 85 p.

Surpless, B., 2008, Modern strain localization in the central Walker Lane, western United States: Implications for the evolution of intraplate deformation in transtensional settings: Tectonophysics, v. 457, nos. 3–4, p. 329–253.

Trexler, J.H., Cashman, P.H., Henry, C.D., Muntean, T., Schwartz, K., TenBrink, A., Faulds, J.E., Perkins, M., and Kelly, T., 2000, Neogene basins in western Nevada document the tectonic history of the Sierra Nevada–Basin and Range transition zone for the last 12 Ma, *in* Lageson, D.R., Peters, S.G., and Lahren, M.M., eds., Great Basin and Sierra Nevada: Boulder, Colorado, Geological Society of America Field Guide 2, p. 97–116.

Troxel, B.W., and Wright, L.A., 1987, Tertiary extensional features, Death Valley region, eastern California: Geological Society of America, Decade of North American Geology, Centennial Field Guide–Cordilleran Section, p. 121–132.

Umhoefer, P.J., Schwenicke, T., Del Margo, M.T., Ruiz-Geraldo, G., Ingle, J.C., Jr., and McIntosh, W., 2007, Transtensional fault-termination basins: An important basin type illustrated by the Pliocene San Jose Island basin and related basins in the southern Gulf of California, Mexico: Basin Research, v. 19, p. 297–322, doi: 10.1111/j.1365-2117.2007.00323.x.

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, p. 539–562, doi: 10.1086/321962.

Wesnousky, S.G., 2005, The San Andreas and Walker Lane fault systems, western North America: Transpression, transtension, cumulative slip and the structural evolution of a major transform plate boundary: Journal of Structural Geology, v. 27, no. 8, p. 1505–1512, doi: 10.1016/j.jsg.2005.01.015.

Wernicke, B., Clayton, R., Ducea, M., Jones, C.H., Park, S., Ruppert, S., Saleeby, J., Snow, A.J., 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, p. 190–193, doi: 10.1126/science.271.5246.190.

Wilson, J.T., 1965, A new class of faults and their bearing on continental drift: Nature, v. 207, p. 343–347, doi: 10.1038/207343a0.

Wright, L.A., Otton, J.K., and Troxel, B.W., 1974, Turtleback surfaces of Death Valley viewed as phenomena of extensional tectonics: Geology, v. 2, p. 53–54, doi: 10.1130/0091-7613(1974)2<53:TSODVV>2.0.CO;2.

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.

Manuscript Received 4 November 2011
Manuscript Accepted 7 November 2011