Introduction: Geodynamics and Consequences of Lithospheric Removal in the Sierra Nevada, California

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The Sierra Nevada of California has long contained paradoxes between the age of the range and the cause of uplift. In the 19th century, J.D. Whitney and J. LeConte disagreed about the interpretation of late Cenozoic incision evident in the Sierra. Whitney (1880, 1882) viewed the incision of Pliocene and older rocks as a result of climatic changes. LeConte (1880, 1886) argued that the recent incision reflected a tilting of the Sierra, which also caused uplift of the crest of the range. LeConte's view was basically upheld and amplified by further geological work (e.g., Christensen, 1966; Huber, 1981, 1990; Lindgren, 1911; Matthes, 1930).

As inquiry advanced to consider the cause of uplift, the first paradox emerged. Andrew Lawson posited that the Sierra had always been in isostatic equilibrium maintained by crustal isostasy (Lawson, 1936). By further assuming that gentle upland surfaces had been created near sea level, Lawson constructed a history of uplift that required crustal thickening at each step. While most of his uplifts coincided with volcanic action that could plausibly have thickened the crust through igneous additions, his last and greatest uplift lacked significant volcanism. Absent igneous thickening, Lawson turned his back on his earlier work and proclaimed that continuing uplift of the Sierra was by thrusting.

Lawson's thrusts never found favor, but Perry Byerly's (1937) follow-up led to decades of apparent geophysical confirmation that there was a thick crust supporting the Sierra (e.g., Eaton, 1963, 1966; Oliver et al., 1961). Because of the great volume of Mesozoic igneous rock throughout the range, it was presumed that the thick crust was Mesozoic in age (e.g., Bateman and Wahrhaftig, 1966). This clearly presented a paradox: how was the young Sierra to rise with the support of an old root?

Renewed geophysical interest seemingly tore away this paradox. Dean Carder (Carder et al., 1970; Carder, 1973) initially challenged the idea that the Sierran crust was unusually thick, instead proposing that mantle structure could support the range. Several other studies confirmed that Sierran mantle was unusually low wavespeed and probably hot and buoyant (Crough and Thompson, 1977; Jones, 1987; Mavko and Thompson, 1983), reducing the necessity of a thick crust. The final blows to a thick crust under the crest of the range were administered in the 1990s (Fliedner et al., 1996; Jones et al., 1994; Jones and Phinney, 1998).

As the geophysical hurdles to a young source of support for the Sierra were cleared, a plausible means of generating the mantle source of buoyancy emerged. Ducea and Saleeby (1996, 1998) noted that lower crustal and upper mantle xenoliths from 8 to 12 Ma age eruptions indicated the presence of a dense, cold, high-wavespeed batholithic residuum at the base of the crust that was not present in younger (<3.5 Ma) xenolith suites. The presence of a substantial high-density residuum layer along the base of the crust beneath the Sierra Nevada was not compatible with the newly emerged geophysical picture of the range that showed relatively low seismic wavespeeds down to the Moho and relatively low P_n wavespeeds below it (Fliedner et al., 1996; Jones et al., 1994). Instead, this dense material had to have been removed between 8 and 3.5 Ma. Later work suggested that high-K lavas erupted at ca. 3.5 Ma marked a rapid removal of this dense rock (Farmer et al., 2002; Manley et al., 2000). Subsequently, important new quantitative constraints on the timing and amount of southern Sierra Nevada river incision of late Cenozoic age were published (Stock et al., 2004). The rock uplift regime indicated by this study correlated in time and space with the mantle xenolith and high-K lava findings, in the context of residuum removal accounting for the temporal change in mantle xenolith suites, focused high-K volcanism, and southern Sierra rock uplift. Looking to the immediately adjacent Great Valley basin and its lithospheric underpinnings, Saleeby et al. (2003) and Saleeby and Foster (2004) noted a zone of anomalous subsidence that formed over the same time interval as the newly documented rock uplift event, and they further noted the correspondence of this zone of anomalous subsidence with the underlying high seismic wavespeed Isabella anomaly (Benz and Zandt, 1993; Biasi and Humphreys, 1992; Jones et al., 1994, 2004). These workers suggested that the Isabella anomaly, at least in part, represents the mobilized residuum, now removed from much of the southern Sierra and concentrated to the west under the basin, and that the process is ongoing.

At this point it became evident to workers that processes driving the most recent uplift phase of the Sierra Nevada mountain range, its most recent phases of volcanism, and accelerated subsidence in the adjacent Great Valley basin could all be linked to the deep time production of a substantial residuum sequence that accumulated during large volume batholith production. Thus the scope of research broadened to consider the processes of creating an andesite-norm crust from basaltic arc melts, which requires the removal of a silica-poor component of the system (e.g., Kay and Mahlburg-Kay, 1991; Kay and Kay, 1993). If removal of the Sierran residuum was relatively recent, it occurred without the complications surrounding an active subduction system. Free of such complications and with the prospect that this process might still be underway, the set of studies encompassed by this themed issue was undertaken. The overarching goal was to constrain enough about the dynamics of removal that lessons from the Sierra could be applied globally to more cryptic orogens.

Even as the old paradox of a young Sierra with an old source of support was swept aside, a new one emerged in its place. The possibility that Sierran elevations were old even as erosion rejuvenated the landscape was first strongly advanced by observations of variations

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Geosphere; April 2013; v. 9; no. 2; p. 188–190; doi:10.1130/GES00907.1.
Received 5 February 2013 ♦ Accepted 6 February 2013 ♦ Published online 6 March 2013

in (U-Th/He) cooling ages along constant-elevation profiles (House et al., 1998, 2001). This was soon augmented by inferences of high topography from isotopic variations dating back to the Eocene, thought to be created by Rayleigh distillation of precipitation (Cassel et al., 2009, 2012; Mulch et al., 2006; Poage and Chamberlain, 2002). Although these interpretations are disputed (Galewsky, 2009a, 2009b; Jones et al., 2004; Molnar, 2010; Wakabayashi and Sawyer, 2001; Wakabayashi, 2013), the prospect of an old Sierra with a young buoyancy source augers a second paradox (Wernicke et al., 1996). This controversy has further stimulated the research reported here, pointing to both the deep time analysis of lithospheric and landscape evolution and the pursuit of the contemporary structural and dynamic states.

KEY ISSUES

The hypotheses for the Sierra guided the kinds of observations that are needed to test and advance our understanding of these processes. The xenoliths that supported foundering of the lower crust were concentrated to a relatively small area of the Sierra not far from the main geophysical observations supporting a relatively thin and low-wavespeed crust under the Sierra crest. Jones et al. (2004) proposed that foundering had occurred under the whole of the Sierra and driven large-scale uplift, while Zandt (2003) limited removal to a smaller area with only a small topographic signal. To address the extent of foundering, we need to know where residuum should have been under the Sierra, where it is no longer present, and, if possible, when it left. Ideally, we would learn where that foundering material is now and identify structures associated with its movement. Variations in topography, heat flow, igneous activity, sedimentation, and faulting that might be driven by this process need to be identified and physical mechanisms for these variations posited. Understanding the physical processes of different mechanisms (e.g., dripping versus delamination) is required to distinguish among causes and recognize differing consequences.

The work addressing the issues in this themed issue falls broadly into four categories: (1) geophysical and geochemical work constraining the modern lithospheric structure of the region; (2) geological, petrological, and geochemical work constraining the lithospheric structure prior to ~12 Ma; (3) geological, sedimentological, and geochronological work bearing on the evolution of uplift and subsidence; and (4) numerical and analytical modeling seeking to relate the geological observations to deep-seated processes.

ACKNOWLEDGMENTS

Our work on this themed issue was supported in part by NSF grants EAR06-07831 to Jones and EAR06-06903 to Saleeby.

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