Topographic response to mantle lithosphere removal in the southern Sierra Nevada region, California

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ABSTRACT

Geological studies of mantle xenoliths entrained in late Neogene–Quaternary lavas from the southern Sierra Nevada region and regional geophysical studies suggest that the high-density mantle lithosphere that formed beneath the Sierra Nevada batholith in conjunction with arc magmatism is being convectively removed as a ''drip'' structure. This structure, as imaged seismically, is roughly cylindrical in shape with a diameter of ~100 km, and extends to ~225 km depth. Centered above this structure is a region ~120 km in diameter that is undergoing active subsidence relative to adjacent regions. Such subsidence is seen in the active fluvial-alluvial sediment flooding of mountainous topography of the southwestern Sierra and in the development of the adjacent Tulare Lake basin of the San Joaquin Valley. Dynamic modeling of such upper-mantle drip structures predicts a phase of overlying surface subsidence during the most vigorous phase of drip formation. The southern Sierra upper mantle drip and the overlying crust appear to be in this phase of their dynamically coupled evolution.

Keywords: dynamic topography, mantle drip, basin subsidence.

INTRODUCTION

Topographic subsidence resulting from downward flow in the convecting mantle has been a subject of interest in tectonics and geodynamics for decades (cf. Griggs, 1939; Morgan, 1965; McKenzie, 1977; Bindschadler and Parmentier, 1990; Gurnis, 1990). Tectonic and geodynamic considerations tell us that there are at least two scales over which convective processes operate in Earth's mantle: plate tectonics and smaller Rayleigh-Taylor instabilities. Rayleigh-Taylor instabilities arise when temperature and density contrasts in adjacent layers drive the growth of drip-like structures at sufficient rates so as to minimize heat diffusion effects (Houseman and Molnar, 1997; Houseman et al., 2000; Jull and Keleman, 2001). The viscous forces of descent in a sufficiently large drip that forms near Earth's surface exert a downward pull, resulting in surface subsidence.

In this paper we describe a region of anomalous topography that has recently (late Pliocene to Holocene) formed along the western Sierra Nevada between latitudes 36° and 37°N (Fig. 1), and review evidence for the Pliocene to Holocene removal of the underlying mantle lithosphere as a result of a Rayleigh-Taylor instability. The spatial and temporal coincidence of these surface and deep-level processes suggests a dynamic link. Furthermore, the scales of the zone of anomalous topography and the lithosphere removal structure are substantially smaller than the regional structural-geomorphic system of the North American–Pacific plate juncture. The phenomena that we discuss are superimposed over the plate juncture features, and appear to represent processes that are at most loosely coupled to the plate juncture dynamic system.

The ~600-km-long Sierra Nevada constitutes part of a semirigid crustal block, which, along with the tightly coupled Great Valley, has been termed the Sierra Nevada microplate (Argus and Gordon, 1991). This microplate is bounded on the west by an active fold-thrust belt in the Coast Ranges that constitutes part of the San Andreas transpressive plate juncture, and to the east by the eastern Sierra escarpment, which forms the boundary between the Sierra Nevada and the Basin and Range extensional province. The Great Valley constituted a forearc basin adjacent to the Sierran magmatic arc in Cretaceous time, and has persisted as a major depositional trough through Cenozoic time, with two connected subbasins, the Sacramento Valley to the north and the San Joaquin Valley to the south (Bartow, 1991). To a first order the Sierra Nevada may be characterized as a westward-tilted fault block, the tilting and related basement exhumation of which are balanced by a linear zone of subsidence and sedimentation in the Great Valley (Lettis and Unruh, 1991; Unruh, 1991). We review evidence that suggests that regional subsidence and depositional patterns of the Great Valley are modified in the southern San Joaquin Valley by the removal of the mantle lithosphere.

ANOMALOUS TOPOGRAPHY

The western Sierra Foothills mark the transition from the Great Valley to the Sierra Nevada. The western foothills display a unique and constant physiographic expression for a strike distance in excess of 300 km between ~37° and ~40°N. This is most evident in the structure and geomorphic setting of what Bateman and Wahrhaftig (1966) call the Superjacent Series. These strata consist primarily of middle to upper Cenozoic strata that nonconformably overlie Sierran basement. Between ~37° and ~40°N the Superjacent Series dips gently westward off the basement; older units have progressively greater dips, and Pliocene to Holocene strata display regional offlap. Such offlap reflects basin subsidence to the west in concert with westward tilting of the Sierra about an axis within the Superjacent Series outcrop belt (Unruh, 1991). Except for major river drainages, the locus of Holocene sedimentation above the Superjacent Series starts about one-third the distance across the Great Valley (Fig. 1A). Topographic profiles across the foothills at these latitudes are regionally smooth, and the general dip of the Pliocene–Pleistocene section can be extrapolated eastward and found to be virtually along major interfluves projecting toward the eastern crest of the range.

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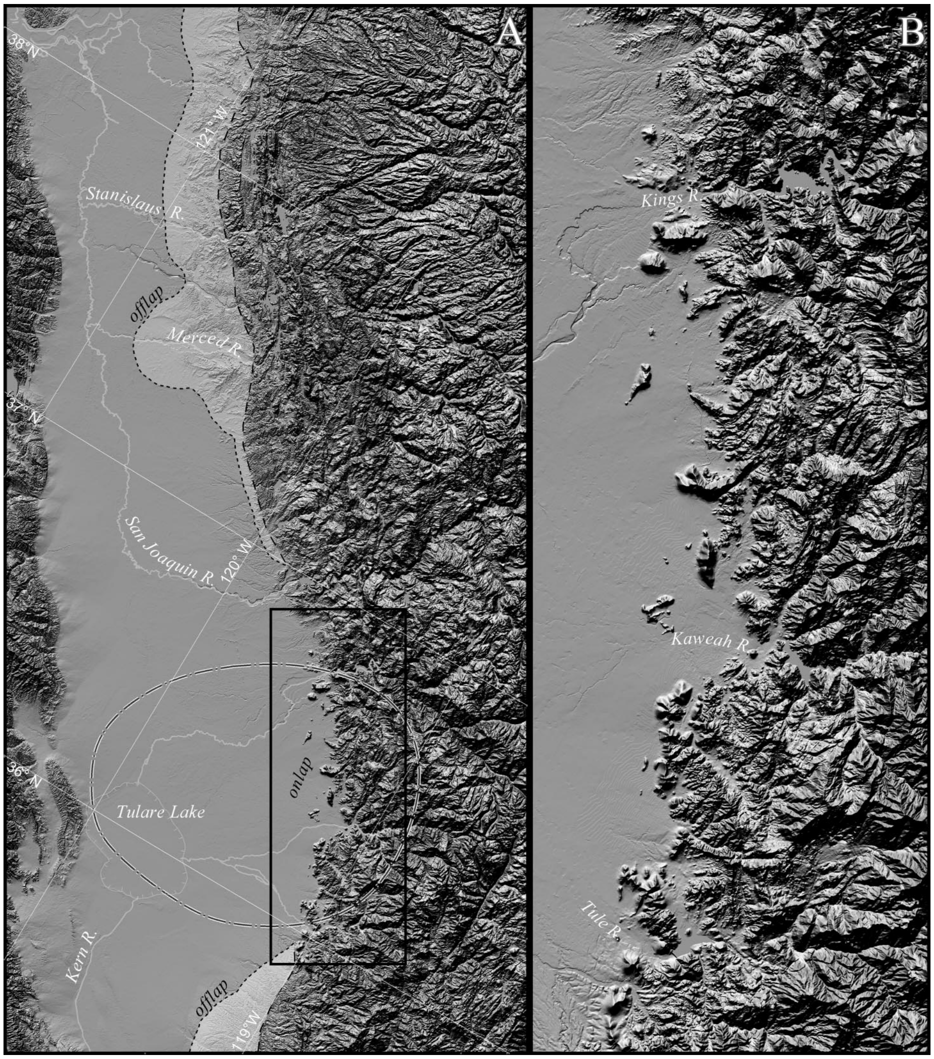

Figure 1. Digital elevation models for axial and western regions of Sierra Nevada, Great Valley, and eastern Coast Ranges. A: Dotted line approximates offlap boundary of Holocene deposits across Superjacent Series (lighter tone), except in major river channels. Dashed line approximates regional nonconformity along western Sierra foothills. Large circular area approximates map projection of high-density anomaly in upper mantle. B: Region of anomalous topography where Holocene fluvial and alluvial deposits onlap mountainous Sierran basement. Sacramento River delta is shown in upper left corner. Scale dimensions of B (shown as inset in A) are 120 km by 45 km.

The geomorphic expression of the western Sierra changes dramatically at ~37°N (Fig. 1A). The edge of Holocene offlap sedimentation diverges from its regional NW trend and cuts eastward in an onlap relation across the Superjacent Series. South of the Kings River area pre-Quaternary strata are not exposed, and Holocene sediments aggrade onto the basement along drainage systems in a fashion that is not observed to the north. This onlap pattern of Holocene fluvial and alluvial sedimentation across the basement intensifies southward into the drainages of the Kaweah and Tule Rivers (Fig. 1B). Farther south at ~36°N the edge of Holocene sedimentation turns southwestward out of the basement exposures toward the central part of the valley to assume an offlap relation with Cenozoic strata, analogous to the relations north of ~37°N.

A remarkable feature of the geomorphology along the foothills between 36° and 37°N is the myriad of isolated steep faceted hills of basement exposures that are surrounded by Holocene fluvial and alluvial sediments (Fig. 1B). In numerous localities steep rockfall faces in coarsely jointed plutonic rock are unsupported by basal debris aprons or boulders. The supporting debris presumably is buried beneath the more distally derived surrounding deposits. The isolated hills represent the ridge tops and peaks of a buried mountainous topography, akin to inselbergs of cratonic settings.

Subsurface data for the San Joaquin Valley in the region of this anomalous topography reveal that Cenozoic strata of the Superjacent Series are buried beneath the Holocene onlap deposits (Bartow, 1991). These relations indicate that the locus of Holocene sedimentation has embayed eastward across the Superjacent Series and into the mountainous topography of the western Sierra for a distance of as much as ~50 km. These anomalous topographic and depositional patterns are complemented by anomalous drainage patterns in the San Joaquin Valley. To the north of this region the major rivers draining off the western Sierra extend along the axis of the Great Valley, and exit to the Pacific Ocean through the Sacramento River delta (Fig. 1A). To the south the main channel of the Kings River and the Kaweah, Tule, and Kern Rivers drain into the internal Tulare Lake basin. Tulare Lake has developed as an internal basin within the San Joaquin Valley over the past ~2.2 m.y. (Croft and Gordon, 1968; Croft, 1972; Miller, 1999). Davis and Green (1962) presented data favoring a tectonic control in the development of the Tulare Lake basin. Structure contour and isopach maps for Pleistocene strata beneath Tulare Lake show that the basin embays for ~40 km eastward across the linear NNW trend of the San Joaquin Valley trough, and that the shape of the basin is controlled by a system of radial and concentric growth faults (see Data Repository[1]). Even in the area east of the Tulare Lake basin published tectonic subsidence rates for Pliocene–Pleistocene time yield the greatest value for the entire Great Valley (Moxom and Graham, 1987). We consider all of these features to be the surface expression of the same dynamic process in the upper mantle beneath the area.

MANTLE DRIP BENEATH THE SOUTHWEST SIERRA NEVADA REGION

An anomalous domain of high P-wave seismic velocities has been imaged beneath the southwestern Sierra Nevada and adjacent San Joaquin Valley (Humphreys, 1987; Zandt and Carrigan, 1993; Jones et al., 1994; Ruppert et al., 1998; Zandt, 2003). This domain has a roughly vertical cylindrical shape ~100 km in diameter, and extends from near the base of the crust to a depth of ~225 km. In its core area it is ~5% faster relative to the P-wave structure of the upper mantle throughout the rest of central California. Standard velocity to density conversions that also satisfy regional gravity profiles yield a positive density con-

[1]GSA Data Repository item 2004038, structure contour data for Tulare Lake deposits, and flexural model for drip load on crust, is available online at www.geosociety.org/pubs/ft2004.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

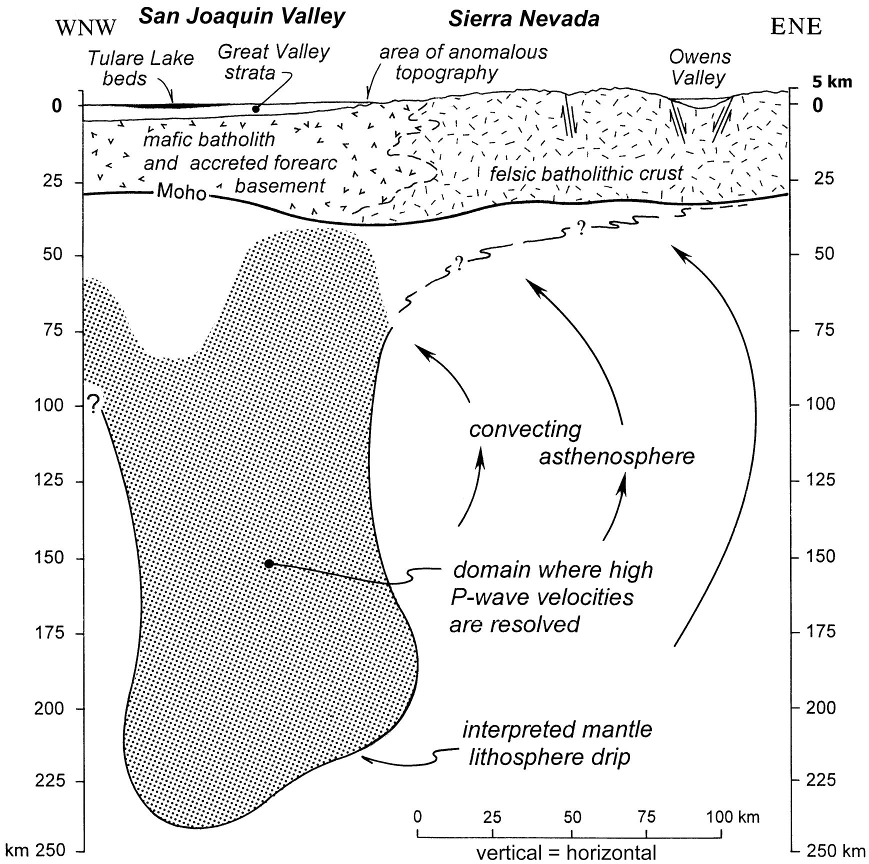

Figure 2. Generalized cross section along course of lower Kaweah River (shown in Fig. 1B) extending from westernmost Basin and Range to western edge of San Joaquin Valley (Zandt and Carrigan, 1993; Jones and Phinney, 1998; Ruppert et al., 1998; Fliedner et al., 2000; Saleeby et al., 2003). Shaded area shows upper-mantle domain over which relatively high P-wave seismic velocities are resolved, interpreted as convectively mobilized mantle lithosphere drip (Humphreys, 1987; Jones et al., 1994).

trast of ~100 kg/m^3 for the anomalous mantle domain. The surface projection of this high-density structure is shown in Figure 1A.

Figure 2 is a generalized cross section that extends along the course of the lower Kaweah River (Fig. 1B), westward from the westernmost Basin and Range to the western edge of the San Joaquin Valley. The shaded area approximates the high-density structure, and a drip outline for the structure is shown diagrammatically (after Humphreys, 1987; Jones et al., 1994). The crust beneath the Sierra Nevada consists primarily of batholithic rocks to a depth of ~35 km. Along the western margin of the range there is a thickening of the crust to ~42 km. Here the thickest crust underlies the lowest elevations of the range. P-wave velocities and teleseismic data for the upper mantle beneath much of the Sierra Nevada east of the drip indicate asthenospheric mantle directly beneath the crust. These findings are corroborated by studies of mantle peridotite xenoliths entrained in Pliocene–Quaternary lavas from the eastern Sierra region; the thermobarometry of the zenoliths defines an anomalously shallow-level asthenosphere adiabat (Ducea and Saleeby, 1996). The common occurrence of quenched glass inclusions in the peridotites also indicates the presence of partial melt in the upper mantle of this region, an observation that is resolved by geophysical data (Park et al., 1996; Jones and Phinney, 1998).

The positive density contrast of the anomalous mantle structure relative to typical upper mantle peridotites is interpreted to arise from its eclogitic composition (Ducea and Saleeby, 1998a; Ruppert et al., 1998; Zandt, 2003). Such eclogitic rocks are abundantly represented in mid-Miocene volcanic-hosted xenolith suites of the central Sierra Nevada region (Ducea and Saleeby, 1996). Petrogenetic studies indicate that these eclogitic rocks are related to the Sierra Nevada batholith as its cumulate residue assemblage (Ducea and Saleeby, 1998b; Ducea, 2001; Saleeby et al., 2003). Together with mantle wedge peridotites, which also occur in the mid-Miocene xenolith suites, the high-density batholith residues constituted the subbatholith mantle lithosphere. The lack of such eclogitic residues in Pliocene–Quaternary xenolith suites of the southern Sierra region, the sharp contrast in peridotite mantle facies fields between the mid-Miocene and Pliocene-Quaternary xenolith suites, and a Pliocene change in the composition of lavas erupted in the region to more primitive compositions are interpreted to indicate the removal of the subbatholith mantle lithosphere and its replacement by asthenosphere (Ducea and Saleeby, 1998a; Farmer et al., 2002). Such convective replacement of the mantle lithosphere is also consistent with the Pliocene to Holocene phase of Sierran uplift and the interpretation of this uplift having originated by buoyancy changes in the upper mantle (cf. Jones et al., 1994). Flexural modeling of the crustal response to the load imposed by the drip predicts subsidence that is in great excess to that recorded in drill-hole logs and seismic data (see footnote 1). These results are consistent with ongoing studies that indicate that the lower crust is deforming viscously over the drip.

DISCUSSION

Dynamic modeling of Rayleigh-Taylor convective instabilities predicts that during the most vigorous phase of drip formation there should be overlying subsidence and a depression along the base of the overlying crust (Bindschadler and Parmentier, 1990; Houseman et al., 2000). Finite strain trajectories produced in these models indicate that traction along the base of the crust as well as downward viscous drag work together to deform the Moho. Thus lower crustal flow into the area above the drip can thicken the crust while depressing the free surface. Applying these results to the southern Sierra region explains the counterintuitive relation of the thickest crust over the region of lowest elevations, complemented by thinner crust to the east floating topographically higher above asthenosphere, which has replaced the mantle lithosphere (Fig. 2).

The question must now be raised as to why the drip is offset to the west of the greater Sierra Nevada batholith, if the drip consists primarily of the high-density residue complex of the batholith. Two possible factors are apparent. The western margin of the southern Sierra Nevada batholith, which extends westward beneath the adjacent San Joaquin Valley, is substantially more mafic in composition and of higher density than the batholith to the east (Saleeby et al., 2003). Dynamic models suggest that initial perturbations in the thickness or density structure of the unstable layer will preferentially nucleate the drip. We suggest that the high relative density of the western domain of the batholith preferentially nucleated the drip along its western margin. Another possible factor is the partial entrainment of the drips in the ambient southwest-directed asthenosphere flow field (Zandt, 2003).

Regional structural and depositional patterns of the San Andreas transpressive plate juncture and adjacent Sierran microplate reflect plate margin processes with general continuity in surface expression along an ~600 km strike length. Superimposed on this structural system is an ~120-km-diameter zone of subsidence that affects mountainous and basinal environments of the Sierra Nevada and adjacent San Joaquin Valley. The marked drop-off in topographic relief along the Coast Range fold-thrust belt (Fig. 1A) and depositional overlap of Pleistocene strata across growing anticlines of the belt adjacent to Tulare Lake (Bloch, 1991; Miller, 1999, their Fig. 1.14) suggest suppression of topographic relief along the fold-thrust belt adjacent to the drip.

CONCLUSIONS

Along the southwestern Sierra Nevada between 36° and 37°N there is a zone of anomalous topography where the regional patterns of Pliocene to Holocene offlap sedimentation change to an onlap pattern across the Sierran basement, where steep faceted mountainous topography is being actively buried. The adjacent San Joaquin Valley shows a complimentary pattern of anomalous internal drainage. These patterns indicate relative subsidence of a roughly circular region ~120 km in diameter. This region is centered over a distinct high-density mantle anomaly that extends from near the base of the crust to an ~225 km depth. A time series in the evolution of the sub-Sierran mantle based on late Cenozoic volcanic entrained xenoliths integrated with geophysical data strongly suggests that the high-density anomaly represents the convectively removed sub–Sierra Nevada batholith mantle lithosphere. Dynamic models of such convective instabilities predict a phase of surface-level subsidence during the most vigorous phase of lithosphere removal. A dynamic link between the zone of anomalous topography and the underlying mantle flow pattern is implied.

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