ABSTRACT
Recent geophysical studies in the southern Sierra Nevada found no significant Airy-type crustal root; the mountain range seems largely supported by the buoyant asthenosphere beneath an abnormally thin mantle lithosphere. We suggest that the late Cenozoic uplift of the Sierra Nevada may have resulted from mantle upwelling under the Basin and Range province, which tends to push ductile material within the surrounding lithosphere, causing it to flow away and downward. Numerical modeling indicates that such ductile flow could lead to pronounced lithospheric thinning under the High Sierra and lithospheric thickening under the western Sierra Nevada, comparable to the observed structure.

INTRODUCTION
The formation of the Sierra Nevada mountain range in eastern California has been a subject of considerable controversy. The Sierra Nevada was uplifted mainly in the past 20 m.y. (Huber, 1981) and is now ~2800 m above the adjacent lowlands (Fig. 1A). Some seismic studies suggested that the range is supported by an Airy-type crust root as thick as 55 km (Eaton, 1966; Pakiser and Brune, 1980). However, batholith formation in Mesozoic time (>75 Ma) was the latest tectonic event capable of significantly thickening the crust; thus the timing is difficult to reconcile (Chase and Wallace, 1988). Other seismic investigations, however, found no significant crustal root under the Sierra Nevada (Carder, 1973; Jones et al., 1994), and the cause of uplift has been attributed to upwelling of the asthenosphere under the range (Crough and Thompson, 1977). This interpretation is supported by the recent multidisciplinary studies in the southern Sierra Nevada (Ducea and Saleeby, 1996; Fliedner et al., 1996; Wernicke et al., 1996). These studies concluded (Fig. 1B) that (1) there is no major crustal root under the Sierra Nevada—the crust there is slightly thicker (<5 km) than it is under the adjacent lowlands, and the thickest crust is ~40 km west of the High Sierra; and (2) the mantle lithosphere is abnormally thin under the High Sierra and thickens to the west. These results are consistent with the high mantle heat flux in the eastern Sierra Nevada and low heat flux to the west (Saltus and Lachenbruch, 1991). The Sierra Nevada seems to be mainly supported by an upwelled asthenosphere (Ducea and Saleeby, 1996; Wernicke et al., 1996).

These studies have greatly refined the lithospheric structure of the Sierra Nevada, but they also raise many new questions about mountain building in this region. In particular, it is not clear what caused the pronounced thinning of the mantle lithosphere under the Sierra Nevada. One hypothesis links the thinning to extension in the adjacent Basin and Range province in a simple-shear model (Jones, 1987), but this model does not explain all aspects of the observed lithospheric structure, especially the thick mantle lithosphere under western Sierra Nevada.

We propose here a new model that links the late Cenozoic uplift of the Sierra Nevada to ductile flow within the lithosphere induced by asthenospheric upwelling under the Basin and Range province.

MANTLE UPWELLING UNDER THE BASIN AND RANGE PROVINCE
The northern Basin and Range tectonic province (the Great Basin), bounded to the west by the Sierra Nevada, is one of the most extended continental regimes in the world (Fig. 1A). Although major extension may have started as early as late Eocene time (Coney, 1987), the present physiography of the province has resulted mainly from basin-and-range extension during late Cenozoic time (<20 Ma) (Wernicke et al., 1988; Zoback et al., 1981). This extension is closely associated with basaltic and bimodal (basaltic-rhyolitic) volcanism. The young (<5–6 Ma) basaltic lavas have an asthenospheric origin (Daley and DePaolo, 1992; Leeman and Harry, 1993). Since the mid-Miocene, both extensional faulting and volcanism have been migrating toward the margins of the Great Basin (Armstrong and Ward, 1991; Wernicke et al., 1987).
NEW MODEL OF SIERRA NEVADA UPLIFT

We suggest that mantle upwelling under the Basin and Range province may have caused the lithospheric thinning beneath the Sierra Nevada. As shown in Figure 2, an upwelling asthenosphere may induce a lateral pressure gradient near its margin, and this pressure gradient tends to push the surrounding lithospheric material causing it to flow outward. This process is similar to the lateral extrusion of ductile lower crust under a thickened crust (Bird, 1991), except that here the lateral density contrast that drives ductile flow is caused by asthenospheric upwelling, and ductile flow may occur within both the lower crust and the mantle lithosphere, the ductility of which may be greatly enhanced by advective heating associated with asthenospheric upwelling. As we show here, such ductile flow may lead to pronounced thinning of the lithosphere surrounding the asthenospheric upwelling.

NUMERICAL RESULTS

We have tested this model by numerically simulating time-dependent ductile flow within the lithosphere near asthenospheric upwelling. The model geometry is shown in Figure 3A.1 The rheologic structure of the model lithosphere includes a brittle upper crust, a ductile lower crust, and a ductile mantle lithosphere. Rheology of the ductile crust and mantle lithosphere is approximated by the experimentally determined parameters for the Westerly granites (Carter et al., 1981) and olivine (Korato et al., 1986), respectively. For the

1GSA Data Repository item 9833, model descriptions, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301. E-mail: editing@geosociety.org.

velocity field, the top boundary is defined as the base of the brittle crust, and the flow rate within the brittle crust is set to zero. The left side is a far-distance boundary, the effects of which on the flow field are proven to be negligible. The model assumes local isostasy. The simulations start with an instantaneous upwelling of the asthenosphere (Fig. 3A). During the experiments, temperature is held at 1300 °C at the initial base of the lithosphere, and temperature within the upwelling asthenosphere is taken to be adiabatic.

Figure 3B shows a snapshot of the predicted velocity field. The horizontal components of the flow result directly from the lateral pressure gradient induced by the upwelling asthenosphere (see Fig. 2). The vertical components are calculated from mass conservation. It is not surprising that ductile flow is concentrated near the corner of the asthenospheric upwelling, where the lateral pressure gradient is the highest. As a result of such flow, mantle lithosphere is gradually replaced by the asthenosphere; the flow is resisted by the stiff mantle lithosphere farther from asthenospheric upwelling, and the removed mantle lithospheric material, being relatively cold and dense, sinks into the asthenosphere. Figure 4A shows the time-integrated boundary between the asthenosphere and the lithosphere. It suggests that ductile flow within the lithosphere could lead to (1) gradual thinning of the mantle lithosphere near the margin of the upwelling asthenosphere and (2) thickening or “dripping” of mantle lithosphere farther away. The resultant lithospheric structure is comparable to that observed under the Sierra Nevada (cf. Fig. 1B).

The outward flow within the ductile crust tends to thin the crust over the inner margin of the upwelling asthenosphere. Farther from the center of mantle upwelling, the cold and stiff ambient crust prohibits the lateral crustal extrusion, and material accumulates and thickens the crust. The concomitant crustal thinning and thickening may reverse the elevation contrast between the region of mantle upwelling and its surroundings, thus reducing the flow rate or even reversing the direction of crustal flow. However, our results indicate that the relatively strong flow within the mantle lithosphere tends to drag crustal material, causing it to flow outward, as long as the density contrast between the upwelling asthenosphere and the surrounding lithosphere is maintained. Felsic material has a higher ductility than mafic material; a more efficient flow of felsic materials within the crust may have contributed to the relatively thick layer of low-density crust under the High Sierra (Fliedner et al., 1996).

The results presented here are meant to illustrate the basic physics; the general flow patterns will not change if different rheological parameters are used, but the predicted flow rates need to be viewed with caution because they are sensitive to uncertainties of rheological parameters and the thermal structure of the upwelling asthenosphere. The results (Figs. 3B and 4) were derived by assuming (1) an adiabatic geotherm sustained through the modeling within the upwelling asthenosphere and (2) a fixed temperature (1300 °C) at the initial asthenosphere-lithosphere boundary. These conditions may be a reasonable first-order approximation, if thermal structure within the upwelling asthenosphere is controlled by convective heating. Considering the dynamic flow field within the upwelling asthenosphere and the thermal-mechanical erosion of the lithosphere may lead to increased thinning of the lithosphere (Liu and Chase, 1989). However, if upwelling of the asthenosphere is passive, such that the thermal structure of the upwelling asthenosphere is controlled by conductive cooling following its initial ascension, the predicted rates of ductile deformation would be much lower.

DISCUSSION

The close spatial and temporal correlations between basin-and-range extension and the late Cenozoic uplift of the Sierra Nevada suggest a genetic link between these two events (Jones, 1987), and it has been long suspected that the mantle structure under the Sierra Nevada is related to that beneath the Basin and Range province (Crough and Thompson, 1977; Wernicke et al., 1996). We suggest here that the lithospheric thinning under the Sierra Nevada, and thus the uplift of the range, may have resulted from ductile deformation of the lithosphere induced by mantle upwelling under the Basin and Range province.
In addition to predicting lithospheric thinning under the Sierra Nevada, the model yields a number of interesting predictions that may have important tectonic implications. It is intriguing to compare the predicted thickening or “dripping” of mantle lithospheric material (Fig. 4A) to the observed seismic high-velocity anomaly in the upper mantle under the western Sierra Nevada (Biasi and Humphreys, 1992; Jones et al., 1994). This anomaly is characterized by compressional velocities as much as 4%–5% higher than its surroundings and extends to >200 km depth in a form close to a vertical cylinder. It is located beneath the thickest crust in the western Sierra Nevada, similar to the model prediction (Fig. 4). Jones et al. (1994) and Zandt and Ruppert (1996) suggested that this seismic anomaly reflects a convective downwelling flow in the upper mantle. Our model does not exclude this convection model. Rather, ductile flow of the lithospheric material suggested here would enhance convective instabilities within the upper mantle, or vice versa. Although this two-dimensional model cannot fully describe the three-dimensional mantle anomaly, the small-scale downwelling flows discussed here would coalesce in nature to form plumelike drips (Liu and Zandt, 1996; Zandt and Carrigan, 1993). A coalescing downwelling flow may be indicated by the merging of the high-velocity body under the western Sierra Nevada at depth (>90 km) with shallower (30–90 km) northwest–southeast–trending high-velocity regions (Biasi and Humphreys, 1992).

This model may also offer some explanation for the observed outward migration of volcanism and extension in the Great Basin since mid-Miocene time (Armstrong and Ward, 1991; Wernicke et al., 1987). As shown in Figure 4A, ductile thinning of the mantle lithosphere is concentrated near the upper corner of the upwelling asthenosphere and migrates outward over time. Because the full dynamic field within the upwelling asthenosphere is not included in this model, we cannot fully simulate the time-progressive changes of the asthenosphere-lithosphere boundary. However, some previous models of continental extension have suggested that, for a broad asthenospheric upwelling, thinning of the lithosphere is more pronounced near the margins where the vorticity is the highest (Keen, 1985). The prolonged mantle upwelling under the Basin and Range province may have caused outward migration of lithospheric thinning and volcanism by both focused mechanical erosion of the lithosphere near its margin and ductile flow within the surrounding lithosphere, as discussed here. Whether the ductile flow also played a role in the late Cenozoic volcanism within the Sierra Nevada province (Moore and Dodge, 1980) is a question for further studies.

If the model presented here is essentially correct, we may speculate whether similar processes have occurred in the other side of the Basin and Range province. Although the uplift history of the Colorado Plateau is long and complicated (Gregory and Chase, 1992; Spencer, 1996), the lithospheric structure of the transition zone between the Basin and Range province and the Colorado Plateau, constrained from seismic and gravity data (Zandt et al., 1995), is somewhat similar to that of the Sierra Nevada, including a significantly thinned mantle lithosphere near the margin of the Basin and Range province.

Probably no simple model can fully account for the tectonic history of the Sierra Nevada and the Basin and Range province, but the model presented here has the potential to explain some major features of the tectonic
evolution in this region. Ductile flow within the mantle lithosphere is known to play an important role in the tectonic evolution of ocean floor; in continental tectonics, however, studies of ductile flow have been largely limited to the lower crust. Given the sensitivity of mantle rheology to temperature and potentially strong thermal interactions between the asthenosphere and lithosphere under active tectonic regions, such as in the Basin and Range province, the role of ductile flow within the mantle lithosphere may be significant and deserves further study.

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