The Sierra Nevada uplift: A ductile link to mantle upwelling under the Basin and Range province

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GSA Data Repository: Model Descriptions

The model used in this paper simulates ductile deformation within the lithosphere surrounding an upwelled asthenosphere. Ductile flow is driven by the lateral pressure gradient \((dP/dx)\) induced by thermal perturbations associated with asthenospheric upwelling (see Figure 2). Density changes with thermal perturbations as:

\[
\Delta \rho = \rho_0 (1 - \alpha \Delta T)
\]  

(1)

where \(\rho_0\) is the reference density, \(\alpha\) is the thermal expansion coefficient, and \(\Delta T\) is thermal perturbation. With transient thermal structures as in this model, we numerically calculate the lateral pressure gradient resulted from density perturbations at each time-step after the thermal field is solved. Local isostasy is assumed in the calculations.

The governing equations are the conservation of mass, momentum, and energy:

\[
D(x,z) = \frac{\partial u_i}{\partial x_i} = 0
\]  

(2)

\[
\frac{\partial \tau_{ij}}{\partial x_j} = \frac{\partial P}{\partial x_i}
\]  

(3)

\[
\frac{\partial T}{\partial t} = k\nabla^2 T + \frac{1}{\rho C_p} A_r
\]  

(4)
where \( u_i \) is the velocity component in the direction of \( x_i \) and \( D(x,z) \) is a function used in the numerical scheme to enforce volume conservation, \( \tau_{ij} \) is the deviatoric stress, \( t \) is the time, \( \kappa \) is the thermal diffusivity, \( C_p \) is the specific heat, and \( A_i \) is the volumetric radiogenic heating. The parameter \( P \) in (3) is the non-lithostatic pressure defined as:

\[
P = p - \rho gy
\]

where \( p \) is pressure, \( \rho \) is density, \( g \) is gravitational acceleration, and \( y \) is the vertical distance.

The lithospheric rheology used in the model is that of a power-law fluid (England and McKenzie, 1982; Kirby and Kronenberg, 1987):

\[
\tau_{ij} = B E^{(1/\eta - 1)} \hat{\varepsilon}_{ij}
\]

where \( \hat{\varepsilon}_{ij} \) is the strain rate tensor:

\[
\hat{\varepsilon}_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)
\]

The parameter \( \hat{E} \) is the second invariant of the strain rate tensor:

\[
\hat{E} = \left( \hat{\varepsilon}_{ij} \hat{\varepsilon}_{ij} \right)^{1/2}
\]

and the coefficient \( B \) is a function of temperature and material property:

\[
B = A^{-1/\eta} \exp \left( \frac{Q}{nRT} \right)
\]
where \( R \) is the gas constant, \( A, n \) and \( Q \) are lithology-dependent rheological constants. The rheological parameters of the Westerly granite (Carter et al., 1981) and olivine (Korato et al., 1986) are used for the model crust and mantle, respectively.

Substitute (6)-(9) into (4), the velocity components can be expressed in the form of the Poisson’s equation:

\[
\nabla^2 u_i = -\frac{\partial D}{\partial x_i} + \frac{2}{B} E^{(1-1/n)} \frac{\partial P}{\partial x_i} + 2 \left( 1 - \frac{1}{n} \right) \dot{\varepsilon}_i - \frac{Q}{nRT^2} \frac{\partial T}{\partial x_i} \dot{\varepsilon}_j; (i, j = 1, 2)
\]

At each time-step the thermal field is solved using the Lax method, and then the velocity field is determined by solving (10) using the simultaneous overrelaxation (SOR) method (Press et al., 1986).

The time-dependent changes of the crustal thickness are determined through volume conservation of crustal rocks:

\[
\frac{\partial h}{\partial t} = -\frac{\partial F_x}{\partial x}
\]

where \( h \) is the thickness of the crust, and \( F_x \) is the net horizontal mass flux in the crust:

\[
F_x = \int_{\text{Surface}}^{\text{Moho}} udz
\]

The changes of the thickness of mantle lithosphere is determined in a similar way by integrating mass flux from the Moho to the base of the reference lithosphere.

The model geometry and boundary conditions are shown in Figure 3a. We have also tested with a free velocity boundary (\( \partial u / \partial x = 0 \)) at the left edge of the model, the results are essentially the same as those of a fixed boundary in Figure 3. This is because the driving pressure gradient and thermal perturbations are concentrated near the margin of the
upwelled asthenosphere, so the left edge of the model, chosen to be a far-distance boundary, has little effects on the flow field.

References


