The Dynamics of the Pacific-North America Plate Boundary Zone since the Oligocene

William Holt
Ali Bahadori
Troy Rasbury
Laurent Montessi
The time-dependent strain rate field for the southwestern North American Lithosphere Since 36 Ma

Contours of dilatational strain rates of western U.S. from 36 Ma to present-day (Bahadori et al., 2018) Geosphere
Our calculation of crustal thickness evolution involves:

1) tracking coordinate changes through time based on the time-dependent horizontal velocity gradient tensor field.

2) tracking the crustal thickness changes of those corresponding coordinates.

Reconstruction of Crustal Thickness Evolution in Western U.S.

Weissen Shen and Michael H. Ritzwoller

Department of Physics, University of California at Santa Barbara, USA.


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We highlight these low-velocity anomalies in the upper mantle that underlie the Appalachians with centers of anomalies in northern Georgia, western Virginia, and most prominently, New England.

present day model of western U.S. crustal thickness in km from Shen and Ritzwoller (2016).
Assumptions:

1) We approximate zero volume change, and thus the vertical strain rates $\epsilon_{zz} = -(\epsilon_{xx} + \epsilon_{yy})$.

2) We assume that the lithosphere deformation is vertically coherent.

3) We ignore erosion and igneous input.
Finite Strain Estimate Inferred From Distribution of Vertical Strain

\[
\frac{dF}{dt} = LF \quad \Rightarrow \quad H_{\text{old}} = H_{\text{young}} \exp (-\varepsilon_{zz} \Delta t)
\]

\textit{Mckenzie and Jackson (1983)}

Contour map of standard error estimates (km) of crustal thickness for the Basin and Range of the western United States at 36 Ma.

White circles are reconstructed position of Metamorphic Core Complexes (MCCs) (Bahadori et al., 2018) Geosphere
Using the Laplace equation and assuming constant thermal conductivity, the steady-state conductive heat distribution with no heat generation is:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = 0$$

Using the Fourier equations, then the heat flow \((Q)\) in the \(x\) and \(y\) directions is calculated as:

\[ Q_x = -k_A \frac{\partial T_{i(x)}}{\partial x} \]
\[ Q_y = -k_A \frac{\partial T_{i(y)}}{\partial y} \]

Based on thermal expansion of upper mantle at constant pressure and differential temperatures the new time and temperature dependent upper mantle is produced as:

\[
\rho_T(\phi_{k-1}, \theta_{k-1}) = \rho_T(\phi_k, \theta_k) / [1 + \alpha \times \Delta T(\phi_{k-1}, \theta_{k-1})]
\]

(Bahadori et al., 2018) Geosphere
Final integrated topography model shows a highland with an average elevation of $\sim 3.9 \pm 0.3$ km in central, eastern, and southern Nevada, western Utah, parts of easternmost California, and for northwestern Arizona. The Mogollon Highlands are also present within central and southeastern Arizona at 36 Ma.

(Bahadori et al., 2018) Geosphere

Paleoelevation evolution of western U.S. from 36 Ma to present-day. Red and gray dots are the reconstructed positions of present-day coordinates of magmatism in western U.S. (Bahadori et al., 2018)
What is the state of deviatoric stress that generated the collapse?

Vertically integrated deviatoric stresses associated with GPE differences
Depth Integrated Forward Dynamic Deviatoric Stresses

1) Invert for stress boundary conditions. Observations = kinematic tensor field

2) Apply Forward model using velocity boundary conditions, GPE gradients (body forces), laterally varying effective Viscosity (T/E) from inverse model. Method outlined in Flesch et al. (2001)
What do boundary condition solutions represent? Answer = coupling with global mantle flow

Deviatoric stresses from lithosphere coupling with global mantle flow S40RTS (Wang et al., 2015)

Best fit boundary condition solution of deviatoric stresses at 0 Ma
[Becker, 2012; Schmandt and Humphreys, 2010; Schmandt and Humphreys, 2011; Simmons et al., 2009]
Stresses from Mantle Flow Associated Trazctions

Total Stresses from Mantle Flow + GPE Gradients

[Becker, 2012; Schmandt and Humphreys, 2010; Schmandt and Humphreys, 2011; Simmons et al., 2009]
Forward Dynamic Model Compared with stretch directions from core complexes, Miocene faults and dikes
The Role of GPE For Driving the Extensional Collapse of the Western U.S.
Forward model: velocity boundary conditions, GPE gradients (body forces), laterally varying effective Viscosity (T/E) from inverse model.
The Role of Slab Roll Back for Lithospheric Deformation and Core Complex Development in Western U.S.

Effective Viscosity of Lithosphere in Western U.S. from Forward Dynamic Model

\[ \bar{\eta}_{\text{effective}} = \frac{T}{E} \]

Hydration hypothesis for Laramide and mid-Tertiary magmatism, tectonism and uplift for western U.S. (Humphrey et al., 2003).

Depth integrated effective viscosity of the lithosphere in western U.S. from 36 Ma to present-day.
Computation of Lithospheric Effective Water Content Variation in Western U.S.

\[ \eta_{\text{eff}} = \varepsilon^{(1-n)} A^{-n} C_{\text{OliH}}^{-r} \left[ \exp \left( -\frac{H + PV}{RT} \right) \right]^{\frac{1}{n}} \times 10^6 \]

\[ \eta_{\text{eff}}: \text{effective viscosity} \]
\[ \varepsilon: \text{strain rate} \]
\[ n: \text{stress exponent (3.5)} \]
\[ r: \text{fugacity exponent (1.2)} \]
\[ R: \text{gas constant} \]
\[ H: \text{activation enthalpy} \]
\[ H = Q + PV (Q: \text{activation energy, V: volume, P: pressure}) \]
\[ T: \text{temperature} \]
\[ A: \text{material constant} \]
\[ n, A, Q \text{ and V were determined experimentally for the given material (olivine) (Dixon et al., 2004)}. \]

- The upper mantle is primarily composed of olivine, which is known to be weakened by water, thus increasing the strain rate.

- Nominally anhydrous minerals (including olivine) may have a significant effect on the viscosity and rheology of the upper mantle.
Velocity and strain rate field from forward dynamic model (velocity boundary conditions, GPE gradients, laterally varying effective viscosity).
Vertically averaged effective viscosities and velocity residuals (dynamic vs. GPS – Pacific frame)
Geodynamic Modeling Vs. Rheological Modeling

Conclusions

• Our results indicate GPE gradients originating from high paleotopography dominated the extensional stress field prior to and during core-complex formation.

• Dramatic weakening of the lithosphere viscosity accompanied the collapse. Some regions have experienced rheological hardening.

• The most likely weakening influence is heat and fluids associated with slab rollback and volcanism.

• The 45° rotation of extension directions between Miocene to present-day can be explained by the increasing importance of Pacific-North America relative plate motions.

• Present-day rheology in Southern California is consistent with intermediate mix between dry and wet end-members.
Shear modulus and upper mantle density are both a function of temperature and pressure.

Using calculated pressures in WUS for each 0.5 km depth (Moho to 100 km) and a reference dataset for pressure, temperature and Vs (Goes et al., 2000) we determine the temperatures for each specific depth.

Using the method of Wu et al. (2013) the depth integral of viscosity is computed using the shear velocity data (Shen and Ritzwoller, 2016) and temperature data.

\[
\log_{10}(\Delta \eta) = \frac{-0.4343 \beta}{[\partial \ln v_s/\partial T]_{ah+an}} \frac{(E^{*} + pV^{*})}{RT_{0}^{2}} \frac{\delta v_{s}}{v_{s}}
\]

Wu et al. (2013)
We find that differences between the two viscosity models can be reconciled if the FLUID CONTENT within the upper mantle lithosphere below the actively straining regions of the Great Basin is elevated relative to areas along the edges of the Colorado Plateau and within the Rio Grande Rift, which are both relatively dry in comparison to the Great Basin.
At 100 km depth, most of the Basin and Range province is essentially at asthenospheric temperatures (Shutt et al., 2012).

TEMPESTAT.ORG

Influence of Thermal Perturbations on Western U.S. Upper Mantle Densities

Present-day localities of western U.S. magmatism vs. time

Magmatism in the western U.S. over the past 40 Myrs from NAVDAT.org
Lithosphere Foundering of Laramide Flat Subduction and Upper Mantle Temperature Variation

Temperatures at 100 km depth

At 100 km depth, most of the Basin and Range province is essentially at asthenospheric temperatures (Schutt et al., 2012)

Upper mantle temperature variation in western U.S. from 36 Ma to present-day. Gray dots are the reconstructed position of western U.S. magmatism from NAVDAT.org
Crustal density from seismic velocities after the estimated thermal variations are removed. (Levandowski et al., 2014)
Present-day Upper Mantle Density Model for Western U.S.

Shear wave speed maps at 90 km depths from *Shen and Ritzwoller (2016)* (left); *Porter et al. (2016)* (right).