

2013 SCEC4 Activity Report

Mechanisms of Postseismic Deformation Following the 2010 M=7.2 El Mayor-Cucapah Earthquake

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Summary

SCEC4 funding has provided support for a project carried out by Chris Rollins, a former SCEC intern and USC geology student who is currently a graduate student in the Caltech Seismological Laboratory; Sylvain Barbot, a former Caltech postdoctoral scholar who is currently an assistant professor at the Earth Observatory of Singapore; and Jean-Philippe Avouac (PI). We used continuous GPS data to constrain the transient surface deformation following the 2010 M=7.2 El Mayor-Cucapah earthquake in Baja California, Mexico, then used a combination of kinematic inversion and forward modeling to infer which deformation mechanisms could have contributed to the transient. Our findings will shed light on the rheology of the lithosphere and asthenosphere, with implications for the mechanics of fault loading, and on the way that the states of stress along the Elsinore, San Jacinto and San Andreas faults may have evolved in the time since the El Mayor-Cucapah earthquake. We have presented preliminary findings from this project at the 2012 SCEC Annual Meeting and the 2012 AGU Fall Meeting and plan to present updated research at the 2013 SSA Annual Meeting. In addition, we plan to submit a paper detailing our findings to the Journal of Geophysical Research in May 2013. Funding from SCEC4 provided partial support for the graduate student salary of Chris Rollins during 2012.

Motivation

In addition to earthquakes, the earth's lithosphere deforms through gradual processes that include aseismic slip on fault zones above and below seismogenic depths, ductile flow in the lower crust and upper mantle, and pore fluid motion in the crust. These processes affect the states of stress on faults and thus the evolution of seismic hazard between earthquakes. The stress changes imparted by a large earthquake can accelerate these processes, resulting in a transient of accelerated surface deformation in the period following the mainshock. The spatiotemporal evolution of this transient can be studied by geodetic methods and can ideally be used to infer the deformation processes that caused it, providing constraints on the spatial extents and behaviors of those processes on longer timescales.

The Salton Trough in northern Mexico may be an ideal site in which to use this method to study the nature of sublithospheric ductile flow. Here the extensional component of relative Pacific-North American plate motion has thinned the lithosphere and brought the asthenosphere up to within ~40 km of the surface [Lekic et al 2011], while the transform component of relative motion produces large strike-slip earthquakes above this shallow asthenosphere. The most recent such earthquake, the 2010 El Mayor-Cucapah shock, was the largest in this region since at least 1892 and occurred directly above shallow asthenosphere (Figure 1a). We postulate that postseismic surface deformation following this earthquake may contain a particularly strong signal of viscoelastic relaxation in the asthenosphere, potentially yielding insights into the nature of sublithospheric flow that may be difficult to extract elsewhere.

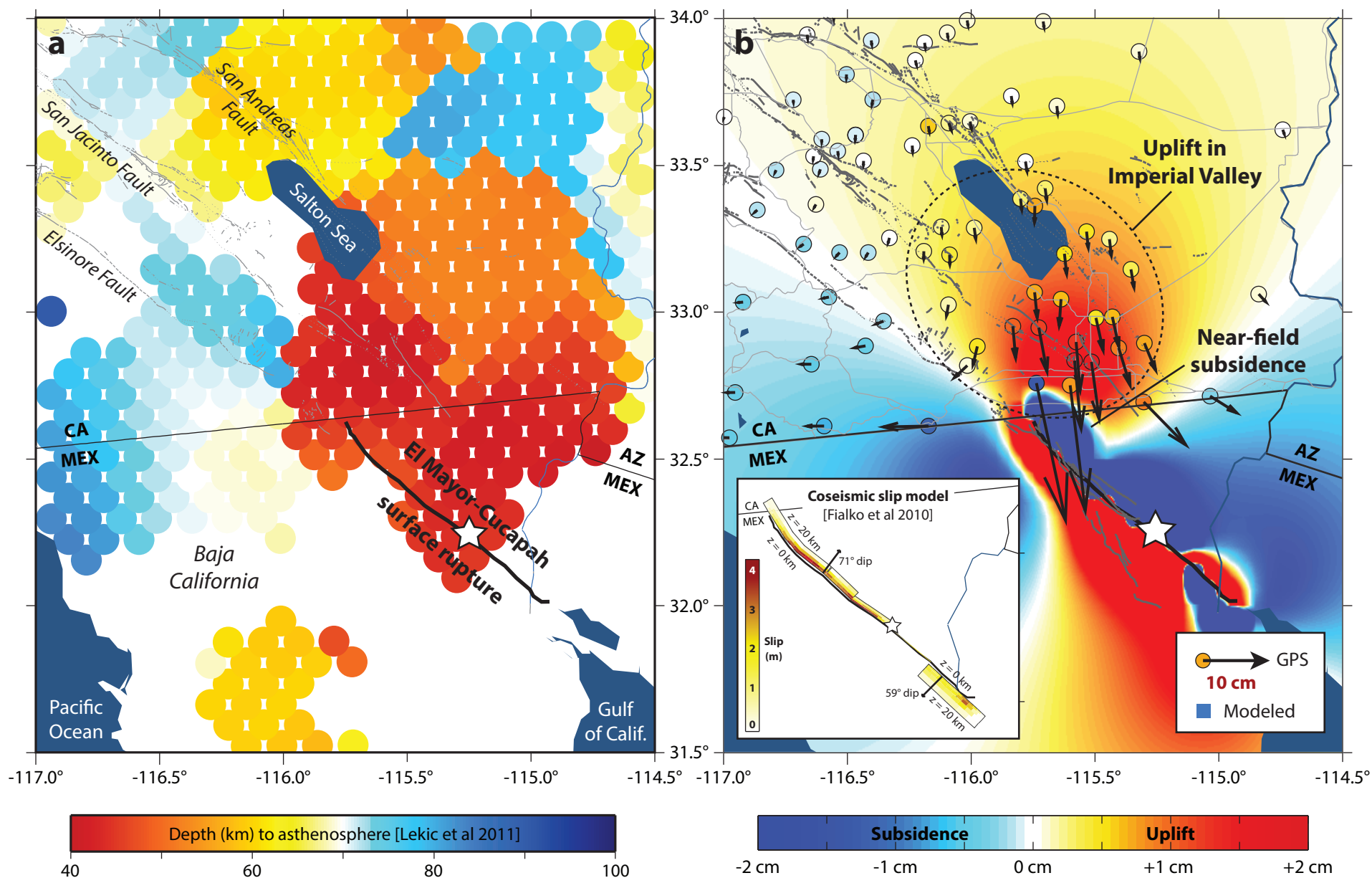


Figure 1. a) Distribution of depths to the lithosphere-asthenosphere boundary inferred by Lekic et al [2011] and location of El Mayor-Cucapah earthquake. Thick black line is surface rupture of earthquake; white star is epicenter. **b)** Deformation during the mainshock. Black vectors represent horizontal offsets at GPS stations on the day of the mainshock; colored circles represent vertical offsets (red is uplift, blue is subsidence). Colored surface is distribution of surface uplift and subsidence calculated from Fialko et al [2010] slip model in an elastic halfspace. Inset: Mapview of slip planes and slip distribution in Fialko et al [2010] model. Note that the northwest and southeast portions of the rupture dip opposite directions.

Preliminary results: modeling of afterslip and asthenospheric flow

Coseismic and postseismic surface deformation was well covered by an array of UNAVCO GPS stations located north of the international border (Figure 1b; Figure 2a), and multiple finite-fault models for the mainshock have been published. We are using the RELAX software (geodynamics.org/cig/software/relax) to simulate the coseismic stress changes imparted by the Fialko et al [2010] mainshock model to the surrounding medium, the relaxation of those mechanisms by hypothesized postseismic processes, and the resulting synthetic timeseries of surface displacement at the locations of GPS stations.

First, to assess whether postseismic deformation following the El Mayor-Cucapah earthquake can be attributed entirely to deep afterslip, we designed a model in RELAX simulating triggered afterslip on the deep extensions of the Fialko et al [2010] coseismic rupture surfaces. The model predicts strong postseismic subsidence in the Imperial Valley in contrast with the systematic uplift observed in extracted GPS displacements there (Figure 2b), indicating that deep afterslip is unlikely to have been the dominant mechanism of postseismic deformation. However, it is possible that a more complex combination of shallow and deep slip could successfully reproduce the displacements observed in GPS.

To assess whether viscoelastic relaxation in the shallow Salton Trough asthenosphere could have played a part in postseismic deformation, we fit the Lekic et al [2011] regional lithosphere-asthenosphere boundary surface with a simple geometry (Figure 3a) and modeled viscoelastic flow below this geometry governed by linear and power-law rheologies. Elastic dislocation modeling suggests that the mainshock extended the shallow Salton Trough asthenosphere upward and southward toward the rupture (Figure 3b-c). The simulated asthenosphere accommodates this extension by flowing upward and southward during the postseismic period, producing uplift in the Imperial Valley consistent with that observed in GPS data (Figure 3d). However, this simulated flow fails to reproduce the southerly component of offsets observed at GPS stations in the Imperial Valley. This suggests that asthenospheric flow did play some role in postseismic deformation but may have occurred in concert with other mechanisms. Multiple studies of postseismic deformation following large strike-slip earthquakes have found that afterslip best explains near-field displacements while viscoelastic relaxation in the upper mantle best explains displacements farther from the rupture [Freed et al, 2006; Freed et al, 2007], and the same may be true for the El Mayor-Cucapah earthquake. The high heat flow in the Salton Trough may result in a regime in which all material below the brittle-ductile transition is relatively weak [Williams 2012], and so the most realistic model may also require viscous flow in the lower crust and mantle lithosphere. Finally, near-field postseismic deformation following several large strike-slip earthquakes has been attributed to the movement of fluids throughout the crust in responses to coseismic changes in pore fluid pressure [Peltzer et al 1998; Fialko et al 2004]. The formulation of RELAX allows us to realistically and efficiently simulate the nonlinear ways in which each of these deformation mechanisms may feed back on each other as each affects the state of stress in the surrounding medium [Barbot et al 2010]. Our objective is to use these capabilities to find a suite of deformation models that, using as few parameters as possible, reproduce the extracted timeseries of displacement at GPS stations in all directions from the rupture and in both the near and far field.

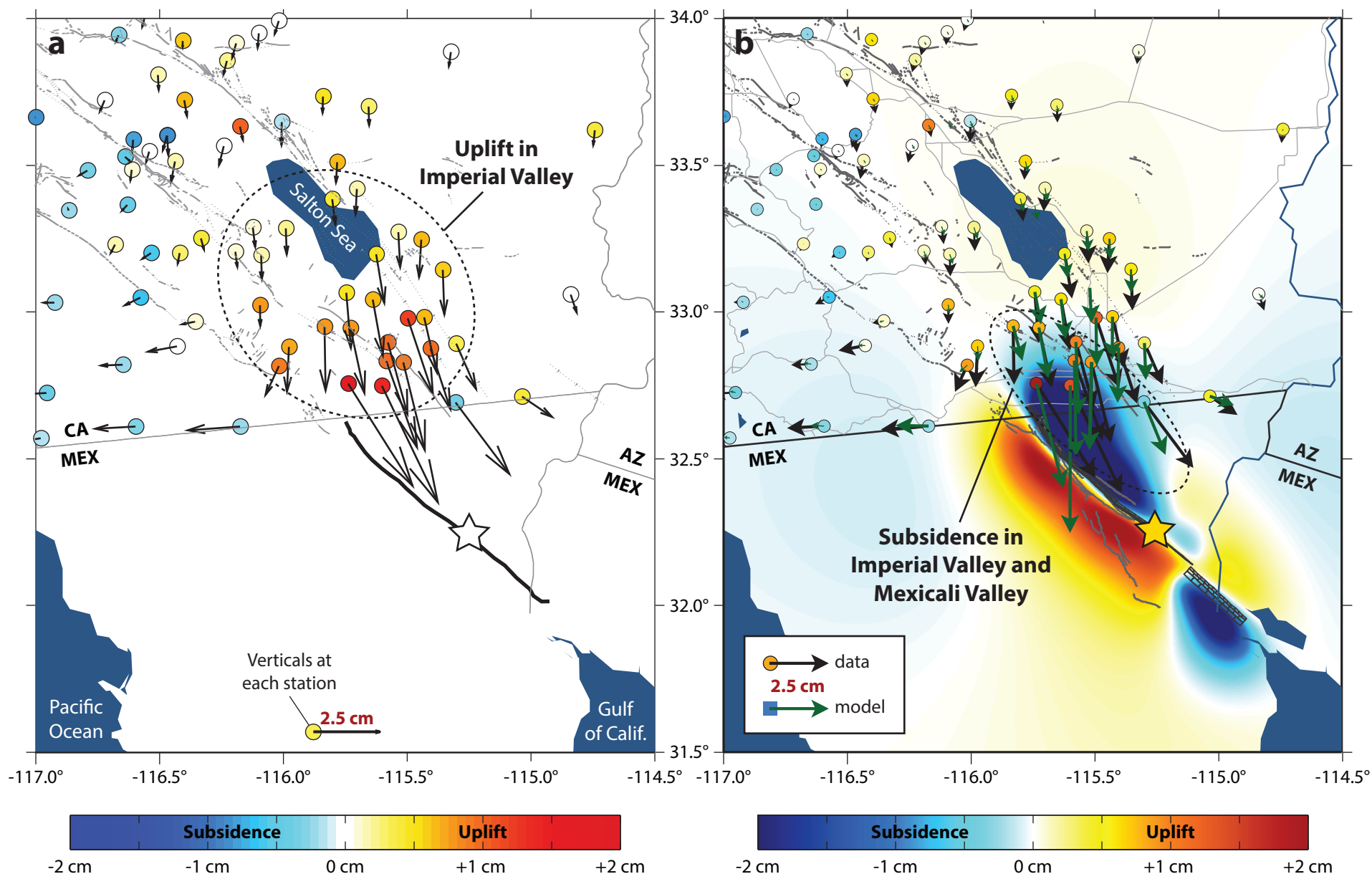


Figure 2. a) Cumulative horizontal and vertical displacements of extracted postseismic signals at UNAVCO GPS stations in the first year after the El Mayor-Cucapah earthquake. Colors of circles represent magnitudes of vertical displacements; black vectors are represent cumulative horizontal offsets. Note change in vector scale from figure 1b: magnitudes of near-field horizontal postseismic displacements are $\sim 1/4$ those of coseismic displacements. **b)** Comparison between data and synthetic one-year displacements produced by modeled afterslip at 10-17 km depth on the deep extension of the rupture. Black vectors and colored circles are GPS displacements shown in figure 2a; green vectors are synthetic displacements at GPS stations; colored surface is distribution of synthetic surface uplift and subsidence.

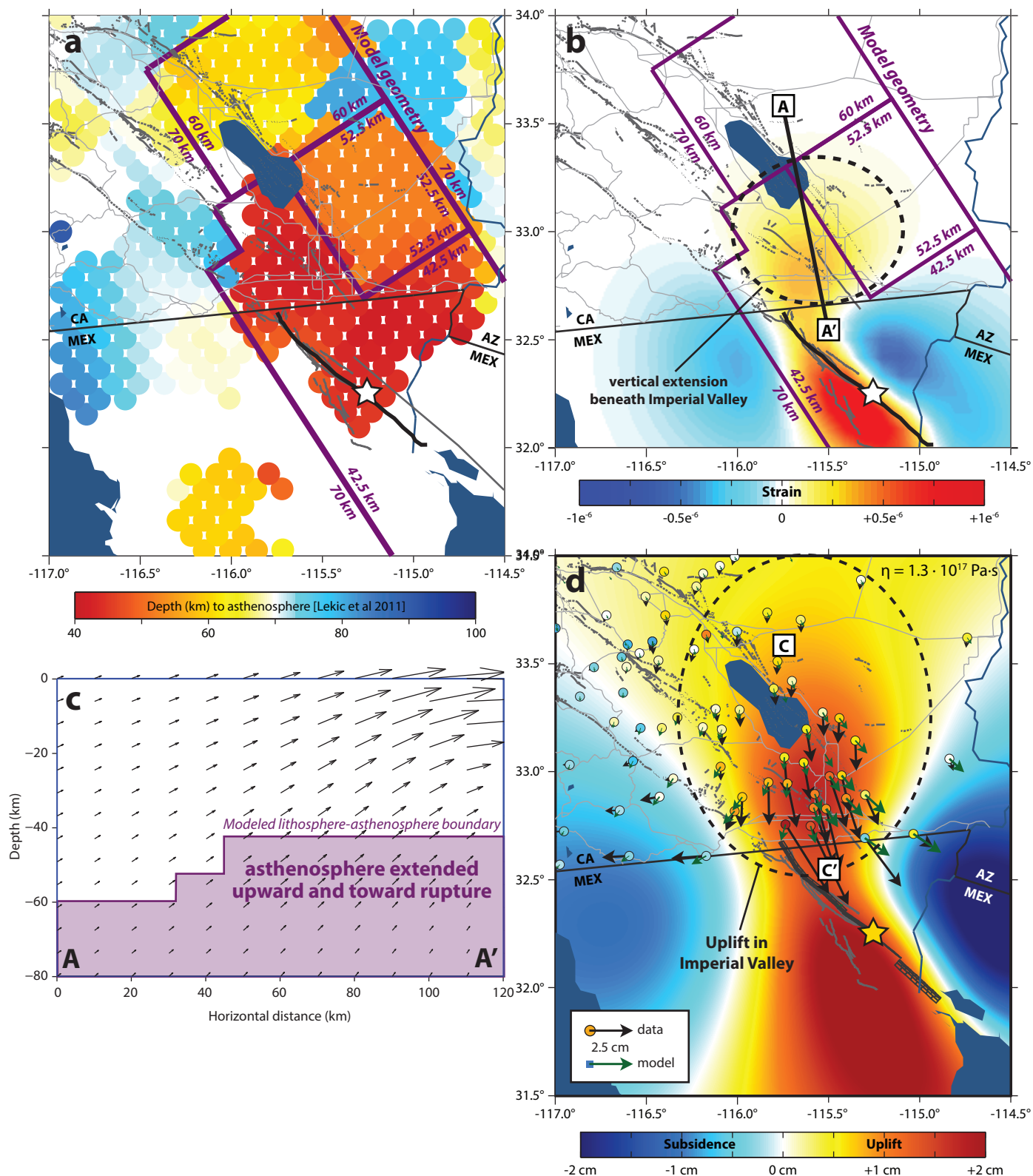


Figure 3. Modeled viscoelastic relaxation in the asthenosphere. **a)** Distribution of depths to the lithosphere-asthenosphere boundary inferred by Lekic et al [2011] and geometric model of shallow asthenosphere in the Salton Trough. Depths in purple are the top depths of the modeled asthenosphere. **b)** Simulated distribution of extensional vertical strain (red indicates extension, blue indicates compression) imparted by the Fialko et al [2010] slip model to an elastic halfspace at 50 km depth, near the top of the modeled viscoelastic asthenosphere in the Salton Trough. **c)** Cross section of displacements at depth in the section of the elastic halfspace corresponding to the Imperial Valley. The purple domain is the modeled asthenosphere in the plane of the cross section, extending up to within 42.5 km of the surface within most of the Imperial Valley. **d)** Comparison between data and synthetic cumulative one-year displacements produced by modeled viscoelastic relaxation in the asthenosphere. Black vectors and colored circles are extracted GPS displacements from figure 2a; green vectors are synthetic displacements at GPS stations; colored surface represents synthetic surface uplift and subsidence.

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