Earth and Planetary Science Letters 402 (2014) 234–246

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

# Static and dynamic support of western United States topography

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ARTICLE INFO

*Article history:*
Accepted 7 October 2013
Available online 31 October 2013
Editor: P. Shearer

*Keywords:*
western United States
dynamic topography
mantle convection
Moho
LAB
EarthScope USArray

ABSTRACT

Isostatic and dynamic models of Earth's surface topography can provide important insights into the driving processes of tectonic deformation. We analyze these two estimates for the tectonically-active western United States using refined structural models derived from EarthScope USArray. For the crust, use of recent Moho depth measurements and crustal density anomalies inferred from passive source seismology improve isostatic models. However, seismically determined lithospheric thickness variations from "lithosphere–asthenosphere boundary" (LAB) maps, and lithospheric and mantle density anomalies derived from heat flow or uppermost mantle tomography, do not improve isostatic models substantially. Perhaps this is a consequence of compositional heterogeneity, a mismatch between thermal and seismological LAB, and structural complexity caused by smaller-scale dynamics. The remaining, non-isostatic ("dynamic") component of topography is large. Topography anomalies include negative residuals likely due to active subduction of the Juan de Fuca plate, and perhaps remnants of formerly active convergence further south along the margin. Our finding of broad-scale, positive residual topography in the Basin and Range substantiates previous results, implying the presence of anomalous buoyancy there which we cannot fully explain. The Colorado Plateau does not appear dynamically anomalous at present, except at its edges. Many of the residual topography features are consistent with predictions from mantle flow computations. This suggests a convective origin, and important interactions between vigorous upper mantle convection and intraplate deformation.

## 1. Introduction

The evaluation of crustal and lithospheric structure in light of seismological, gravity, and topography constraints can provide insights into the forces that drive tectonic deformation. One issue arising especially for continental plates is how much of the topographic signal is compensated by lateral variations in crustal and lithospheric thickness and densities (sometimes called the "static" component, even though lithospheric density variations may be of past convective origin), and how much is actively being supported by basal tractions due to mantle convection ("dynamic" in the sense of viscous stresses due to present-day convection leading to surface deflection) (e.g. Braun, 2010; Flament et al., 2013).

Such an analysis has a long history for distributed zones of tectonic deformation ("mobile belts") like the western United States (U.S.) (e.g. Crough and Thompson, 1977; Lachenbruch and Morgan, 1990; Jones et al., 1992, 1996; Lowry et al., 2000; Chase et al., 2002). Yet, many inferences, including the overall terminology, remain debated. For example, one may also use a broader definition of "mantle-driven dynamic topography" as that component of topography that has been modified within the last ~10 Ma by means of either active mantle tractions, or modified mantle lithospheric density (Karlstrom et al., 2012). Here, we proceed with the classic static vs. dynamic distinction in order to be able to conduct straightforward tests of isostatic compensation. However, we recognize the necessarily blurred nature of the dynamic processes at work within the thermo-chemical boundary layer of a convecting mantle, and will comment on some related issues in the discussion.

In general, most horizontal tectonic deformation in the western U.S. is related to Farallon plate subduction and hence a classic example of the link between plate system evolution and tectonics (Atwater, 1970). However, much of the region also appears to have experienced significant vertical forcing, across a range of spatial scales, and the relationship of such forcing to mantle dynamics remains to be fully quantified (e.g. Humphreys and Coblentz, 2007; Forte et al., 2010; Ghosh et al., 2013). Smaller-scale, upper mantle convection likely modulates the large-scale features and causes

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http://dx.doi.org/10.1016/j.epsl.2013.10.012

deformation within the actively deforming domain that extends from the Rocky Mountain front to the San Andreas Fault (Fig. 1a). Suggested connections range from shallow upper mantle processes, due to a flat slab subduction scenario (e.g. Spencer, 1996; Xue and Allen, 2007; Liu and Gurnis, 2010), perhaps via slab-plume interactions (Xue and Allen, 2007; Faccenna and Becker, 2010; James et al., 2011), to a link to deep mantle flow (e.g. Moucha et al., 2008; Forte et al., 2010). Within this context, it was suggested, for example, that a mantle upwelling may be the source of large-scale uplift in the Cordillera, perhaps associated with the Yellowstone plume (Crough and Thompson, 1977; Parsons et al., 1994). The Basin and Range region would then be expected to sit anomalously high compared to its crustal structure because it is atop a hot back-arc (Hyndman and Currie, 2011) and/or mantle plume supported (Lowry et al., 2000; Goes and van der Lee, 2002).

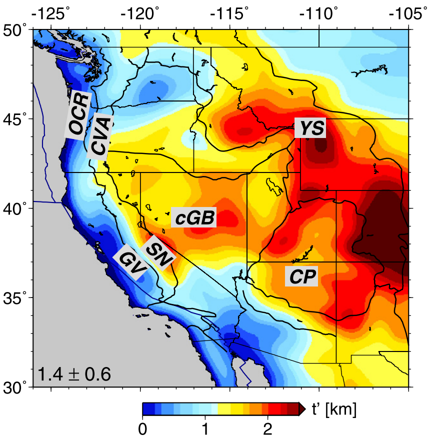
Within the western Cordillera, the Colorado Plateau is another tectonic region of interest due to its apparent anomalous high topography, minimal deformation, thickened crust, and recent volcanism. There is growing consensus that volcanism and local uplift is pronounced around tectonic units such as the plateau itself (Parsons and McCarthy, 1995; Roy et al., 2009; Crow et al., 2010), perhaps because of small-scale convective or delamination processes (Bird, 1979; van Wijk et al., 2010; McQuarrie and Oskin, 2010; Levander et al., 2011). What is debated, however, is the large-scale dynamic support and the uplift history throughout the Cenozoic (e.g. Flowers, 2010; Karlstrom et al., 2012). One view holds that convective flow established dynamic support of the high topography fairly recently (Moucha et al., 2009; Karlstrom et al., 2012) including a present-day dynamic topography high underneath the plateau (Moucha et al., 2008). Others have shown that relatively steady, but positive dynamic topography might have been reached at ~40 Ma based on mantle flow (Liu and Gurnis, 2010), or thermal modeling in light of geological constraints and volcanism (Roy et al., 2009; Crow et al., 2010).

Structural models for the lithosphere that are well defined down to ~100 km scales are key for unraveling the issue of topographic support, and those have now been greatly facilitated in the western U.S. by the advent of dense instrumentation such as EarthScope USArray (e.g. Lowry and Pérez-Gussinyé, 2011; Kumar et al., 2012; Levander and Miller, 2012; Shen et al., 2013). The resulting seismological constraints from passive imaging augment the patchwork of higher resolution, active source data (e.g. Mooney et al., 1998; Bassin et al., 2000) and regional broadband experiments (e.g. Karlstrom et al., 2012; Gilbert et al., 2012).

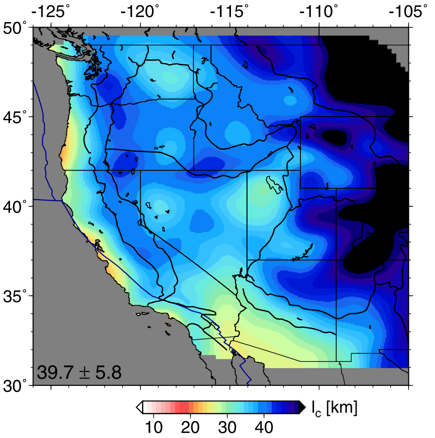
Here, we make use of these recent imaging advances and focus on a regional analysis, using receiver-function based crustal and lithospheric models on scales up to ~1500 km (Fig. 1), rather than a more local analysis (e.g. Parsons and McCarthy, 1995; Frassetto et al., 2006; Coblentz et al., 2011; Schulte-Pelkum et al., 2011; Bailey et al., 2012; Karlstrom et al., 2012). The latter can provide tighter bounds on the trade-offs, e.g. between layer thickness and density, and utilize local geological, and petrological constraints. The former is more readily compared with large-scale mantle-flow based estimates of topography, and can provide a backdrop upon which to improve with regional refinement.

Since it is a stress-based quantity, dynamic topography amplitudes from mantle flow scale, to first order, linearly with the density anomalies that cause mantle flow alone, unlike uplift rates, which go as density anomaly squared over mantle viscosity (e.g. Gurnis et al., 2000). Estimates of dynamic topography are predominantly sensitive to density structure in the upper ~400 km of the mantle for horizontal scales of $\lesssim$1000 km. Incorporating higher resolution tomographic constraints is therefore not merely an incremental advance, but the necessary requirement to analyze the potential link between tectonics and mantle dynamics at regional scales.

*a)* observed topography



*b)* LM-*P* Moho



*c)* LPG Moho

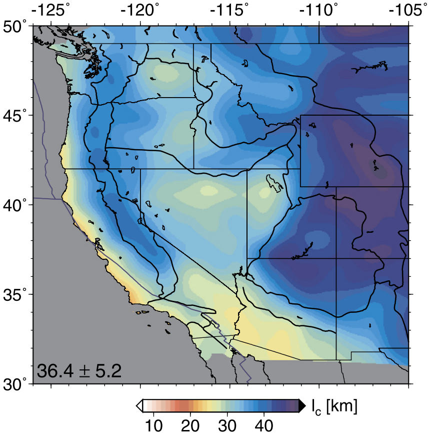


**Fig. 1.** (a) Long-wavelength filtered ETOPO2 (NOAA, 2006) topography (coloring, only showing positive topography, gray implying no available data in this and all subsequent plots). Dark blue lines are plate boundaries from Bird (2003). Geographic features: cGB, central Great Basin; CP, Colorado Plateau; CVA, Cascade Volcanic Arc; OCR, Oregon Coastal Ranges; SN, Sierra Nevada; YS, Yellowstone. Major morphological provinces shown with black lines. Legend inset in this and all subsequent maps indicates the mean and RMS variation of the property shown (units as in color scale). (b) Crustal thickness based on *P* receiver function estimates from Levander and Miller (2012), LM. (c) Crustal thickness from Lowry and Pérez-Gussinyé (2011), LPG. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

We first present a reanalysis of isostatic models for western U.S. topography using new structural models for the lithosphere, and