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Seismic tomography of the Colorado Rocky Mountains upper mantle from CREST: Lithosphere–asthenosphere interactions and mantle support of topography

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ABSTRACT

The CREST experiment (Colorado Rocky Mountains Experiment and Seismic Transects) integrated the EarthScope USArray Transportable Array with portable and permanent stations to provide detailed seismic imaging of crust and mantle properties beneath the highest topography region of the Rocky Mountains. Inverting approximately 14,600 P- and 3600 S-wave arrival times recorded at 160 stations for upper mantle V_p and V_s structure, we find that large V_p perturbations relative to AK135 of 7% and V_s variations of 8% take place over very short (approaching tens of kilometers) lateral distances. Highest heterogeneity is observed in the upper 300 km of the mantle, but well resolved low velocity features extend to the top of the transition zone in portions of these images. The previously noted low velocity upper mantle Aspen Anomaly is resolved into multiple features. The lowest V_p and V_s velocities in the region are found beneath the San Juan Mountains, which is clearly distinguished from other low velocity features of the northern Rio Grande Rift, Taos/Latir region, Aspen region, and below the Never Summer Mountains. We suggest that the San Juan anomaly, and a similar feature below the Taos/Latir region of northern New Mexico, are related to delamination and remnant heat (and melt) beneath these sites of extraordinarily voluminous middle-Cenozoic volcanism. We interpret a northeast–southwest grain in velocity structure that parallels the Colorado Mineral belt to depths near 150 km as being reflective of control by uppermost mantle Proterozoic accretionary lithospheric architecture. Further to the north and west, the Wyoming province and northern Colorado Plateau show high velocity features indicative of thick (∼150 km) preserved Archean and Proterozoic lithosphere, respectively. Overall, we interpret the highly heterogeneous uppermost mantle velocity structure beneath the southern Rocky Mountains as reflecting interfingered chemical Proterozoic lithosphere that has been, is currently being, replaced and modified by upwelling asthenosphere. Low velocity features resolved here indicate that this process may be sourced as deeply as the top of the mantle transition zone at 410 km. One driving mechanism for this is upper mantle interaction between upwelling hydration-induced partial melt and destabilized downwelling lithosphere in the deeper upper mantle. Tomographic imaging of mantle seismic velocity and crustal thickness results and modeling from the CREST experiment indicate that the highest elevations of the Colorado Rocky Mountains are substantially supported by the mantle, and strong correlations between low velocity mantle and thin crust/high topography are noted across the region. This, along with rich upper mantle seismic heterogeneity, suggests that mantle buoyancy and dynamics are central to present day topographic support and recent geomorphic evolution of the region.

1. Introduction

The Colorado Rocky Mountain (CRM) region of the western US orogenic plateau, lying near the boundary of traditionally considered tectonically active and stable provinces of North America, presents an outstanding natural laboratory to advance understand-

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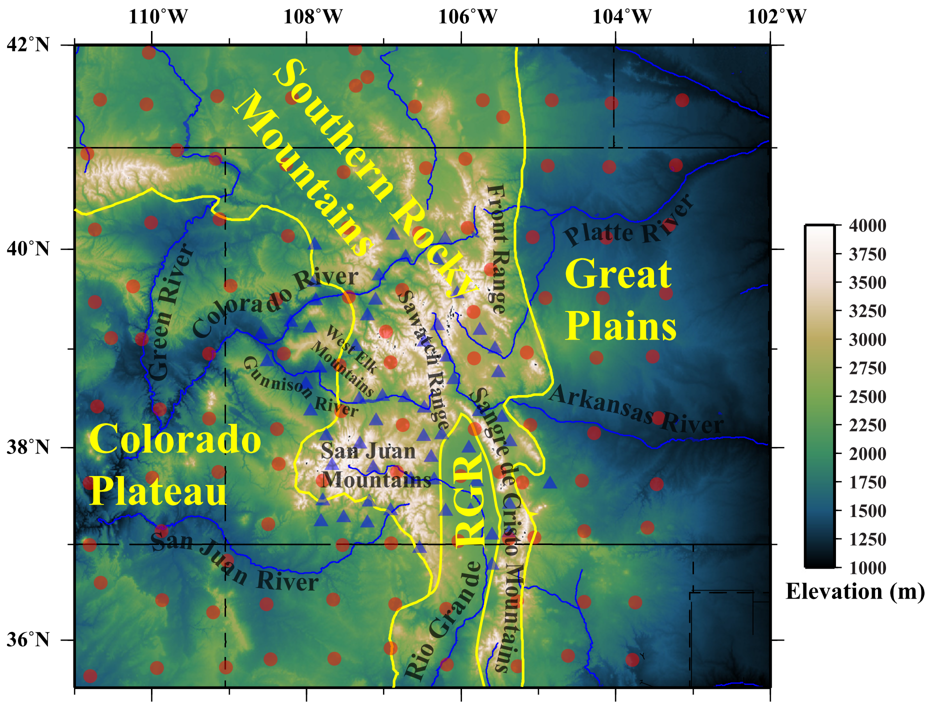

Fig. 1. Topographic map showing location of CREST (blue triangles) and US-ALL seismic stations (red circles) used in this study, with physiographic provinces, major rivers, and mountain ranges noted; RGR: Rio Grande Rift province.

ing of intraplate interactions between mantle, lithospheric, and surfical processes through time. Although approximately 1000 km from the North American/Pacific plate boundary, the Colorado Rocky Mountains form a broad topographic dome that encompasses the highest average elevations on the continent, with mean elevations in excess of 2.5 km above sea level, and over 50 distinct mountain massifs with elevations >4 km (McMillan et al., 2006; Karlstrom et al., 2012). Explanations for high CRM topographic support as well as for overall high western US elevations in general have been controversial and variously attributed to thermal, dynamic, and/or chemical buoyancy contributions from the crust (Li et al., 2002; Decker, 1995), uppermost mantle (Roy et al., 2004; van Wijk et al., 2010; Coblentz et al., 2011), and/or deeper mantle (Moucha et al., 2008; Hansen et al., 2013). This is also an instructive region to examine the influence that accretionary and other pre-existing structures may have on subsequent lithospheric modification, and the extent to which this can control the geometry of deformational tectonics. Understanding processes associated with the degree and timing of uplift are key to unraveling the erosional and general geomorphic evolution of the region (Karlstrom and Humphreys, 1998; Mutschler et al., 1998; Dueker et al., 2001; Karlstrom et al., 2002). Compelling neotectonic questions include the processes and extent of mantle-driven uplift in the region and mantle-to-surface connections for understanding the erosional and geomorphic evolution of the iconic landscapes of the Colorado Plateau-Rocky Mountain region (Karlstrom et al., 2012).

A key to addressing the 4-dimensional evolution of continental lithosphere is the acquisition and interpretation of increasingly high-resolution seismic tomographic images. Continental U.S. EarthScope Transportable Array images, based on ∼70 km interstation spacing, provide extraordinary synoptic images of the upper mantle. However, the Transportable Array in isolation yields relatively poor resolution of lithosphere, crustal and Moho structures. Strategic seismic station densifications, such as the mean ∼23 km spacing here (Fig. 1), have been used in many instances, using the EarthScope Flexable Array or other resources to enhance resolution above and beyond the Transportable Array alone.

We use this densification strategy in CREST to illuminate the geometry of anomalously slow mantle beneath Proterozoic province boundaries, revealing surprisingly rich, blob-like mantle heterogeneity in the CRM, and sharp (tens of kilometers) transitions between low from high velocity mantle domains. We also seek to integrate geologic and geomorphic studies to examine spatial associations between mantle domains and Cenozoic and observed geologic features of different age. This facilitates inclusion of the time dimension and better understanding of mantle modification and associated geodynamic forcing in multiple regions of the Rocky Mountain corridor (Gao et al., 2004; Schmandt and Humphreys, 2010a; Obrebski et al., 2011). Further constraining recent mantle processes with geomorphological consequences are observations of late Miocene accelerated river incision (McMillan et al., 2006; Karlstrom et al., 2008, 2012), and tilted epeirogenic flanks (McMillan et al., 2002; Eaton, 2008).

This paper presents and interprets seismological images of the mantle beneath the Colorado Rocky Mountains. This region and these images form important observations to help illuminate "asthenospherization" of North American lithosphere and mantle influences on support of high topography in continental interiors. Tomographic results illuminate the architecture and dynamics of the upper mantle at a revised level of spatial resolution and provide improved constraints on the genesis and modes of support for high topography. These images document newly resolved mantle heterogeneity that, we argue, plays, and has played, an important role in supporting and evolving modern and past landscapes.

1.1. Geologic context

It has been suggested that Proterozoic basement structures may have exerted geodynamic control over the nature and distribution of Laramide and younger lithospheric modification in the Colorado Rocky Mountains region (Karlstrom and Humphreys, 1998; Mutschler et al., 1998; Dueker et al., 2001; Karlstrom et al., 2005). The continental lithosphere of southern Laurentia, which underlies the CRM, was assembled largely from 1.8–1.6 Ga accretion