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Recent craton growth by slab stacking beneath Wyoming

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ABSTRACT

Seismic tomography images high-velocity mantle beneath the Wyoming craton extending to >250 km depth. Although xenoliths and isostatic arguments suggest that this mantle is depleted of basaltic component, it is not typical craton: its NE elongate shape extends SW of the Wyoming craton; xenoliths suggest that the base of Archean mantle was truncated from ∼180–200 to ∼140–150 km depth since the Devonian, and that the deeper mantle is younger than ∼200 Ma. The Sevier–Laramide orogeny is the only significant Phanerozoic tectonic event to have affected the region, and presumably caused the truncation. Apparently, the base of the Wyoming craton was removed and young, depleted mantle was emplaced beneath the Wyoming craton during the Sevier–Laramide orogeny. We suggest that the Wyoming craton experienced a ∼75 Ma phase of growth through a three-stage process. First, flat-slab subduction removed 40–50 km off the base of the Archean Wyoming craton. This was followed by emplacement of basalt-depleted ocean plateau mantle lithosphere of the Shatsky Rise conjugate, which arrived in the early Laramide. The geologic recorded of vertical motion in the Wyoming region suggests that the plateau's crust escaped into the Earth's interior at 70–75 Ma. Initiation of Colorado Mineral Belt magmatism at this time may represent a slab rupture through which the ocean crust escaped.

1. Introduction

Archean cratons of continents are stabilized and protected from tectonic and magmatic disruption by their highly viscous, basalt-depleted mantle lithosphere whose thermal negative buoyancy is balanced by their compositional buoyancy (Jordan, 1978). The basis for this understanding is provided by seismic observations and isostatic arguments, and by xenolith samples of this mantle. However, the origin of the depleted mantle is not agreed upon, with three primary hypotheses being considered (Arndt et al., 2009; Lee et al., 2011; Snyder et al., 2014). Most prominent among these is the "slab stacking" hypothesis, in which subducted slabs of Archean ocean lithosphere under-accrete the continent. Alternatives include an origin as plume heads and as mantle depleted below volcanic arcs. In all these hypotheses a question arises as to the whereabouts of the basaltic complement to the depleted mantle (Arndt et al., 2009). For the plume and volcanic arc hypotheses, a common suggestion is eruption and erosion of the basalt. For slab stacking – where the basaltic oceanic crust would have transformed to eclogite – a sinking of the dense eclogite into the asthenosphere is required.

This paper addresses the well-studied Wyoming craton. As a result of USArray seismic coverage, it is among the best-imaged cratons, and it is unusual for having experienced recent and significant modification. As a consequence of this modification it stands high, and it provides xenolith sampling of its structure at times both before and after this modification. The record created by this relatively young activity sheds light on the processes of craton creation and destruction.

A range of geophysical, geochemical and geologic evidence, discussed below, leads us to suggest that the Wyoming craton experienced Sevier-to-Laramide-age basal erosion followed by the emplacement of highly depleted oceanic mantle lithosphere. The geologically-recorded history of vertical motions provides clues as to how the ocean crust was lost during this young slab-stacking event.

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2. Geologic history

The Wyoming craton was created by addition of Neoarchean volcanic arcs to a continental core of Paleoarchean to Mesoarchean age (Chamberlain et al., 2003). Then, through a rapid succession of amalgamation events at ∼ 1.8 Ga, this craton was added to the southern margin of the North American shield and placed deep within the continental interior by south-side terrane accretion (Whitmeyer and Karlstrom, 2007). Through the Proterozoic and until the late Cretaceous the Wyoming craton remained stable (Blackburn et al., 2012). Wyoming subsided slowly and, in a series of transgressions and regressions, was covered by a westward thickening 1.5–3 km of sediment (Peterson, 1988) deposited in shallow seas and broad flood plains. The late Paleozoic orogeny responsible for the Ancestral Rockies created major mountains and basins within the Proterozoic crust south of Wyoming, but left the Archean crust nearly unaffected (Erslev and Koenig, 2009). Another layer of sediment was deposited in the Cretaceous Interior Seaway, starting ∼100 Ma and covering most of Wyoming with 1.5–5 km of sediment (Molenaar and Rice, 1988; Scott et al., 2009; Liu et al., 2011; Cook and Bally, 1975). Seaway subsidence is attributed to dynamic suction associated with a shallowing of Farallon slab dip (Mitrovica et al., 1989; Spasojevic et al., 2009). Unusually thick deposits were laid down in westernmost Wyoming, NW Colorado and eastern Utah (Roberts and Kirschbaum, 1995; Liu et al., 2011; Chapin, 2012) as a combined result of flexural downwarping driven by the ∼east-verging Sevier overthrust system (DeCelles, 2004) and a more regional dynamic suction (Liu et al., 2011).

Then, with the first significant deformation in over a billion years, crystalline basement was thrust over its sedimentary cover as Wyoming crust was shortened by 50–60 km (Bird, 1998) during the Laramide orogeny (∼75–45 Ma, Dickinson et al., 1988). The accommodating thrust faults are distributed across Wyoming in a branch-like pattern that created closed and nearly closed basins. Sediment was stripped from areas of high relief, often exposing crystalline basement, and was deposited into the basins and then largely evacuated (McMillan et al., 2006).

Based on the occurrence of thrust faulting in the deep continental interior and the termination of California arc volcanism at ∼80 Ma, the Laramide orogeny generally is attributed to flattening of subducted Farallon slab against the base of North America (Coney and Reynolds, 1977; Saleeby, 2003). This is supported by the xenolith record, which suggests basal erosion of cratonic western U.S. to depths of 135–150 km sometime between the Devonian and the Eocene periods, presumably during the Sevier and Laramide orogenies (Li et al., 2008; Eggler et al., 1988). The primary cause of slab flattening is thought to be subduction of the large ocean plateau created as a conjugate to the Shatsky Rise (Livaccari et al., 1981; Saleeby, 2003). The calculated path of the plateau takes it under southern California, the Colorado Plateau and Wyoming (Liu et al., 2008). During this time the Colorado Plateau and Rocky Mountain region began ascending to their current high elevations (Flowers et al., 2008; Karlstrom et al., 2012), and the region became magmatically quiet except along the Colorado Mineral Belt.

3. Mantle structure

Our goal is to understand the origin of the deep part of the Wyoming craton, and we make use of three approaches. Seismic tomography provides the best constraint on the shape of thermal structure in this region. Isostatic calculations provide constraint on lithospheric density and its time evolution, and when combined with the seismic constraints on temperature, it sheds light on the degree of basalt depletion. Xenoliths sample the mantle to depths ≥170 km at a few locations, thereby providing information on composition and temperature at their time of eruption. The time spanned by the xenolith eruptions supply information on lithospheric evolution. We then consider our understanding of the deep Wyoming craton in the context of Late Cretaceous subduction of the Shatsky conjugate and flat-slab subduction. Subduction of this ocean plateau provides both a source of depleted mantle and a means for delivering it to the base of the Wyoming craton.

3.1. Mantle seismic structure

Regional upper mantle structure has been imaged well with both surface waves and body waves. We use the Rayleigh-wave tomography of Shen et al. (2013; online download), which they inverted jointly with receiver-functions to constrain Moho depth. Fig. 1 shows this model in our study area. To make these figures, we remove the mean velocity of each layer and divide the result by the average S-wave velocity for that layer to obtain a layer-wise velocity perturbations that can be compared to the body-wave tomography. The surface-wave model images a 400-km wide high-velocity ($V_S = 4.65$–4.8 km/s; in Fig. 1, $\delta V_S > 3\%$ fast) structure extending SW–NE across Wyoming and extending from ∼60 to 180 km in depth. The deeper parts of this model are not well resolved: the published model extends to 150 km depth – considered a depth that is reliably resolved – whereas the online version provides the entire 200 km depth extent of the model. The NE-trending high-velocity mantle structure beneath Wyoming is the only major high-velocity upper-mantle structure imaged with surface waves west of the Great Plains. We associate the deep parts of this structure with the Shatsky conjugate.

The teleseismic P-wave tomography provides the best resolution on the deeper structure. We use the model of Schmandt and Humphreys (2010, Fig. 1). Resolution of body-wave tomography diminishes at depths above the average station spacing, which for our data is ∼70 km. For deeper structure, relatively high resolution is achieved through the use of abundant data recorded over a broad area. Inversion also makes use of finite-frequency sensitivity kernels, although at the highest frequencies (∼1 Hz) used for arrival-time estimation (by cross correlation), finite-frequency effects are of little significance. Lower frequency measurements are also included to reduce the reliance on regularization to stabilize the inversions and obtain smooth images. Resolution tests indicate that lateral and depth resolution is excellent over the 75–700 km depth range, with only minor amplitude degradation of the model amplitude at each node (Fig. S1). Visually there is little degradation of the input image. Synthetic resolution tests, however, do not address artifacts created by effects that are not included in the test (including seismic anisotropy, ray-path deviation from that in a 1-D Earth, and structure of scale smaller than our node spacing). Considering these limitations, the actual uncertainty in the imaged structure is greater than that represented by the resolution tests, and resolution estimation becomes somewhat subjective. Two lines of reasoning suggest that the actual resolution of the P-wave model is good across the upper mantle.

First, when the body- and surface-wave models are compared, it is clear that the two tomographic techniques image similar structure over the 75–160 km depth range where resolution is good in both models. The average amplitudes of the S-wave anomalies are about twice that of the P-wave anomalies, as is common (Schmandt and Humphreys, 2010, found $d\ln V_P/d\ln V_S = 1.8$ for the western U.S.). The main difference seen in the body- and surface-wave images over this depth range is the presence in the body-wave images of shorter wavelength lateral structure, as expected for inversions based on teleseismic arrivals, whereas the surface-wave model resolves shorter wavelength depth variation in structure. The similarity of results between inversions using