The following text was accepted to Geology on June 4, 2018. The published version has minor edits, but the substance is the same. GSA Publications owns the copyright to the edited version, which can be found at https://doi.org/10.1130/G40328.1.

Eclogite-driven subsidence of the Columbia Basin (Washington State, USA) caused by deposition of Columbia River Basalt

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ABSTRACT

The south-central portion of the Columbia Basin in Washington State, although not the primary eruptive center for the Columbia River Basalt (CRB), contains the thickest package of CRB lavas at over 4 km. Prior to CRB deposition, the region was a sediment-filled rift basin dating back to the early Eocene. Previous studies interpret a lower-crust high velocity body below the thick basalt deposits as a syn-extensional magmatic underplate. CRB layers thicken toward the center of the basin, revealing a pulse of subsidence during deposition that ceased coincident with cessation of CRB eruptions. We propose a subsidence mechanism based on metamorphic transition of the underplate from basalt to eclogite facies, driven by the increased pressure of CRB loading. We demonstrate the plausibility of our interpretation using numerical models of the mechanical and chemical components of the system. Further, we constrain the effective elastic thickness of the Miocene Columbia Basin lithosphere, finding it to be much thinner (5–10 km) than previous estimates.

INTRODUCTION

The Columbia River Flood Basalt (CRB) erupted ~17–6 Ma from NE Oregon and adjacent portions of Idaho and Washington (Fig. 1). These flows covered the Columbia Basin as nearly flat, self-leveling, inflation flows. Basalt accumulation was greatest not near the primary source of eruption, but in the center of the Columbia Basin (Fig. 1), where over 4 km of CRB ponded (Reidel et al., 1989). As evidenced by the CRB flows thickening toward the center of the basin (Fig. 2), progressive basin subsidence occurred during CRB activity, deepening a depression that CRB flows repeatedly filled and over-topped. Subsidence ended with the cessation of CRB deposition, and the region has not experienced significant subsidence since (Reidel et al., 2013). We use the name central Columbia Basin downwarp (CCBD) to refer to the region of subsidence roughly outlined by the 2 km CRB isopach in Figure 1.

GEOLOGIC CONTEXT

Basic aspects of crustal structure in the greater Columbia Basin region are represented in Figures 1 and 2. A major phase of regional extension and volcanism occurred during the ca. 53 Ma accretion of Siletzia, accompanied by an outward stepping of subduction and establishment of the present Cascadia subduction zone (Christiansen and Yeats, 1992). Regional extension includes the creation of large core complexes in NE Washington and trans-tensional basins now exposed along the eastern flank of the north Cascades uplift. The Swauk and Chiwaukum basins (Fig. 1) preserve the most complete record of sedimentation. They are filled with Eocene sediments and volcanic rocks ranging in age from ~55–40 Ma (Taylor et al., 1988). These basins trend SE into the CCBD, where they are covered by CRB flows. Drill holes through the CCBD penetrate these same Eocene sedimentary units (Campbell, 1989). The formation ages of the early Swauk, Chiwaukum, and (where resolved) Eocene rift basin in the CCBD are similar to the unroofing of nearby core complex (54–47 Ma, Kruckenberg et al., 2008) and vigorous regional volcanism (Christiansen and Yeats, 1992; Gaschnig et al., 2010).

The active source seismic study of Catchings and Mooney (1988) and the surface wave and receiver function study of Gao et al. (2011) provide images of the deep structure in the CCBD and surrounding area. Eocene sediments in the CCBD locally extend to ~11 km beneath the surface, defining a deep, local (~110 × 80 km), rift structure. Immediately below the area of deep sediment accumulation, and of similar horizontal dimensions, is an anomalous region of seismically high velocity (V_P = 7.5 km/s) lower crust extending from ~23 km to ~40 km depth (Fig. 1). We assume this to be the basaltic underplate portion of the rift structure, as proposed by Catchings and Mooney (1988), with the 40 km seismic Moho representing local basalt-eclogite coexistence pressure, and underlying root seismically indistinguishable from surrounding mantle. The crustal section from 11 km–23 km has been interpreted as either crystalline North America (Catchings and Mooney, 1988) or Farallon slab connected at depth to Siletzia (Gao et al., 2011). Either interpretation is consistent with our modeling.

ECLOGITE-DRIVEN SUBSIDENCE

The rate and magnitude of Miocene subsidence in south-central Washington is far greater than any other CRB depocenter, at up to 10 mm/yr throughout Grande Ronde deposition (Reidel et al., 2013). Because this time period does not coincide with any major change in regional tectonics (Christiansen and Yeats, 1992), we infer subsidence was driven by local vertical forcing rather than far-field horizontal tectonics.

Isostasy and Flexure

The core logic of our model is a simple isostatic argument. Loading from CRB deposition increases lithostatic pressure throughout the crust, pushing lower-crustal basaltic rocks across the phase transition to eclogite facies. As rocks metamorphose from basalt to eclogite they densify, contracting the crust and creating a topographic low relative to a column that did not eclogitize. The resulting depression traps subsequent lava flows, compounding the effect over time.

Conceptually, we model the mechanical aspects of this system in two distinct steps. First, when a new basalt flow is deposited, we assume that its weight is transmitted hydrostatically to the lower crust. This implies that an equal volume of lower crust is eclogitized, directly below the new deposit.

Mechanical contraction is filtered by the elastic strength of the plate, producing a smoothed topographic response. We model this effect as an equivalent load applied to an isostatically-supported elastic plate. We use a thin-plate assumption (Turcotte and Schubert, 2014), for which the dominant forces are buoyancy, and elastic bending stress, as expressed by the equation

$$\nabla^2 D \nabla^2 w(x,y) + [\rho_m - \rho_b]\, g\, w(x,y) = L(x,y), \quad (1)$$

where w is displacement as a function of position (x,y); ρ_b and ρ_m are respectively density of basalt and mantle; L is vertical loading stress; and D is flexural rigidity. Flexural rigidity is defined as

$$D = (E\, T_e^3)/[12\, (1 - \nu^2)], \quad (2)$$

where E is Young's Modulus, T_e is effective elastic thickness, and ν is Poisson's ratio.

We numerically solve Equation 1 with the finite difference method. We initialize our model with a small topographic depression, representing the Eocene basin just prior to CRB onset, which we take to be in isostatic equilibrium. Assuming that an equal volume of lower-crustal basalt eclogitizes upon deposition, we expect a proportional reduction in crustal volume.

We use reference densities 3000, 3300, and 3370 $kg.m^{-3}$ for basalt, mantle, and eclogite, respectively to calculate the effective load of eclogitization. We assume an elastic plate with Young's modulus 7×10^{10} Pa, and Poisson's ratio 0.25. Each time step represents a lava flow filling the existing depression, and the crustal downwarping caused by the newly formed eclogite load. Each event adds a proportional volume of eclogite to the root structure, for a cumulative root growth proportional to cumulative deposition.

Our calculations assume the system reaches isostatic equilibrium between lava flows, and omits dynamic effects such as mantle convection and lateral crustal flow, which may affect the long-term evolution of the system (Wang and Currie, 2017).

The nature of Equation 1 results in a smooth subsidence response, making the model relatively insensitive to the detailed shape of the initial basin. For the models presented in Figure 3, our initial geometry is a radial Gaussian function with RMS width of 15 km and depth of 50 m. Any short-wavelength load excites the natural bending wavelength of the crust. If the initial basin is much wider than the natural bending wavelength, the basin localizes to the natural bending wavelength with repeated lava flows. A deeper initial basin results in faster basin development. The long-term resulting structure is qualitatively the same in all cases. Model results are shown in Figure 3, and further details of our methods can be found in the GSA Data Repository[1].

Based on our modeling, the observed basin geometry is possible only if the crust has an effective elastic thickness between 5–10 km. This differs from the 25–35 km estimate of Lowry and Pérez-Gussinyé (2011), which is based on the ratio of topography to Bouguer gravity. We think the discrepancy in estimated effective elastic thickness is a consequence of topographic flattening created by the CRB deposits.

Reaction Kinetics

Although we describe our flexural model as an iteration over individual lava flows, it makes no predictions of the actual time elapsed between steps. Rather, each model step represents time taken for the slowest physical process in the system to act. In the following paragraphs we show that neither reaction processes, nor latent heat release hinders the basalt to eclogite transition on scales relevant to eclogite-driven subsidence. Therefore, we conclude that the duration of the CRB deposition is the limiting mechanism for this system. That is, by the time each new flow begins, metamorphism owing to the previous flow has come to equilibrium.

Previous studies on the basalt to eclogite transition have found that eclogitization takes place on geologically relevant time scales at temperatures above 400–600 °C in dry basalt (Ito and Kennedy, 1971; Ahrens and Schubert, 1975), although dry gabbroic facies may remain metastable for substantial time, even at high temperatures (Hacker, 2013). However, the same reactions progress rapidly to stable equilibrium in the presence of small amounts of water (Ahrens and Schubert, 1975; Hacker, 2013), as we expect to exist in abundance in the Cascadia backarc. Hence we assume the lower crust of the

Columbia Basin is capable of reacting quickly and completely from basalt to eclogite upon local changes in pressure and temperature.

The latent heat of reaction inhibits eclogitization. As this heat diffuses away, the reaction can continue. The following analysis shows the release of latent heat has negligible effect on the reactions we consider. Following O'Connell and Wasserburg (1972), we consider a vertical thermo-chemical profile through the crust. The deposition of lava both advects the geotherm down with the sinking crust, and causes the release of latent heat at depth. This modified geotherm then conductively cools back toward its original equilibrium slope.

We model the thermo-chemical system with a heat conservation equation and an Arrhenius reaction equation, respectively:

$$\rho\, C_p\, (\partial T/\partial t + u \bullet \nabla T) - \nabla \bullet (\rho\, C_p\, \alpha\, \nabla T) = \rho\, T\, \Delta S\, (\partial X/\partial t + u \bullet \nabla X), \quad (3)$$

and

$$\partial X/\partial t = A \exp(-E_a / [R\, T])\, (1/2\, [1 + \tanh([P - P_c]/\delta_p)] - X), \quad (4)$$

where T is temperature, u is deposition rate, P is pressure, P_c is facies coexistence pressure as a function of temperature, X is fraction eclogite facies, ρ is density, C_p is specific heat capacity, α is thermal diffusivity, ΔS is specific entropy change of eclogitization, E_a is activation energy of reaction, R is the universal gas constant, δ_p is a smoothing factor for the coexistence boundary as a function of pressure, and A is an Arrhenius coefficient.

We non-dimensionalize Equations 3 and 4 using a modified Péclet number for chemically reactive continuum,

$$Pe_r = (\boldsymbol{U}^3) / (\boldsymbol{\Delta S}\ \boldsymbol{G}\ \boldsymbol{\alpha}), \quad (5)$$

where $\boldsymbol{G}$ is a reference geothermal gradient, and other boldface variables are representative values of variables in Equation 3. Finite element solutions to Equations 3 and 4, and instructions for reproduction, are provided in the GSA Data Repository[1]. However, one can easily verify that, for any geological system, Pe_r<<1. Therefore, the system tends toward the limiting case of instantaneous thermal diffusion, implying that latent heat has negligible effect on this system.

DISCUSSION

Eclogitization has been discussed before as a driver of localized dynamic topography. A model similar to the one presented here has been proposed for sediment-loaded intracratonic basins (Naimark and Ismail-Zadeh, 1995; Hamdani et al., 1994), where eclogitization is driven primarily by a cooling geotherm, and surface loading is of secondary importance. Compressional tectonics may also drive eclogitization, forming basins like the East Barents Sea (Gac et al., 2013), and affecting the buoyancy structure of aging mountain belts (Fischer, 2002).

The minimum requirement for eclogite-driven subsidence is the presence of basaltic lower crust. Rift structures are common localities for lower crustal magmatic underplates. The CCBD, and intracratonic basins mentioned above all have rift histories. However, lower crustal gabbro may also form in significant quantities in other settings, such as at arcs and hot spots.

Additional lower crustal density owing to eclogitization could be a precursor to lithospheric delamination, and associated lithospheric recycling, uplift, and volcanism (Krystopowicz and Currie, 2013). It is noteworthy that the mechanisms discussed here are examples of so-called vertical tectonics, driven not by far-field horizontal forces, but by localized changes in lithospheric buoyancy. This class of tectonic processes appears to be a significant driver of tectonic evolution from the local and concentrated scale of the CCBD, to uplift of the entire North American Cordillera.

CONCLUSION

The occurrence of a local downwarp occurring only during the short duration of CRB deposition, and at the site of an apparent earlier magmatic underplate, strongly suggests the event was driven by creation of a local load on the crust. With simple numerical models of the physical and chemical components of the system, and inferring from the pre-Miocene geology a basaltic lower crust straddling the basalt-eclogite transition, we show that formation of lower-crustal eclogite during CRB loading would drive localized subsidence in a manner consistent with the modern Columbia Basin geometry and structure. We can think of no other satisfactory explanations for the anomalous, localized Miocene subsidence of the central Columbia Basin. Further, our models constrain the effective elastic thickness of the Miocene Columbia Basin crust to under 10 km.

Our study supports the hypothesis, proposed by others, that similar mechanisms may explain other localities of anomalous subsidence. In general, lower-crustal eclogitization is capable of producing deep basins without far-field tectonic driving, and may be responsible for anomalous topographic features globally.

ACKNOWLEDGEMENTS

We would like to thank Claire Currie, Vic Camp, and an anonymous reviewer for constructive reviews that improved the quality and clarity of this paper. This work was supported by NSF grant EAR-1727451.

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FIGURE CAPTIONS

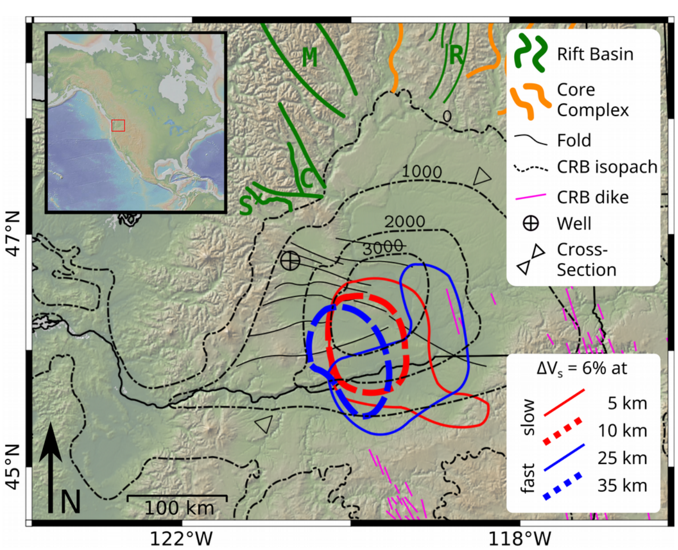

Figure 1. Map showing features that correlate with the central Columbia Basin downwarp. Accumulated thickness of the CRB flows is indicated with black dashed lines (thickness in meters). CRB ponding filled the downwarp, which subsided during the CRB eruptions. Subsidence centered on an Eocene rift basin associated with coeval core complex and trans-tensional basin activity in northern Washington. The Swauk (S), Chiwaukum (C), Republic (R), and Methow (M) grabens are labeled. The rift basin is imaged with active-source seismology along the cross section (indicated with triangles) (Catchings and Mooney, 1988; Fig. 2) and with surface waves (Gao et al., 2011). The anomalous crustal structure imaged in the immediate vicinity of the downwarp includes 5–6 km of sediment beneath ~4 km of CRB, and ~16 km of high-velocity lowermost crust interpreted by Catchings and Mooney (1988) to be rift-related magmatic underplate. Red and blue lines outline areas of low- and high-velocity crust (Gao et al., 2011). Topography adapted from GMRT synthesis (Ryan et al., 2009).

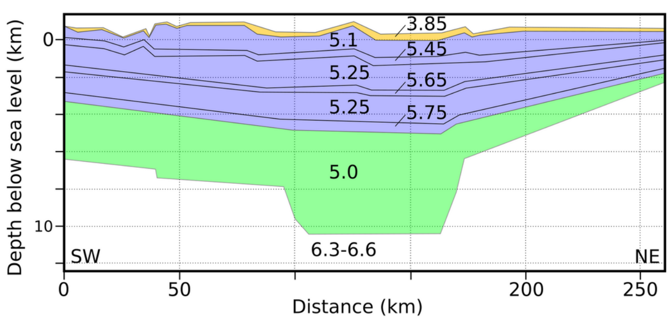

Figure 2. The upper crust along the cross section indicated in Figure 1, after Catchings and Mooney (1988). Numbers on plot give the P-wave velocity in km/s. Tan = post-Columbia River Basalt (CRB) sediment. Blue = CRB flows. Green = Eocene sediment. White = basement. Note the deep sediment-filled rift basin, and CRB flows thickening toward the basin center, indicating that the basin subsided during deposition, and not after.

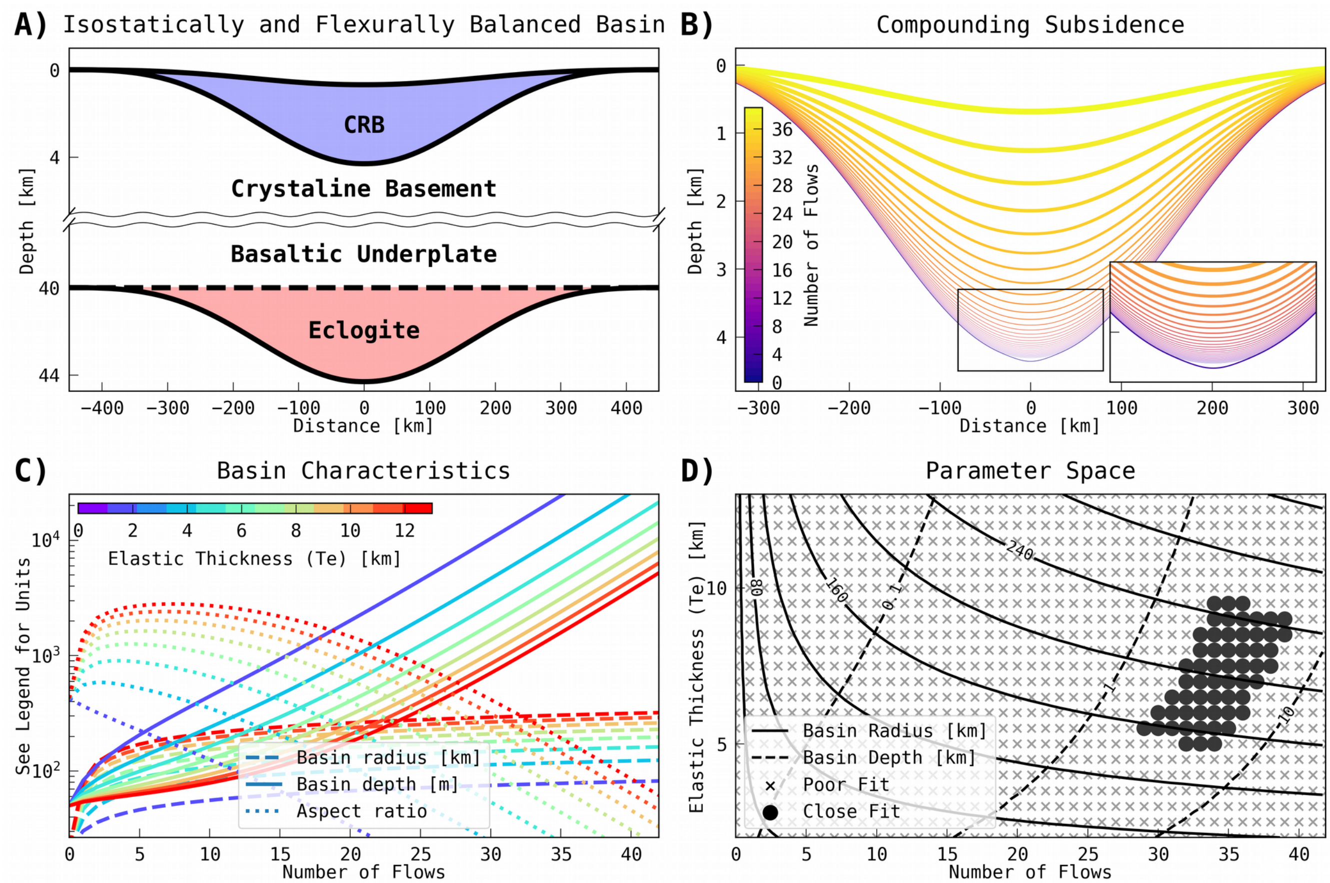

Figure 3. Models of time-evolving eclogite loading on an isostatically-supported elastic plate. A: Beginning with a small depocenter, a larger basin develops by repeatedly filling the existing topography and calculating new subsidence owing to lower-crustal eclogite formation. B: Depositional interfaces over time, illustrating the compounding effect of the eclogitization subsidence mechanism. Each flow is deposited as a flat layer filling the previous depression, and subsequently downwarps as a result of newly generated eclogite. Color represents the sequence of deposition. Line thickness is proportional to the thickness of the basalt layer. Inset shows zoom-in of initial topography. C: Basin geometry characteristics over time for varying elastic plate thicknesses. Other parameters are held constant across models. Basin depth increases slowly at first, and accelerates as the basin size, and hence load, increases. Basin radius rapidly adjusts to reflect the plate's natural flexural wavelength.

Aspect ratio (radius/depth) reveals that in this adjustment stage, radial growth briefly out-paces deepening. Long-term basin growth is dominated by deepening. D: The effects demonstrated in (C) trade off differently for different elastic plate thicknesses. Contours denote basin depth and radius over time for different plate thicknesses. Models whose geometries are similar to the Columbia Basin are plotted in filled circles, setting narrow limits on possible Miocene plate thickness.

[1]GSA Data Repository item 2018xxx, physical and thermo-chemical models of eclogite-induced subsidence, is available online at http://www.geosociety.org/datarepository/2018/ or on request from editing@geosociety.org.