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Westward underthrusting of thick North American crust: The dominant thickening process that built the Cordilleran orogenic plateau

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ABSTRACT

Quantification of the crustal thickening processes that construct orogenic plateaus is essential for interpreting their genesis. In the North American Cordillera, a 2.75–3.5-km-elevation, 200–250-km-wide plateau was constructed to the west of the Cretaceous–Paleogene Sevier fold-and-thrust belt (SFTB). The SFTB deformed a Mesoproterozoic to Mesozoic sedimentary package that thickened westward from a 2–3-km-thick platform section that was deposited above the ~40-km-thick craton to a 15–25-km-thick continental margin section that was deposited above middle to lower crust that had been significantly thinned during Neoproterozoic rifting. Shortening in the SFTB translated this thick sedimentary package as much as 265 km eastward, which resulted in the relative westward underthrusting of an equivalent length of thick cratonic basement beneath the hinterland region. Measurement of components of thickening with respect to the initial and final crustal thickness above and below the basal thrust décollement demonstrates that thickening accommodated by underthrusting outweighed thickening in the overlying SFTB by a factor of 1.5–3 and was likely the dominant thickening mechanism that constructed the broad hinterland plateau. In eastern Nevada, the reconstructed western edge of the underthrusted craton underlies the western limit of 2.75–3.5 km paleoelevations, which supports this interpretation. This analysis provides an important case study for underthrusting as a first-order thickening process in fold-and-thrust systems that deform sedimentary packages with a high pre-orogenic taper.

INTRODUCTION

Orogenic plateaus are interpreted to impart diverse impacts that extend far beyond their physical extent, including forcing global climate change, influencing sediment flux and chemical weathering rates, and altering ocean chemistry (e.g., Raymo and Ruddiman, 1992; Richter et al., 1992). However, despite their far-reaching significance, the mechanisms of plateau construction are vigorously debated, with disagreements over the relative importance of upper-crustal shortening, lower-crustal underthrusting, magmatic addition, and lithospheric delamination (e.g., Garzione et al., 2017).

In the North American Cordillera, a Late Cretaceous–Paleogene plateau was constructed in the hinterland region to the west of the Sevier fold-and-thrust belt (SFTB; Fig. 1), prior to its dismemberment by extension (e.g., DeCelles, 2004). At the latitude of the Great Basin (37°N–42°N), the existence of this plateau is supported by reconstructions of extension (Coney and Harms, 1984; McQuarrie and Wernicke, 2005; Long, 2019), isotopic crustal thickness proxies (Chapman et al., 2015), and paleoaltimetry (Snell et al., 2014; Cassel et al., 2018), which demonstrate that crustal thicknesses of at least ~50 km and elevations of ~2–4 km were attained across an ~300–350-km-wide (~200–250 km wide after restoration of extension) region of eastern Nevada and western Utah by ca. 70–40 Ma. This brings into question the dominant thickening processes that drove construction of such a broad hinterland plateau. This high-elevation region of eastern Nevada and western Utah experienced minimal upper-crustal shortening (~35 km total at 39°N) and thickening (e.g., Gans and Miller, 1983; Long, 2012; Di Fiori et al., 2021; Blackford et al., 2022). As much as ~10–20 km of localized Jurassic–Cretaceous thrust-related thickening has been interpreted in the vicinity of metamorphic core complexes on the basis of thermobarometry (e.g., McGrew et al., 2000; Lewis et al., 1999). However, structural reconstructions of core complexes demonstrate that this thrust-related burial only affected a narrow area (~25–50 km east-west width) of the hinterland (e.g., Camilleri et al., 1997; Lewis et al., 1999). Therefore, middle- and upper-crustal thickening above the basal SFTB décollement alone cannot account for construction of an ~200–250-km-wide hinterland plateau.

In this study, I addressed this problem by highlighting an important additional thickening process: underthrusting of thick continental crust beneath the basal fold-and-thrust belt décollement (e.g., Lowell, 1977; Price, 1981). I utilized new and published geometries from balanced cross sections, which demonstrate the five- to tenfold western thickening of the sedimentary package deformed by the SFTB. The eastward translation of this thick package during shortening in the SFTB resulted in the relative westward underthrusting of thick North American crust beneath the Sevier hinterland region, which I argue was the dominant thickening process that constructed the Cordilleran plateau.

GEOLOGIC FRAMEWORK

The 10–20-km-thick Belt Supergroup was deposited in an intracratonic basin in northern Idaho, western Montana, and southern British Columbia between ca. 1.5 and 1.4 Ga (Fig. 2; e.g., Price and Sears, 2000). Rifting of the western margin of Laurentia began in the Neoproterozoic (ca. 720 Ma), which marked the beginning of an ~600 m.y. history of marine-dominated deposition that lasted until the Mesozoic (e.g., Yonkee et al., 2014). This composite depocenter consisted of a thin continental platform section on the east, which was deposited above the

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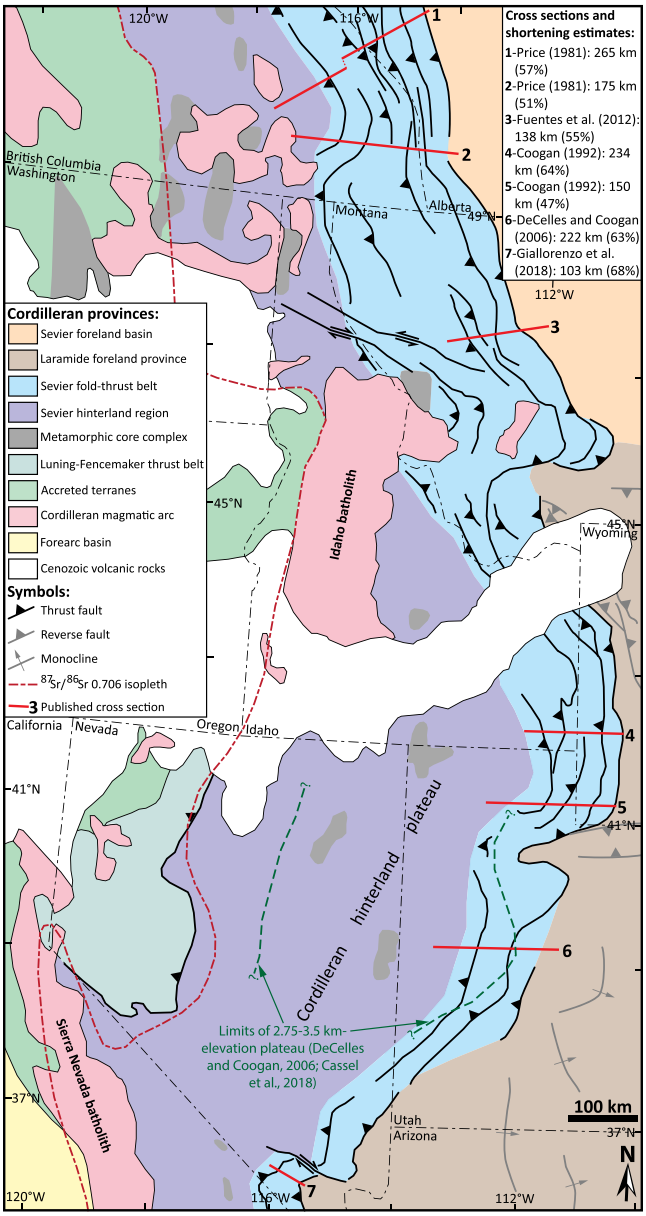

Figure 1. Map showing Cordilleran structural provinces (sources: DeCelles, 2004; Yonkee and Weil, 2015; Giallorenzo et al., 2018) and locations of published cross sections.

unrifted craton, which transitioned westward to a thick sedimentary package that was deposited above the rifted crust of the continental margin (e.g., Picha and Gibson, 1985). The Cambrian–Jurassic platform section attained a cumulative thickness of 2–3 km, while the continental margin section consists of 5–7 km of Neoproterozoic–early Cambrian rift-related clastic rocks overlain by up to 5–11 km of middle Cambrian–Jurassic shallow-marine carbonates (Fig. 2; e.g., Stewart, 1980; Yonkee et al., 2014).

During the Jurassic, magmatism and east-west shortening along the western North American margin marked the initiation of Cordilleran orogenesis (e.g., DeCelles, 2004). A retroarc fold-and-thrust system was progressively constructed, culminating in east-directed shortening within the SFTB between ca. 125 and 50 Ma (Figs. 1 and 2A; e.g., Yonkee and Weil, 2015). The SFTB deformed the Mesoproterozoic to Mesozoic sedimentary package described above and propagated eastward across the transition from the 15–25-km-thick continental margin section to the 2–3-km-thick platform section (e.g., Price, 1981; Coogan, 1992). The SFTB exhibits a similar first-order geometry along strike, consisting of one or two far-traveled western thrust sheets that carried the thick continental margin section and a series of closely spaced, frontal thrust faults that deformed the thin platform section (Fig. 2A; e.g., Yonkee and Weil, 2015). A foreland basin subsided in front of the SFTB and was progressively filled with as much as ~3–4 km of Cretaceous–early Eocene synorogenic sedimentary rocks (e.g., DeCelles, 2004), which were deformed during the youngest stages of thrusting.

Following the early Eocene termination of shortening in the SFTB (e.g., Yonkee and Weil, 2015), portions of the Cordillera transitioned to an extensional regime in the late Eocene–Oligocene, which included extensional reactivation of thrust faults in the SFTB (e.g., Constenius, 1996), initial extension in core complexes (e.g., Coney and Harms, 1984), and regional upper-crustal extension in eastern Nevada (e.g., Gans and Miller, 1983). Neogene extension that constructed the Basin and Range Province complexly dismembered the Cordillera and is attributed to the termination of subduction and growth of the San Andreas transform (e.g., Dickinson, 2006).

COMPILATION OF CROSS SECTIONS

To illustrate the pre- and postorogenic geometries of the SFTB, I compiled seven balanced cross sections (Figs. 1 and 2A; see Supplemental Material[1] for versions of all seven cross sections; Price, 1981; Coogan, 1992; DeCelles and Coogan, 2006; Fuentes et al., 2012; Giallorenzo et al., 2018). I made new interpretations of deformation geometries in the hinterland portions of cross sections 1 and 2, and I present modified restored sections for cross sections 1–3 and a new restored section for cross section 7 (details in the Supplemental Material). Cross sections 1–6 yielded shortening estimates between 138 and 265 km, which decrease southward to 103 km on cross section 7 (Fig. 1).

On cross sections 1–3, the cumulative thickness of pre-orogenic (i.e., pre-Cretaceous) sedimentary rocks above the basal SFTB décollement increases westward from 1–2.5 km at the thrust front to 20–25 km at their western edge (Fig. 2B). On cross sections 4–7, pre-Cretaceous rocks thicken westward from 2.5–3 km at the thrust front to 12.5–20 km at their western edge (Fig. 2B). This westward thickening is interpreted to correspond with an approximately equivalent westward thinning of underlying Precambrian basement rocks, transitioning from the unrifted craton on the east to crust that was highly thinned by rifting on the west (e.g., Picha and Gibson, 1985). Therefore, the translation of this thick sedimentary package 138–265 km eastward during construction of the SFTB requires that an equivalent length of thick, unrifted cratonic basement beneath the basal SFTB décollement was underthrusted relatively westward beneath the hinterland region.

To estimate the spatial extent to which this thick crust was underthrusted to the west, I measured thickness trends of pre-Cretaceous sedi-

[1]Supplemental Material. Includes a figure with detailed versions of all seven cross sections, a summary of rock units on each cross section, and supporting data for cross section reconstructions, shortening and extension calculations, stratigraphic thicknesses, and measured thickening and thinning components. Please visit https://doi.org/10.1130/GEOL.S.24112725 to access the supplemental material; contact editing@geosociety.org with any questions.

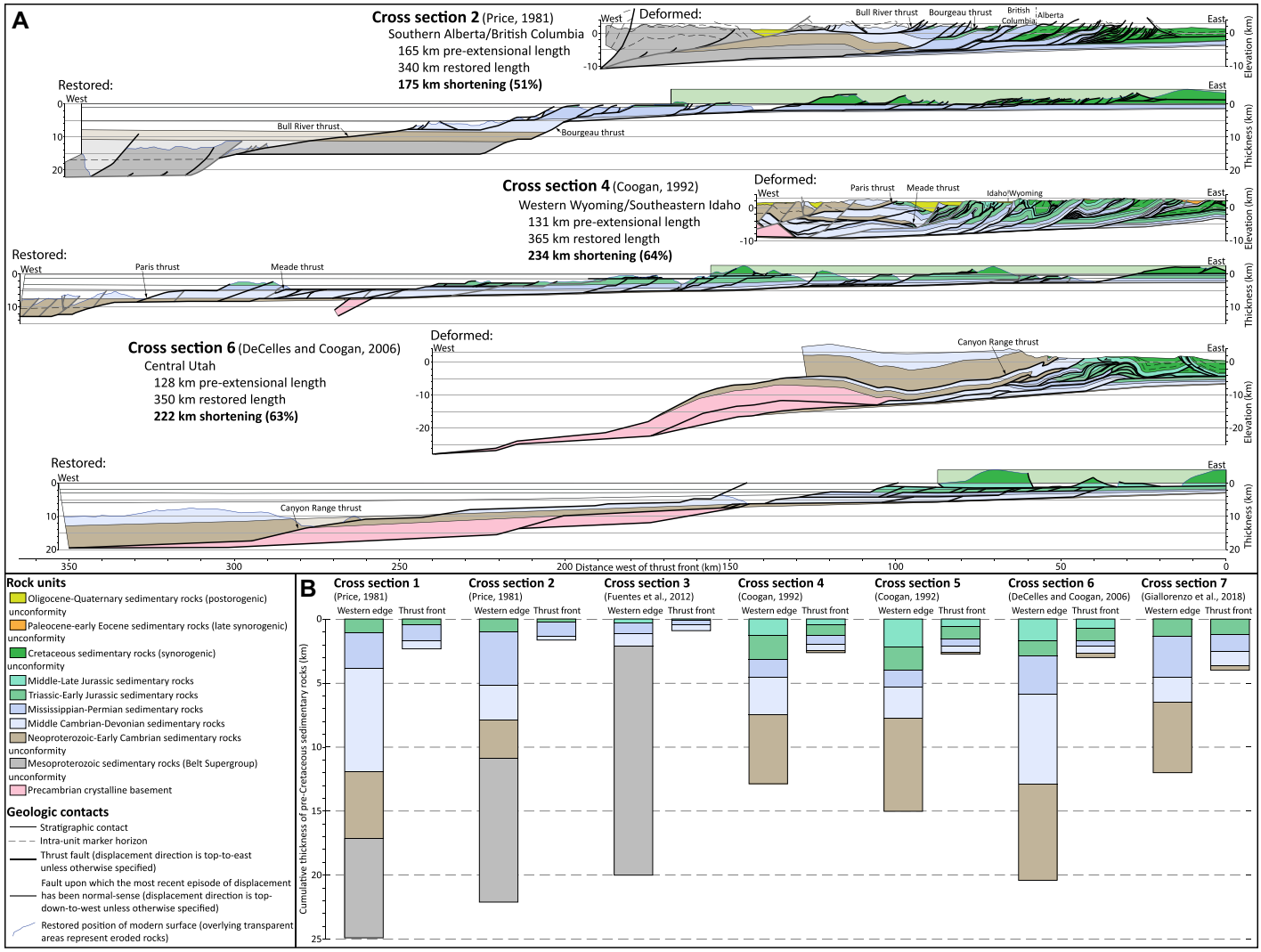

Figure 2. (A) Three representative cross sections through Sevier fold-and-thrust belt (SFTB; additional cross sections are available in the Supplemental Material [see text footnote 1]). (B) Columns for each cross section showing cumulative thickness of pre-Cretaceous sedimentary rocks at their western edge (thick continental margin section) and at Sevier thrust front (thin platform section).

mentary rocks above the basal SFTB décollement on the restored cross sections (Fig. 3A). To account for the overprinting effects of Cenozoic extension, I incorporated extension estimates from published reconstructions across southern Idaho, western Utah, and Nevada for cross sections 4–7 (Rodgers et al., 2002; McQuarrie and Wernicke, 2005; Long, 2019; details in the Supplemental Material). On Figure 3A, I interpreted a restored "craton edge zone" upon which 7.5–15 km of pre-Cretaceous rocks were deposited, which separates the minimally thinned craton to the east (<7.5 km of pre-Cretaceous rocks) from the highly thinned continental and/or transitional crust to the west (>15 km of pre-Cretaceous rocks). The $^{87}Sr/^{86}Sr$ 0.706 isopleth, which is interpreted to approximate the western edge of North American crust in the subsurface (e.g., Armstrong et al., 1977), lies within the highly thinned western domain. The reconstructed position of the western limit of the craton edge zone trends through central Nevada, southwestern Idaho, northwestern Montana, and eastern British Columbia (Fig. 3A).

QUANTIFYING CONTRIBUTIONS OF THICKENING PROCESSES

Thickening accommodated by fold-and-thrust belts is often measured using the vertical magnitude of structural repetition of strata (e.g., Boyer and Elliott, 1982). However, this approach does not account for the potential increase in crustal thickness added beneath the basal décollement by underthrusting. On Figure 4A, I define a new approach for quantifying crustal thickening. By comparing the crustal thicknesses above and below the basal décollement between the initial and final locations of a point at the modern surface, components of thickening accommodated by underthrusting (Z_u), deformation in the fold-and-thrust belt (Z_{thr}), and deposition and deformation of synorogenic rocks in the foreland basin (Z_{fb}) can be measured, as well as thinning accommodated by erosion (Z_e). Net thickening (Z_{net}) is equal to $Z_u + Z_{thr} + Z_{fb} - Z_e$.

Using this approach, I quantified these components for cross sections 2 and 6 (Fig. 4B). I assumed a consistent 40 km initial Moho depth for both cross sections, which is supported by the ~36–44 km Moho depth range for the Colorado Plateau in central Utah (38°N–40°N) determined from receiver function data (Gilbert, 2012) and the ~40 km thickness estimated for the Hudsonian crust in southwestern Alberta from seismic refraction, magnetic, and gravity data (Price, 1981). Both cross sections exhibit similar patterns, with Z_{fb} values as high as 4 km dominating in the frontal portion, which transition to a middle zone with Z_{thr} and Z_u values typically between 2 and 5 km. Moving westward, once the traces of thick, far-traveled hinterland thrust sheets are crossed (the Bourgeau and Bull River thrusts on cross section 2 and the Canyon Range thrust on cross section 6), Z_u and Z_e increase significantly. In the western portion

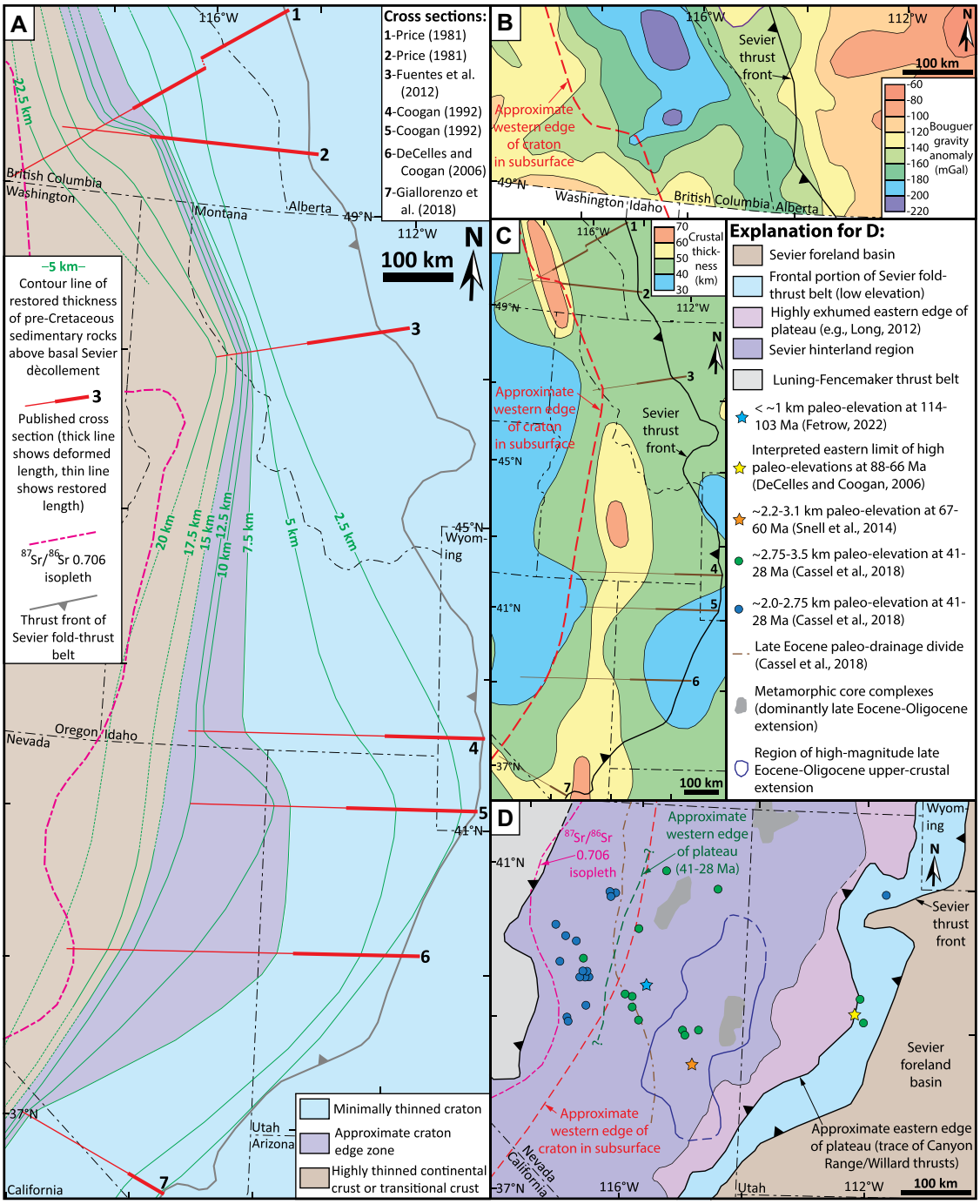

Figure 3. Maps of: (A) cumulative thickness of pre-Cretaceous sedimentary rocks above basal Sevier fold-and-thrust belt (SFTB) décollement on restored cross sections, as a proxy for the subsurface extent of the underthrusted craton (cross sections 4–7 are restored to account for Cenozoic extension; see details in the Supplemental Material [see text footnote 1]); (B) negative Bouguer gravity anomaly beneath southern Canadian Cordillera (modified from Price, 1981); (C) restored pre-extensional crustal thickness (modified from Coney and Harms, 1984); and (D) paleoelevation data and locations of high-magnitude late Eocene–Oligocene extension in Nevada and Utah.

of cross section 2, Z_u varies between 13 and 19 km, Z_e is generally between 13 and 15 km, and Z_{thr} typically ranges between 4 and 7 km. In the western portion of cross section 6, Z_u and Z_e are approximately constant at 14 km and 9–10 km, respectively, and Z_{thr} varies between 4 and 10 km. Z_{net} increases westward from 4 km at the thrust front to 9 km on cross section 2 and 14 km on cross section 6.

DISCUSSION

Thickening processes are dominated by foreland basin deposition and thrust sheet stacking in the frontal portion of the SFTB and transition westward to being dominated by underthrusting in the hinterland portion, with a net thinning above the basal décollement via significant erosion of thick hinterland thrust sheets (Z_e is 2.7 and 1.8 times greater than Z_{thr} in the western portions of cross sections 2 and 6, respectively). To the west of the area of the deformed cross sections, Z_u values between 5 and 17 km persist for an additional across-strike distance of 115 km on cross section 2 and 95 km on cross section 6 (Fig. 4B). The $^{87}Sr/^{86}Sr$ 0.706 isopleth, which is interpreted to correspond with significant crustal thinning accompanying the westward transition to oceanic crust in the subsurface (e.g., Armstrong et al., 1977), lies between 0 and 60 km to the west of the restored sections (Fig. 3A). Therefore, the 5–17 km range of Z_u values beneath the Sevier hinterland region, which I measured assuming a consistent initial Moho depth of 40 km, are likely minima. Additionally, the use of a static deformed and restored length and shape for the underthrusted footwall also likely provides a minimum estimate for Z_u; any internal duplexing or ductile thickening beneath the basal décollement would increase Z_u values. The results on Figure 4B demonstrate that underthrusting was the dominant thickening mechanism beneath the western

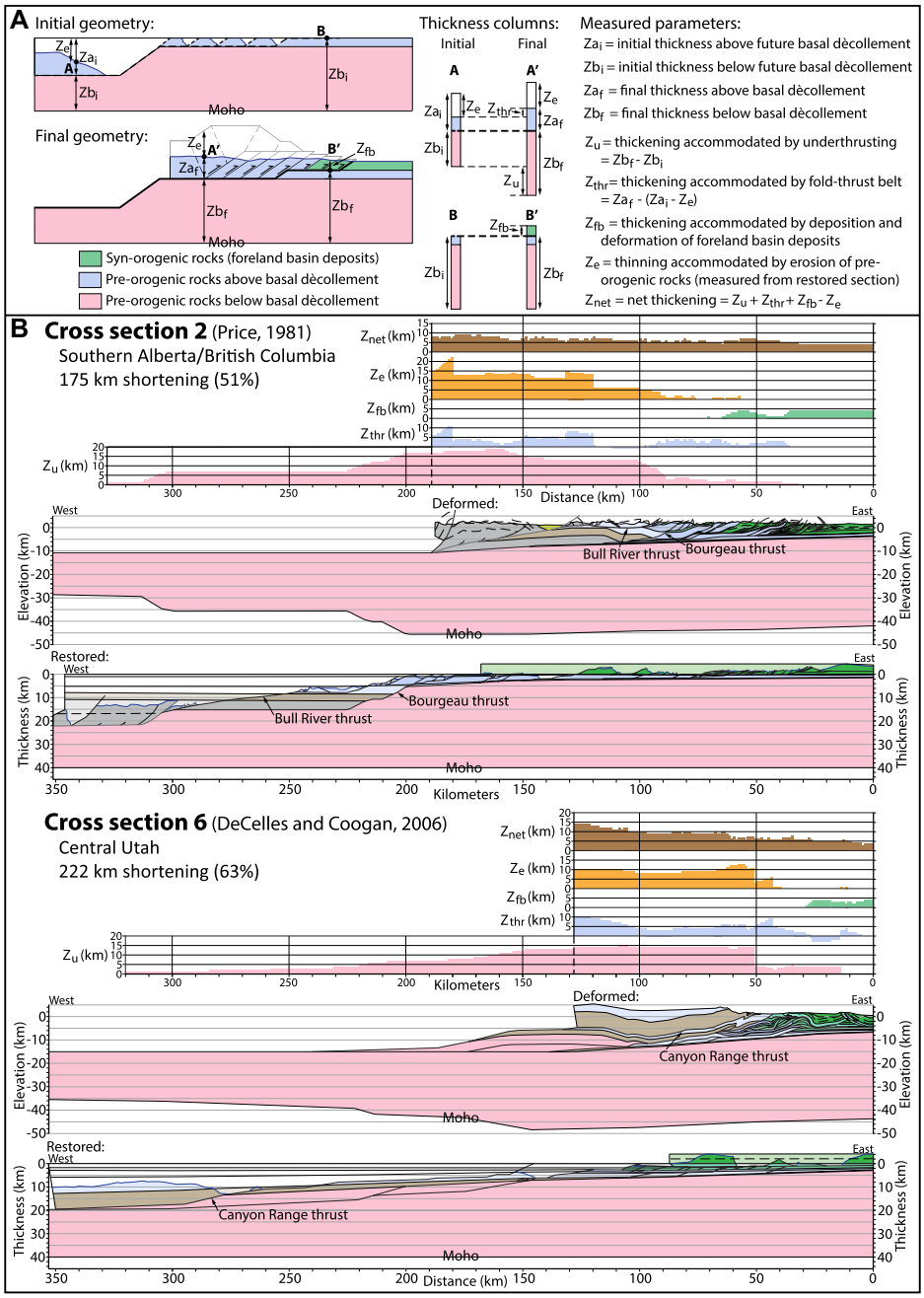

Figure 4. (A) Definition of parameters used to calculate components of thickening and thinning. Small negative Z_{thr} values can locally result when portions of thrust sheets restore across footwall ramps to positions above much deeper hinterland décollement levels. (B) Components of thickening and thinning calculated for cross sections 2 and 6.

80–100 km of the SFTB, and it was likely the dominant thickening mechanism beneath at least an additional 95–115 km width of the hinterland region to the west. In general, Z_u is predicted to attain a maximum value approximately equal to the total change in thickness of the deformed sedimentary package, and it should affect an across-strike area that is approximately equal to the shortening magnitude in the overlying fold-and-thrust belt.

The interpretation that underthrusting was the dominant thickening process that constructed the Cordilleran hinterland plateau is consistent with published geophysical data and paleoaltimetry. In southern Canada, a negative Bouguer gravity anomaly corresponds with the reconstructed spatial extent of the ~40-km-thick, underthrusted Hudsonian craton (Fig. 3B; Price, 1981). At the latitude of the Great Basin, progressive westward underthrusting of the thick craton is compatible with eastern Nevada residing at <1 km elevation at 114–103 Ma (Fetrow, 2022) and then rising to 2.2–3.1 km elevation by 67–60 Ma (Fig. 3D; Snell et al., 2014). The restored western edge of the underthrusted craton spatially corresponds with the western limit of 2.75–3.5 km paleoelevations at 41–28 Ma, which Cassel et al. (2018) interpreted to demarcate the western plateau boundary (Fig. 3D). The western craton edge also lies just to the west of the reconstructed ~50–60-km-thick "crustal welt" of Coney and Harms (1984) (Fig. 3C). The underthrusted craton underlies core complexes that accommodated significant extension during the late Eocene–Oligocene (e.g., Dickinson, 2006), as well as a region of high-magnitude late Eocene–Oligocene upper-crustal extension in eastern Nevada (Fig. 3D; e.g., Gans and Miller, 1983). This supports the hypothesis that gradients in crustal thickness (and thus gravitational potential energy) exerted a primary spatial control on the initial extensional collapse of the Cordillera (e.g., Coney and Harms, 1984; Long, 2019).

CONCLUSIONS

(1) Westward underthrusting of the thick North American craton, as a geometric requirement of shortening in the SFTB, was the dominant thickening process that constructed the ~200–250-km-wide Cordilleran hinterland plateau. The restored western edge of the craton underlies the western limit of the 2.75–3.5-km-elevation plateau.

(2) Underthrusting is a first-order thickening process in fold-and-thrust belts that deform sedimentary packages with a high pre-orogenic taper. Thickening via underthrusting is predicted to attain a maximum value equivalent to the total change in thickness of the deformed sedimentary package, and to affect an across-strike length approximately equal to cumulative shortening.

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