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Deep-crustal metasedimentary rocks support Late Cretaceous "Mojave-BC" translation

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ABSTRACT

Metasedimentary rocks in the mid- to lower crust of exhumed continental arcs preserve information about both sedimentary provenance and metamorphic pressure-temperature paths, providing a unique perspective on the tectonic history of an arc, including margin-parallel translation and sediment-burial mechanisms. The Swakane Biotite Gneiss (Washington State, USA) and the Pelona, Orocopia, Rand, Sierra de Salinas, and related schists (PORS) (California and Arizona) represent metasedimentary rocks that were incorporated into the deep levels of North American Cordilleran arc systems. We evaluated the provenances for the sedimentary protoliths of these units by detrital zircon U-Pb and Hf-isotope analyses to assess paleogeographic reconstructions for western North America. All samples have similar Mesozoic peaks, and Proterozoic age populations (1.38 Ga and 1.6–1.8 Ga) are present in samples with maximum depositional ages younger than ca. 86 Ma. Zircon Hf-isotope results are similar for these Proterozoic populations, but the Swakane Mesozoic zircon samples reveal slight differences in comparison to PORS samples. Similar detrital zircon patterns, timing of emplacement, lithology, and structural setting suggest that these two distinct units formed at the same latitude and are consistent with recent interpretations of paleomagnetic data that indicate "moderate" (~1600 km) northward translation for the North Cascades arc. This study provides an example of how sediment provenance signatures combined with interpreted metamorphic histories can be used to track vertical displacement and horizontal translation within a complex, long-lived, convergent-margin system.

INTRODUCTION

Convergent margins are typically defined by large-scale structures that accommodate geologically rapid orogen-normal translation of crustal material. However, many convergent margins are oblique, which may lead to a component of orogen-parallel strike-slip faulting (e.g., Teyssier et al., 1995). Quantifying strike-slip offsets can be difficult, as similar geologic processes can occur for potentially tens of millions of years over thousands of kilometers along strike, making it hard to establish the amount of margin-parallel translation. This is the case for wide swaths of coastal terranes that form the western North American continental margin.

The paleogeography of western North America has been widely debated since paleomagnetic studies over 40 years ago revealed anomalously shallow magnetic inclinations in rocks within the Coast Plutonic Complex–North Cascades range, British Columbia (BC; Canada) and Washington State (USA) (Fig. 1) (Beck and Noson, 1972). The paleomagnetic data were interpreted as evidence that these rocks originated in Baja California, Mexico (Baja) and were translated ~3000 km northward from 85 to 55 Ma (i.e., the "Baja-BC" hypothesis); Irving et al., 1985). More recent paleomagnetic studies suggest moderate (~1600 km) amounts of northward translation (Krijgsman and Tauxe, 2006; Rusmore et al., 2013) from near the modern-day northwestern Mojave Desert or southernmost Sierra Nevada (California) (i.e., the "Mojave-BC" hypothesis). However, measured offsets on known strike-slip faults only account for ~700–1000 km of margin-parallel displacement (Wyld et al., 2006). The discrepancies between the paleomagnetic and geologic data sets have resulted in two main Late Cretaceous reconstructions, restoring the suspect terranes of Washington and British Columbia to the latitude of either the Klamath Mountains (California and Oregon; ~700 km) or the southern Sierra Nevada batholith (~1600 km).

Detrital zircon geochronology can serve as a "crucial test" for discerning between paleogeographic hypotheses (e.g., Mahoney et al., 1999; Matthews et al., 2017). Here, we compare detrital zircon U-Pb ages and Hf-isotope compositions with interpreted emplacement histories for deep-crustal metasedimentary rocks of the Pelona, Orocopia, Rand, Sierra de Salinas, and related schists (PORS) in southern California and Arizona (USA) and the Swakane Biotite Gneiss (herein referred to as the Swakane Gneiss) in north-central Washington (Fig. 1) to evaluate Late Cretaceous–Paleogene translation hypotheses for the western margin of the North American Cordillera.

GEOLOGIC SETTING

The PORS and Swakane Gneiss are composed of ≥90% homogeneous quartzofeldspathic schist or gneiss with minor metabasite and rare ultramafite, metachert, and marble (Haxel and Dillon, 1978; Tabor et al., 1987), consistent with a sandstone protolith imbricated with slices of oceanic material. These protoliths reached depths of as much as ~40 km within a few million years after deposition within the trench and/or forearc basin (Grove et al., 2003; Matzel et al., 2004). Neither unit is intruded by Late Cretaceous–Eocene arc-related plutons, nor are

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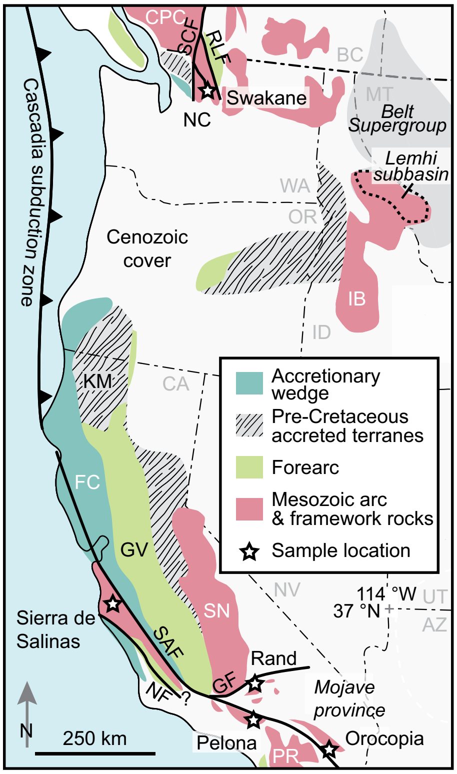

Figure 1. Major Mesozoic tectonic elements of western North American Cordilleran arc and sample locations of Pelona, Orocopia, Rand, and Sierra de Salinas schists and Swakane Gneiss. CPC—Coast Plutonic Complex; FC—Franciscan Complex; GF—Garlock fault; GV—Great Valley Group; IB—Idaho batholith; KM—Klamath Mountains; NC—North Cascades; NF—Nacimiento fault; PR—Peninsular Ranges batholith; RLF—Ross Lake fault zone; SAF—San Andreas fault; SCF—Straight Creek fault; SN—Sierra Nevada. States and provinces: AZ—Arizona; BC—British Columbia; CA—California; ID—Idaho; MT—Montana; NV—Nevada; OR—Oregon; UT—Utah; WA—Washington.

the bases of the units exposed. Both are separated by low-angle faults from overlying units.

The PORS are interpreted as underplated accretionary wedge and/or forearc basin sediments analogous to the Franciscan Complex and Great Valley Group of California (Grove et al., 2003; Jacobson et al., 2011; Chapman, 2016). Progressive underplating of sediment along a low-angle subduction system began by ca. 90 Ma (Grove et al., 2003; Saleeby, 2003) followed by ca. 85 Ma cessation of magmatism throughout the Sierra Nevada arc. The PORS record epidote-blueschist to upper-amphibolite facies metamorphism (Chapman, 2016). Maximum metamorphic temperature, maximum depositional ages (MDAs) (>ca. 90 to ca. 65 Ma), and ^{40}Ar-^{39}Ar mica-cooling ages (90–40 Ma) generally decrease to the southeast (Grove et al., 2003; Jacobson et al., 2011; Chapman, 2016).

In comparison, the Swakane Gneiss is interpreted to represent forearc and/or accretionary wedge units that were imbricated along thrust faults in a continental magmatic arc (Matzel et al., 2004; Gatewood and Stowell, 2012; Sauer et al., 2018). The Swakane protolith reached upper-amphibolite facies conditions (Valley et al., 2003) by 74–66 Ma (Gatewood and Stowell, 2012; Sauer et al., 2018) during active arc magmatism elsewhere in the North Cascades and proposed margin-parallel translation of the arc (e.g., Umhoefer and Blakey, 2006). Exposures of the Swakane Gneiss are largely isobaric (Valley et al., 2003), and Late Cretaceous MDAs (93–81 Ma; Sauer et al., 2018) and Eocene mica-cooling ages (51–48 Ma; Paterson et al., 2004) are observed throughout.

METHODS

Zircon was separated from one sample each of the Rand, Sierra de Salinas, Pelona, and Orocopia schists and subsequently imaged for cathodoluminescence (CL) zoning. The CL images were used to guide laser ablation–inductively coupled plasma–mass spectrometry U-Pb and Hf-isotope analyses (see Item DR1 in the GSA Data Repository[1] for detailed methods). MDAs were estimated using the youngest cluster of U-Pb dates consisting of three or more analyses that overlap at the 2σ level (Dickinson and Gehrels, 2009). The new U-Pb and Hf-isotope results from the PORS (presented in Item DR2) are compared to equivalent results from 11 previously analyzed Swakane Gneiss samples (Sauer et al., 2018) (Fig. 2).

DETRITAL ZIRCON U-Pb AND Hf-ISOTOPE RESULTS

Southern Californian Schists

The CL images of PORS zircon show a variety of zoning patterns; some grains have thick (~10–50 µm) overgrowths, referred to as mantle zones, on preexisting cores (Fig. DR1 in the Data Repository). All grains are slightly rounded, and most have a very thin (<5 µm), CL-bright outermost rim that was too thin to analyze. The U-Pb data from the PORS samples define MDAs between ca. 87 and 72 Ma and exhibit multiple age peaks that mostly fall within the range of 1.8–1.3 Ga and/or 250–70 Ma. The MDAs correlate inversely with the abundance of Proterozoic dates, and positively with the number of 250–100 Ma dates. The ca. 87 Ma Rand sample is characterized by dominantly Mesozoic zircon, whereas the ca. 85 Ma Sierra de Salinas, ca. 85 Ma Orocopia, and ca. 72 Ma Pelona samples also have narrow 1.38–1.40 Ga and broad 1.8–1.6 Ga populations (Fig. 2A). The thick mantle zones yielded Late Cretaceous dates and were found on Proterozoic cores (Fig. DR1). These dates overlapped in age with those of oscillatory-zoned cores and are interpreted as detrital; they were typically within the population used to calculate MDAs.

Most Late Cretaceous (100–70 Ma) zircon from the PORS have unradiogenic ε_{Hfi} values (+1 to −15) (Fig. 2B). Triassic–Early Cretaceous grains have supra-chondritic compositions mostly between depleted-mantle values and ε_{Hfi} = +6, with less-radiogenic values for some 160–150 Ma grains. Zircon ε_{Hfi} values from the two main Proterozoic populations from the Orocopia and Sierra de Salinas samples fall between depleted-mantle and chondritic uniform reservoir (CHUR) values, whereas some of the zircon of this age range from the Pelona sample have less-radiogenic compositions (Fig. 2).

Comparison with the Swakane Gneiss

The Swakane Gneiss samples yield MDAs between 93 and 81 Ma and zircon age populations similar to those of PORS samples with coeval MDAs (i.e., the Rand, Sierra de Salinas, and Orocopia) (Fig. 2A). For example, the Swakane and Rand samples with the oldest MDAs (93–87 Ma) lack distinct Proterozoic peaks, whereas the Swakane, Orocopia, and Sierra de Salinas samples younger than ca. 86 Ma all have narrow ca. 1.38 Ga and broad 1.8–1.6 Ga peaks. Further, some Proterozoic zircon from the Swakane samples also have Late Cretaceous (86–81 Ma) mantle overgrowths, which are interpreted to be part of the youngest detrital population (Sauer et al., 2018).

Though the Swakane and PORS samples with comparable MDAs have similar zircon age patterns, the Hf-isotope data reveal some differences (Fig. 2B). For example, Late Cretaceous zircon from the Rand sample have only unradiogenic, <ca. 100 Ma grains (ε_{Hfi} = −6 to −12), whereas all but one analysis of Swakane Late Cretaceous zircon have uniform, near–depleted mantle compositions (ε_{Hfi} = +13 to +8) (Fig. 2B). In addition, <ca. 100 Ma zircon from the younger (MDA <ca. 86 Ma) Swakane samples have a wide range of ε_{Hfi} values (+13 to −15), whereas the majority in the Orocopia and Sierra de Salinas samples show mostly unradiogenic ε_{Hfi} values (+1 to −15) (Fig. 2B).

SEDIMENT PROVENANCE

The Swakane Gneiss, PORS, and Californian accretionary wedge strata (Franciscan Complex) all record a switch in zircon provenance ca. 86 Ma: pre–86 Ma rocks contain dominantly Mesozoic zircon, whereas strata deposited at or post–86 Ma include ~10%–65% Proterozoic grains (Jacobson et al., 2011; Dumitru et al., 2016; Sauer et al., 2018). The shift in sediment provenance has been linked to two different sources. Dumitru et al. (2016) proposed that Proterozoic zircon in the ca. 85 Ma Sierra de Salinas schist and the post–ca. 86 Ma Swakane Gneiss are

[1]GSA Data Repository item 2019042, sample information, analytical methods, cathodoluminescence images, and zircon U-Pb and Lu-Hf data (Items DR1 and DR2), is available online at http://www.geosociety.org/datarepository/2019/, or on request from editing@geosociety.org.

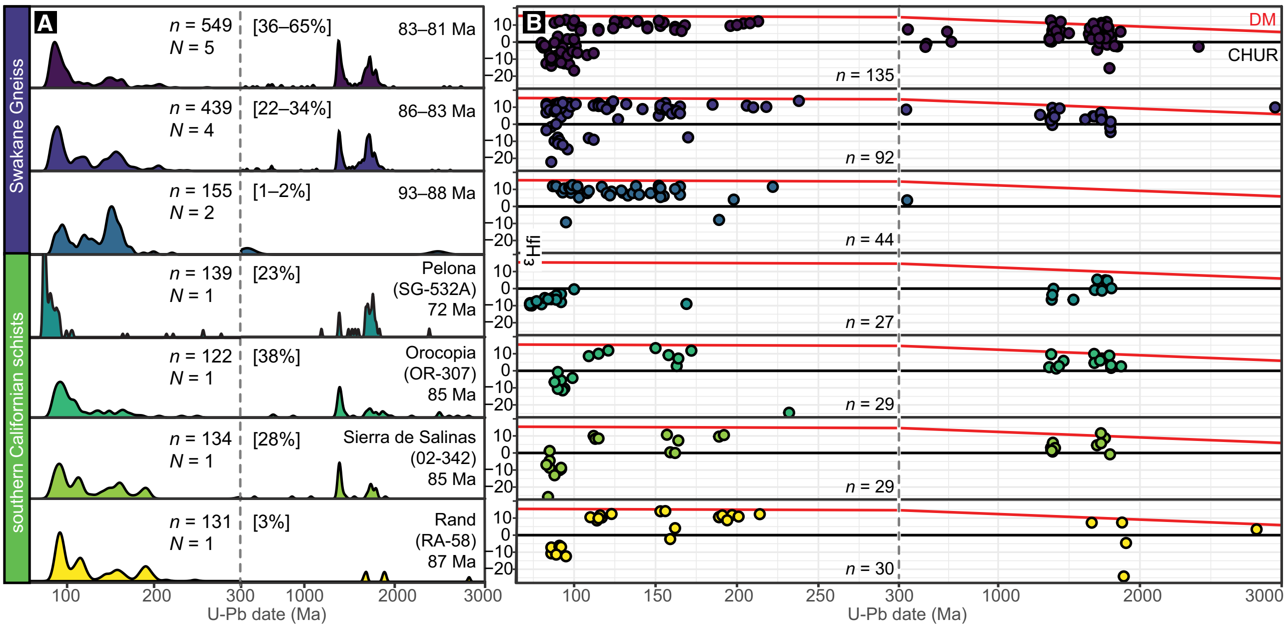

Figure 2. A: Kernel density estimate plots of U-Pb results from samples of Swakane Gneiss (Washington State, USA; Sauer et al., 2018) and Pelona, Orocopia, Rand, and Sierra de Salinas schists (this study). Curves for 300–3000 Ma are exaggerated by factor of ten relative to <300 Ma. Square brackets indicate percentage of Proterozoic analyses. B: Hf-isotope results. In both A and B, note scale change at 300 Ma. CHUR—chondritic uniform reservoir; DM—depleted mantle; *n*—number of analyses; *N*—number of samples.

derived from sediment partly eroded from ca. 1.38 Ga anorogenic intrusions in the Lemhi subbasin of the Belt Supergroup (northwestern Laurentia) and the Late Cretaceous Idaho batholith (Fig. 1). In contrast, others have linked the influx of Proterozoic grains in the protolith of the PORS to the tectonic dismemberment of the southern Sierra Nevada batholith, which allowed sediment derived from the Mojave terrane (southwestern Laurentia) to reach west of the arc (Jacobson et al., 2011).

Hafnium isotopes can be used to distinguish between these sources. The Proterozoic zircon from the Mojave terrane and the Lemhi subbasin have similar ε_{Hfi} values (cf. Stewart et al., 2010; Wooden et al., 2013); however, the unradiogenic ε_{Hfi} values for the Late Cretaceous detrital zircon are distinct. Late Cretaceous zircon from both the Idaho batholith and intrusions in the Mojave province have ε_{Hfi} values that reflect assimilation of Proterozoic crust. Idaho batholith zircon yield a more unradiogenic range of ε_{Hfi} values (–9 to –23; Gaschnig et al., 2011) than are observed in the majority of Swakane Gneiss (+13 to –15) and PORS (+1 to –15) zircon. In comparison, zircon from the Late Cretaceous plutons that intrude Mojave crust have a wider range of $\varepsilon_{Hf(80\ Ma)}$ values (–2 to –25) and include xenocrystic Proterozoic cores (Barth et al., 2016). The mantle overgrowths on Proterozoic cores and unradiogenic ε_{Hfi} values for <ca. 100 Ma zircon in the Swakane and PORS are characteristic of reworked older crust, and, together, likely tie the sediment provenance to the Mojave region. In addition, Archean grains would likely be found in the Lemhi subbasin (Stewart et al., 2010), but these have not been observed in the samples studied here.

The zircon results demonstrate that both the PORS and Swakane protoliths likely contain sediment eroded from the Mojave province; however, some of the Swakane age populations show important Hf-isotope differences in comparison to the PORS. The oldest Swakane samples (MDAs = ca. 93 and 88 Ma) are characterized by 160–140 and 120–90 Ma peaks that have mostly supra-chondritic ε_{Hfi} values, whereas similar-aged zircon from the PORS have a wider range, including subchondritic ε_{Hfi} values (Fig. 2). The age peaks and limited range of radiogenic ε_{Hfi} values in the 160–90 Ma Swakane zircon strongly match those of plutonic zircon from the southern Coast Plutonic Complex (Homan et al., 2017). Swakane samples deposited after ca. 86 Ma also include 100–81 Ma unradiogenic zircon (Fig. 2), likely derived from the Mojave intrusions, as described above.

A CONNECTED ORIGIN FOR THE METASEDIMENTARY UNITS

In addition to the zircon similarities, the PORS and Swakane Gneiss were coevally buried to as much as 40 km depth during the Late Cretaceous. Overall, the similarities in lithology, tectonic setting, timing of burial, and zircon characteristics suggest a link between the protolith and emplacement of the Swakane Gneiss and those of the PORS. These combined results indicate that the Swakane protoliths likely originated at similar latitudes as those of the PORS. The PORS were probably underplated beneath the arc, as there is strong evidence for shallow-angle subduction in southern California during the Late Cretaceous (e.g., Saleeby, 2003). Underplating has been less favored for the Swakane Gneiss, as previous studies have highlighted differences in peak pressure-temperature conditions and the lack of evidence for low-angle subduction north of Idaho (e.g., Matzel et al., 2004). If, however, the Swakane Gneiss did originate at the latitude of southern California, it would restore to the shallowly subducting segment of the slab, and the Swakane may represent the outboard continuation of the PORS (Fig. 3). This interpretation is consistent with previous reconstructions based on both geologic and paleomagnetic data (e.g., Umhoefer and Blakey, 2006). Furthermore, the detrital zircon results indicate that the Swakane protolith was deposited near the Coast Plutonic Complex, which implies that the latter was likely translated ~1600 km northward as well.

CONCLUSIONS

Detrital zircon from the PORS and the Swakane Gneiss share distinct U-Pb date and Hf-isotope provenance markers that, when coupled with MDA estimates, analogous structural settings, similar lithologies, and coeval burial, demonstrate that these units formed in the same place at the same time. These results support paleomagnetic data, which indicate that ~1600 km of northward, margin-parallel displacement occurred at 85–55 Ma. Many questions remain pertaining to the mechanism and history of translation along the western North American continental margin, e.g., which terranes are included in the Mojave-BC block, whether there is evidence for the presence of the Coast Plutonic Complex outboard of the Sierra Nevada batholith, and which structure(s) accommodated this translation. However, the connected origin of

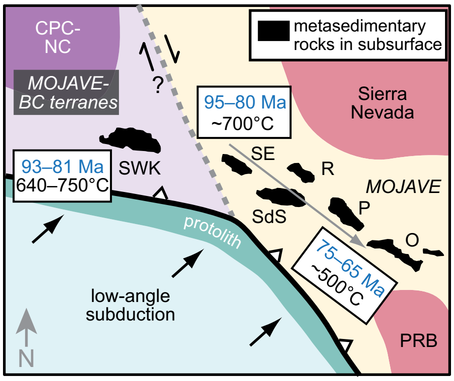

Figure 3. Cartoon of connected burial of Swakane Gneiss and Pelona, Orocopia, Rand, Sierra de Salinas, and related schists (PORS) at ca. 75 Ma. Boxed numbers indicate range of maximum depositional ages and peak metamorphic temperature for metasedimentary rocks (Valley et al., 2003; Chapman, 2016). Gray dashed line indicates hypothetical Mojave-BC (British Columbia) fault zone. Gray arrow represents decreasing metamorphic grade and maximum depositional ages. BC—British Columbia; CPC—Coast Plutonic Complex; NC—North Cascades; O—Orocopia Schist; P—Pelona Schist; PRB—Peninsular Range batholith; R—Rand Schist; SdS—schist of Sierra de Salinas; SE—San Emigdio Schist; SWK—Swakane Gneiss.

these distinct metasedimentary assemblages support a "Mojave-BC" hypothesis. Thus, translation at convergent margins that includes both vertical and horizontal components can be tracked using sediment provenance markers coupled with interpreted metamorphic histories.

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REFERENCES CITED

Barth, A.P., Wooden, J.L., Mueller, P.A., and Economos, R.C., 2016, Granite provenance and intrusion in arcs: Evidence from diverse zircon types in Big Bear Lake Intrusive Suite, USA: Lithos, v. 246–247, p. 261–278, https://doi.org/10.1016/j.lithos.2015.12.009.

Beck, M.E., and Noson, L., 1972, Anomalous paleolatitudes in Cretaceous granitic rocks: Nature Physical Science (London), v. 235, p. 11–13, https://doi.org/10.1038/physci235011a0.

Chapman, A.D., 2016, The Pelona-Orocopia-Rand and related schists of southern California: A review of the best-known archive of shallow subduction on the planet: International Geology Review, v. 59, p. 664–701, https://doi.org/10.1080/00206814.2016.1230836.

Dickinson, W.R., and Gehrels, G.E., 2009, Use of U-Pb ages of detrital zircons to infer maximum depositional ages of strata: A test against a Colorado Plateau Mesozoic database: Earth and Planetary Science Letters, v. 288, p. 115–125, https://doi.org/10.1016 /j.epsl.2009.09.013.

Dumitru, T.A., Elder, W.P., Hourigan, J.K., Chapman, A.D., Graham, S.A., and Wakabayashi, J., 2016, Four Cordilleran paleorivers that connected Sevier thrust zones in Idaho to depocenters in California, Washington, Wyoming, and, indirectly, Alaska: Geology, v. 44, p. 75–78, https://doi.org/10.1130/G37286.1.

Gaschnig, R.M., Vervoort, J.D., Lewis, R.S., and Tikoff, B., 2011, Isotopic evolution of the Idaho batholith and Challis intrusive province, northern US Cordillera: Journal of Petrology, v. 52, p. 2397–2429, https://doi.org/10.1093/petrology/egr050.

Gatewood, M.P., and Stowell, H.H., 2012, Linking zircon U-Pb and garnet Sm-Nd ages to date loading and metamorphism in the lower crust of a Cretaceous magmatic arc, Swakane Gneiss, WA, USA: Lithos, v. 146–147, p. 128–142, https://doi.org/10.1016/j.lithos.2012.04.030.

Grove, M., Jacobson, C.E., and Barth, A.P., 2003, Temporal and spatial trends of Late Cretaceous–early Tertiary underplating of Pelona and related schist beneath southern California and southwestern Arizona, *in* Johnson, S.E., et al., eds., Tectonic Evolution of Northwestern México and the Southwestern USA: Geological Society of America Special Paper 374, p. 381–406, https://doi.org/10.1130/0-8137-2374-4.381.

Haxel, G.B., and Dillon, J.T., 1978, The Pelona-Orocopia Schist and Vincent–Chocolate Mountain thrust system, southern California, *in* Howell, D.G., and McDougall, K.A., eds., Pacific Coast Paleogeography Symposium 2: Mesozoic Paleogeography of the Western United States: Los Angeles, Pacific Section, Society of Economic Paleontologists and Mineralogists, p. 453–469.

Homan, E.C., Cecil, M.R., Gehrels, G.E., Rusmore, M.E., Yokelson, I.N., Stowell, H.H., Valley, J.W., and Kitajima, K., 2017, U-Pb geochronology and zircon Hf and O isotope analysis of plutons in the southern Coast Mountains batholith, British Columbia: Insight into episodic magmatism in continental arcs: Geological Society of America Abstracts with Programs, v. 49, no. 6, https://doi.org/10.1130/abs/2017AM-307175.

Irving, E., Woodsworth, G.J., Wynne, P.J., and Morrison, A., 1985, Paleomagnetic evidence for displacement from the south of the Coast Plutonic Complex, British Columbia: Canadian Journal of Earth Sciences, v. 22, p. 584–598, https://doi.org/10.1139/e85-058.

Jacobson, C.E., Grove, M., Pedrick, J.N., Barth, A.P., Marsaglia, K.M., Gehrels, G.E., and Nourse, J.A., 2011, Late Cretaceous–early Cenozoic tectonic evolution of the southern California margin inferred from provenance of trench and forearc sediments: Geological Society of America Bulletin, v. 123, p. 485–506, https://doi.org/10.1130/B30238.1.

Krijgsman, W., and Tauxe, L., 2006, E/I corrected paleolatitudes for the sedimentary rocks of the Baja British Columbia hypothesis: Earth and Planetary Science Letters, v. 242, p. 205–216, https://doi.org/10.1016/j.epsl.2005.11.052.

Mahoney, J.B., Mustard, P.S., Haggart, J.W., Friedman, R.M., Fanning, C.M., and McNicoll, V.J., 1999, Archean zircons in Cretaceous strata of the western Canadian Cordillera: The "Baja B.C." hypothesis fails a "crucial test": Geology, v. 27, p. 195–198, https://doi.org/10.1130/0091-7613(1999)027<0195:AZICSO>2.3.CO;2.

Matthews, W.A., Guest, B., Coutts, D., Bain, H., and Hubbard, S., 2017, Detrital zircons from the Nanaimo basin, Vancouver Island, British Columbia: An independent test of Late Cretaceous to Cenozoic northward translation: Tectonics, v. 36, p. 854–876, https://doi.org/10.1002/2017TC004531.

Matzel, J.E.P., Bowring, S.A., and Miller, R.B., 2004, Protolith age of the Swakane Gneiss, North Cascades, Washington: Evidence of rapid underthrusting of sediments beneath an arc: Tectonics, v. 23, TC6009, https://doi.org/10.1029/2003TC001577.

Paterson, S.R., Miller, R.B., Alsleben, H., Whitney, D.L., Valley, P.M., and Hurlow, H., 2004, Driving mechanisms for >40 km of exhumation during contraction and extension in a continental arc, Cascades core, Washington: Tectonics, v. 23, TC3005, https://doi.org/10.1029/2002TC001440.

Rusmore, M.E., Bogue, S.W., and Woodsworth, G.J., 2013, Paleogeography of the Insular and Intermontane terranes reconsidered: Evidence from the southern Coast Mountains Batholith, British Columbia: Lithosphere, v. 5, p. 521–536, https://doi.org/10.1130/L288.1.

Saleeby, J.B., 2003, Segmentation of the Laramide Slab—Evidence from the southern Sierra Nevada region: Geological Society of America Bulletin, v. 115, p. 655–668, https://doi.org/10.1130/0016-7606(2003)115<0655:SOTLSF>2.0.CO;2.

Sauer, K.B., Gordon, S.M., Miller, R.B., Vervoort, J.D., and Fisher, C.M., 2018, Provenance and metamorphism of the Swakane Gneiss: Implications for incorporation of sediment into the deep levels of the North Cascades continental magmatic arc, Washington: Lithosphere, v. 10, p. 460–477, https://doi.org/10.1130/L712.1.

Stewart, E.D., Link, P.K., Fanning, C.M., Frost, C.D., and McCurry, M., 2010, Paleogeographic implications of non–North American sediment in the Mesoproterozoic upper Belt Supergroup and Lemhi Group, Idaho and Montana, USA: Geology, v. 38, p. 927–930, https://doi.org/10.1130/G31194.1.

Tabor, R.W., Frizzell, V.A., Jr., Whetten, J.T., Waitt, R.B., Swanson, D.A., Byerly, G.R., Booth, D.B., Hetherington, M.J. and Zartman, R.E., 1987. Geologic map of the Chelan 30-minute by 60-minute quadrangle, Washington: U.S. Geological Survey Miscellaneous Investigations Map I-1661, scale 1:100,000, 33 p., https://doi.org/10.3133/i1661.

Teyssier, C., Tikoff, B., and Markley, M., 1995, Oblique plate motion and continental tectonics: Geology, v. 23, p. 447–450, https://doi.org/10.1130/0091-7613(1995)023<0447:OPMACT>2.3.CO;2.

Umhoefer, P.J., and Blakey, R., 2006, Moderate (1600 km) northward translation of Baja British Columbia from southern California: An attempt at reconciliation of paleomagnetism and geology, *in* Haggart, J.W., et al., eds., Paleogeography of the North American Cordillera: Evidence For and Against Large-Scale Displacement: Geological Association of Canada Special Paper 46, p. 307–329.

Valley, P.M., Whitney, D.L., Paterson, S.R., Miller, R.B., and Alsleben, H., 2003, Metamorphism of the deepest exposed arc rocks in the Cretaceous to Paleogene Cascades belt, Washington: Evidence for large-scale vertical motion in a continental arc: Journal of Metamorphic Geology, v. 21, p. 203–220, https://doi.org/10.1046/j.1525-1314.2003.00437.x.

Wooden, J.L., Barth, A.P., and Mueller, P.A., 2013, Crustal growth and tectonic evolution of the Mojave crustal province: Insights from hafnium isotope systematics in zircons: Lithosphere, v. 5, p. 17–28, https://doi.org/10.1130/L218.1.

Wyld, S.J., Umhoefer, P.J., and Wright, J.E., 2006, Reconstructing northern Cordilleran terranes along known Cretaceous and Cenozoic strike-slip faults: Implication of the Baja British Columbia hypothesis and other models, *in* Haggart, J.W., et al., eds., Paleogeography of the North American Cordillera: Evidence For and Against Large-Scale Displacement: Geological Association of Canada Special Paper 46, p. 277–298.

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