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Subduction Polarity in Ancient Arcs: A Call to Integrate Geology and Geophysics to Decipher the Mesozoic Tectonic History of the Northern Cordillera of North America

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ABSTRACT

Recent syntheses of Cordillera tectonics contain contradictory views of subduction polarity in the late Mesozoic, and this contradiction has implications for whole-earth processes. The long-held view of east-dipping subduction throughout the Late Jurassic–Early Cretaceous Cordillera is challenged by tectonic models calling on a west-dipping subduction system that led to the collision of oceanic arcs, ribbon-continents, or both, with North America. Evidence in support of these models are seismic anomalies in the deep mantle inferred to represent subducted lithosphere from a west-dipping slab. We argue that this "bottom-up" approach to tectonic synthesis carries assumptions that are as great as or greater than ambiguities from the "top-down" approach of surface geology. Geologic evidence from the northern Cordillera is inconsistent with west-dipping subduction in Jura-Cretaceous time and requires long-lived east-dipping subduction along much of the Cordilleran margin. West-dipping subduction in Triassic–Early Jurassic time has been documented and may be the source of the seismic anomalies. We encourage the broader community to come to consensus on integration of these deep images with surface geology.

INTRODUCTION

Regional syntheses of Cordilleran tectonics were central to the plate tectonic revolution with a series of papers that placed the geology of the continental United States into the new paradigm (e.g., Burchfiel and Davis, 1972) in which the Sierra Nevada, Great Valley, and Franciscan triad formed above a late Mesozoic, east-dipping subduction zone. Similar relations have since been used to reconstruct arc polarity in many other orogens.

Cordilleran tectonics saw a paradigm shift in the late 1970s when paleomagnetic data (e.g., Hillhouse, 1977) together with geologic syntheses led to the terrane concept (e.g., Coney et al., 1980). These insights led to the recognition that both collision and strike-slip juxtaposition must have occurred along the Cordillera margin, and multiple terranes comprising different arc elements were scrambled to make the terrane collage.

There has been a recent resurgence in Cordilleran-wide syntheses based in large part on three new data sources: (1) developments in geochronology; (2) Earthscope geophysical data; and (3) geodetic data that reveal active deformation in the Cordillera. The integration of these data provides new opportunities for understanding the long-term evolution of the Cordillera. Challenges arise from a disconnect between two approaches: (1) geological studies that use a *top-down approach*, in which surface geology is projected to infer relations at depth and back in time; and (2) geophysical studies that use a *bottom-up approach* that projects features imaged in the lower crust and mantle to the surface and back in time. Although these approaches should converge on a similar solution, they are often diametrically opposed because of different underlying assumptions.

We here consider an example of where geologic and geophysical interpretations lead to fundamentally different conclusions regarding the polarity of subduction along the Cordilleran margin during late Mesozoic time. We argue from a northern Cordilleran perspective that some recent syntheses (e.g., Johnston, 2008; Hildebrand, 2009; Sigloch and Mihalynuk, 2017) ignored or dismissed a fundamental observation; namely, that there is compelling geologic evidence that subduction along the northern Cordilleran margin has been east-dipping for at least the last ~125 m.y., and likely can be traced ~75 m.y. further back into the Late Triassic. The objective of this article is to compare these approaches for evaluating subduction polarity in ancient margins. Successful integration of the two approaches will be required to fully understand the configuration of ancient subduction zones.

FUNDAMENTAL CONTROVERSY OF SUBDUCTION POLARITY

Uncertainties regarding the late Mesozoic evolution of the Cordilleran margin focus primarily on (1) the size of the ocean basin separating the Wrangellia composite terrane (WCT) or Insular superterrane from the continental margin; and (2) the location, polarity, and age of subduction zones that closed this basin (Fig. 1). One set of models, mainly based on geologic observations, shares an interpretation that this basin closed during Jura-Cretaceous time along an east-dipping[1] subduction zone built along the continental margin,

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[1]Note that because the Alaskan margin is curved this terminology can be confusing. We generally use east dipping or west dipping to reflect the pre-oroclinal geography, but also use north or south dipping when discussing modern geometries.

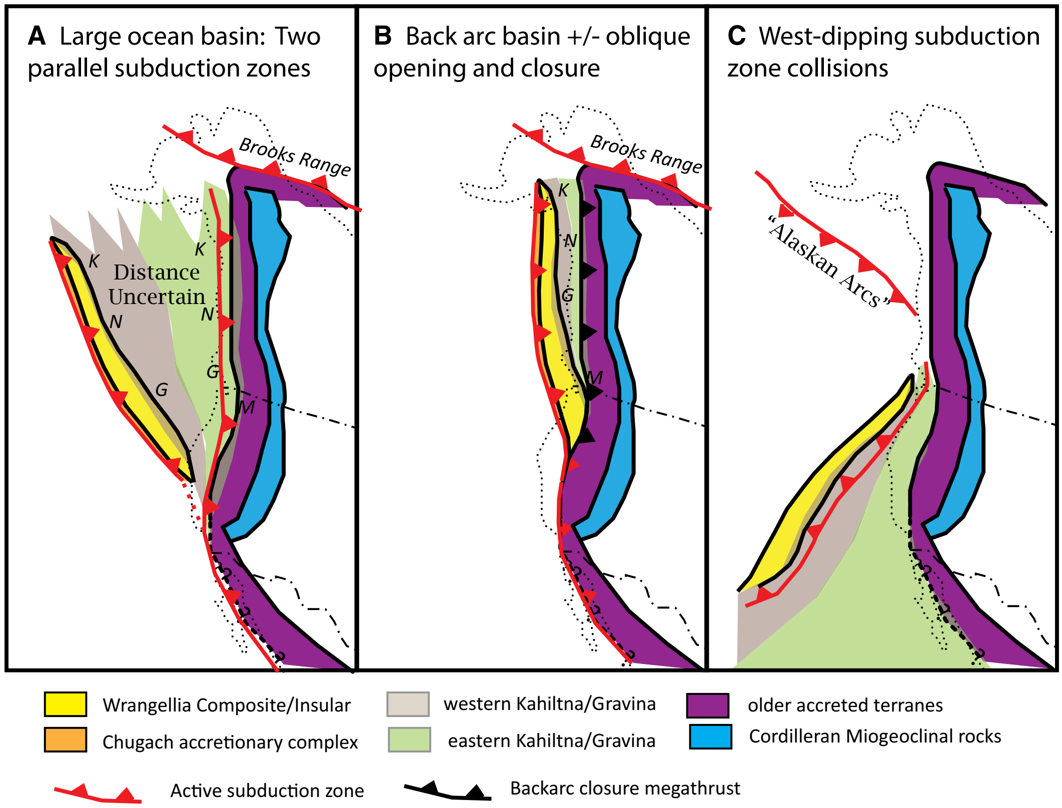

Figure 1. End-member models for Early Cretaceous paleogeography. (A) and (B) are both east-dipping subduction models distinguished by the magnitude of the east-dipping megathrust between the Insular (Wrangellia composite terrane [WCT]) and Intermontane terranes (purple); either as a normal subduction zone (A) or a megathrust closing a backarc basin (B) that opened in the Jurassic after an earlier collision of the Insular terrane. Marine basins: K—Kahiltna; N—Nutzotin; G—Gravina; M—Methow. (C) West-dipping subduction zone between the Insular (WCT) and Intermontane terranes (purple) after Sigloch and Mihalynuk (2017). In this model, the Insular terrane migrates from an offshore position during Late Jurassic time and collides far to the south with a north-to-south closure during mid-Cretaceous time. Note also the inferred polarity of north Pacific subduction zones in this model (labeled Alaskan arcs) and distinctions with subduction polarities in models A and B. Figure modified from Kapp and Gehrels (1998).

and that a second east-dipping subduction zone existed along the outboard margin of the WCT (Figs. 1A and 1B [see footnote 1]). A second group of models emphasizes collision along a west-dipping subduction zone on the inboard margin of the WCT (Sigloch and Mihalynuk, 2017; Fig. 1C) or between the entire terrane collage and North America (Johnston, 2008; Hildebrand, 2009).

The top-down interpretation of subduction polarity is based on (1) structural vergence in accretionary prisms; (2) the presence and position of high-P/T mineral assemblages; (3) the location of forearc versus backarc strata; and (4) age and geochemical patterns within the magmatic arc. These features have been used to infer subduction polarity since the advent of plate tectonics (e.g., Miyashiro, 1972; Ernst, 1973; Dickinson, 1974). These interpretations are complicated by the potential for large-scale displacement along strike-slip faults within and between the various convergent margin assemblages, and by removal of elements by subduction erosion or exhumation during collision. These complications are the reasons for discrepancies among existing models based on geology (Fig. 1). For example, a minimum of 700–1500 km of post-latest Cretaceous dextral strike-slip is known from geologic relationships alone in the northern Cordillera (Stamatakos et al., 2001), and the total dextral slip could be far larger (e.g., Garver and Davidson, 2015). Similarly, the boundary between the WCT and the continent records closure of an ocean basin, a relationship first established by Richter and Jones (1973), but along much of the suture zone[2], exhumation along this contact reaches lower-crustal depths in the hanging-wall (e.g., Hollister, 1982), confounding any attempts to reconstruct the eroded material.

The bottom-up interpretation of polarity is based on tomographic images of large, near-vertical features in the mantle interpreted as subducted slabs (Sigloch and Mihalynuk, 2017). These slabs are now in the mantle more than 3000 km from their presumed paleotrench. To restore the pathway over this distance requires multiple assumptions, including the nature of the mantle anomaly, uncertainties in slab sinking rates, and models of absolute plate motion. Problems with absolute plate motion models based on hot spots have been known since the first plate reconstructions that used them (Engebretson

[2]We use the terms suture or suture zone as nongenetic terms for areas showing demonstrable evidence of the closure of a deep ocean basin, regardless of basin size; i.e., open ocean versus marginal basin.

et al., 1984). Nonetheless, the evidence used to support west-dipping subduction is that when North America is restored to its mid-Cretaceous position, the Cordilleran margin lay *east* of the deep mantle anomalies. Hence, a west-dipping subduction zone provides a simple explanation, albeit dependent on these assumptions.

GEOLOGIC OBSERVATIONS SUPPORTING EAST-DIPPING SUBDUCTION—THE TOP-DOWN APPROACH

Here we review the geologic evidence for subduction polarity in the northern Cordillera using distributions of key tectonic elements.

Chugach Accretionary Complex

The Chugach accretionary complex is exposed outboard of Early–Middle Jurassic plutonic rocks of the Jurassic Talkeetna arc built on the northern WCT (Fig. 2). It records progressive outboard accretion of an ~60–100-km-wide package of sedimentary/volcanic rocks with metamorphic or maximum depositional ages that young consistently to the south, away from the arc (e.g., Plafker et al., 1994; Amato et al., 2013). This age progression matches classic forearc accretionary models with gaps in the record compatible with subduction erosion.

The oldest rocks in the accretionary complex from north (closest to the arc) to south (outboard) are blueschist-facies fault-bounded slices of oceanic material, with 204–185 Ma crystallization ages (e.g., Sisson and Onstott, 1986; Roeske et al., 1989). The accretion record is missing between ca. 185–170 Ma, which corresponds to an inboard migration of the arc, when subduction erosion destroyed part of the forearc (Clift et al., 2005) and the forearc basin became well established (Stevens Goddard et al., 2018). This lack of preservation is cited by Sigloch and Mihalynuk (2017) as evidence that the accretionary complex is not linked with the Jurassic arc system despite the clear evidence globally that subduction erosion removes material from subduction complexes (e.g., von Huene and Scholl, 1991). Continued accretion and underplating produced (1) a mélange assemblage with maximum depositional ages (MDA) of 170–155 Ma; (2) blueschists constrained by MDA to ca. 135–100 Ma (Day et al., 2016); (3) sinistral-oblique south-directed thrusting at 125–120 Ma (Labrado et al., 2015); (4) a greywacke/conglomerate package from 100 to 90 Ma (Amato et al., 2013); and (5) turbidites from 90 to 70 Ma (Amato et al., 2013). Intermittent accretion continues to the present day.

These data demonstrate a strong temporal link between this accretionary complex and the adjacent forearc basin and arc. When younger strike-slip displacement is restored, this link has led to the long-standing interpretation that subduction polarity along what is now the southern/western margin of Alaska to British Columbia and the Pacific Northwest has been continuous from ca. 210 Ma to present. The recent reference to this interpretation as a "myth" (Sigloch and Mihalynuk, 2017) is perplexing, as no other reasonable tectonic scenario has been suggested to explain the presence of blueschist-facies rocks located in the "backstop" of an accretionary complex and coeval with an oceanic magmatic arc in the adjacent terrane.

Forearc Basin Strata (Cook Inlet–Matanuska–Wrangell Mountains Basins)

Thick successions of Middle Jurassic to Upper Cretaceous siliciclastic strata and minor volcanic rocks lie inboard (north) of the Chugach accretionary complex and outboard (south) of volcanic-plutonic belts attributed to arc magmatism in south-central Alaska. These strata reflect deposition in intra-arc and forearc depocenters with respect to the Talkeetna-Chitina-Chisana arcs to the north (Trop and Ridgway, 2007), and sediment was sourced chiefly from these arcs (Stevens Goddard et al., 2018). Locally, sediment was eroded from sources within the Chugach accretionary complex starting in early Late Cretaceous time. U-Pb detrital zircon data show a shared source of magmatic-arc sediment for both the forearc basin and accretionary complex during the Jurassic and Cretaceous, and this Mesozoic detrital link between the accretionary complex, the forearc basin, and the magmatic arc on the upper plate indicates a kinship between these different elements (Stevens Goddard et al., 2018). Moreover, detrital zircon populations from Albian and younger strata reflect sedimentary linkage with sources in the WCT and Intermontane terranes (Reid et al., 2018). The spatial configuration of these three tectonic elements requires north-dipping (present coordinates) subduction beneath the outboard margin of WCT (Fig. 2) throughout late Mesozoic time.

Magmatic Arc Rocks (Talkeetna-Chitina-Chisana-Kluane–Coast Mountains Arcs)

In southern Alaska, the Jurassic arc system built on the WCT is the Peninsular terrane, or Talkeetna arc. This arc shows a continuous magmatic record from ca. 200–150 Ma, but magmatism migrated northward in time with Early Jurassic rocks exposed in an upturned crustal-mantle section to the south and an Early to Middle Jurassic granitic batholith on the north (e.g., Clift et al., 2005; Hacker et al., 2011). Although early studies using geochemical trends in the batholith allowed from south-dipping subduction (Reed et al., 1983), those studies failed to recognize that the Early Jurassic rocks to the south were part of the same arc system. Thus, a broader view of geochemical trends shows a pattern indicative of northward subduction with mafic rocks to the south and more silicic rocks to the north and an age trend indicating northward migration of the magmatic arc (Clift et al., 2005; Rioux et al., 2007). This pattern, together with age-equivalent accretionary complex rocks exposed to the south (Amato et al., 2013), leaves virtually no doubt that Jurassic subduction was north dipping (Fig. 2A).

Middle Jurassic to Late Cretaceous plutons and associated volcanic rocks intrude and overlie much of the WCT in south-central Alaska (Plafker and Berg, 1994) and continue southward along the coast to central British Columbia, where they become the western Coast Mountains batholith (Gehrels et al., 2009). A first-order observation concerning the polarity of these arcs is that all segments record eastward migration of magmatism at ~2 km/m.y. from ca. 120–80 Ma (Cecil et al., 2018). This rate, age, and direction of arc migration are also shared by the Sierra Nevada and Peninsular Range batholiths, which are interpreted to have faced to the west in nearly all Cordilleran syntheses. These magmatic shifts are consistent with evidence in the accretionary complex for subduction erosion and ridge subduction (e.g., Amato et al., 2013).

Backarc/Retroarc Basin Strata (Kahiltna-Nutzotin-Dezadeash-Gravina–Tyaughton/Methow Basins)

From Alaska to Washington, a belt of Jura-Cretaceous marine assemblages separates the WCT from terranes that had previously been attached to the continental margin (Fig. 1). This basin consists of an outboard belt that was deposited on and derived from the WCT and an inboard belt that was deposited on and derived from the Intermontane terranes. These stratigraphic ties are accepted by Sigloch and Mihalynuk (2017), but in their interpretation the outboard belt formed in the forearc of a west-dipping subduction zone located along the inboard margin of the WCT (Figs. 1C and 2B).

In south-central Alaska, the Upper Jurassic to Upper Cretaceous marine clastic strata are referred to as the Kahiltna assemblage (K on Fig. 1) (Hults et al., 2013). Prior to final closure, Kahiltna assemblage strata along the southern margin of the basin were sourced from WCT rocks in a backarc position. Northern Kahiltna assemblage strata were sourced from the Intermontane terrane in a forearc basin position related to north-dipping subduction beneath inboard terranes. Metamorphic rocks, mélange, and submarine fan strata are all part of the Kahiltna assemblage and represent a zone of crustal thickening with south-vergent structures (e.g., Brennan et al., 2011). Results from these studies indicate an inboard- (north-) dipping subduction zone along the northern margin of the Kahiltna basin that closed during Late Cretaceous time (Hampton et al., 2010). In eastern Alaska and the Yukon Territory, age-equivalent basinal strata belong to the Nutzotin Mountains sequence and the Dezadeash Formation (N on Fig. 1). Sedimentological and detrital data reflect a provenance chiefly from Mesozoic arc sources within the WCT (e.g., Lowey, 2018).

In southeastern Alaska, age-equivalent basinal strata, referred to as the Gravina belt, accumulated along the inboard margin of the Insular terrane and the outboard margin of the Intermontane terrane (G on Fig. 1) (McClelland et al., 1992). Western Gravina strata depositionally overlie and were derived chiefly from the WCT to the west (Yokelson et al., 2015). In contrast, Jurassic–Cretaceous strata of the eastern Gravina belt depositionally overlie Middle Jurassic or older rocks of inboard terranes

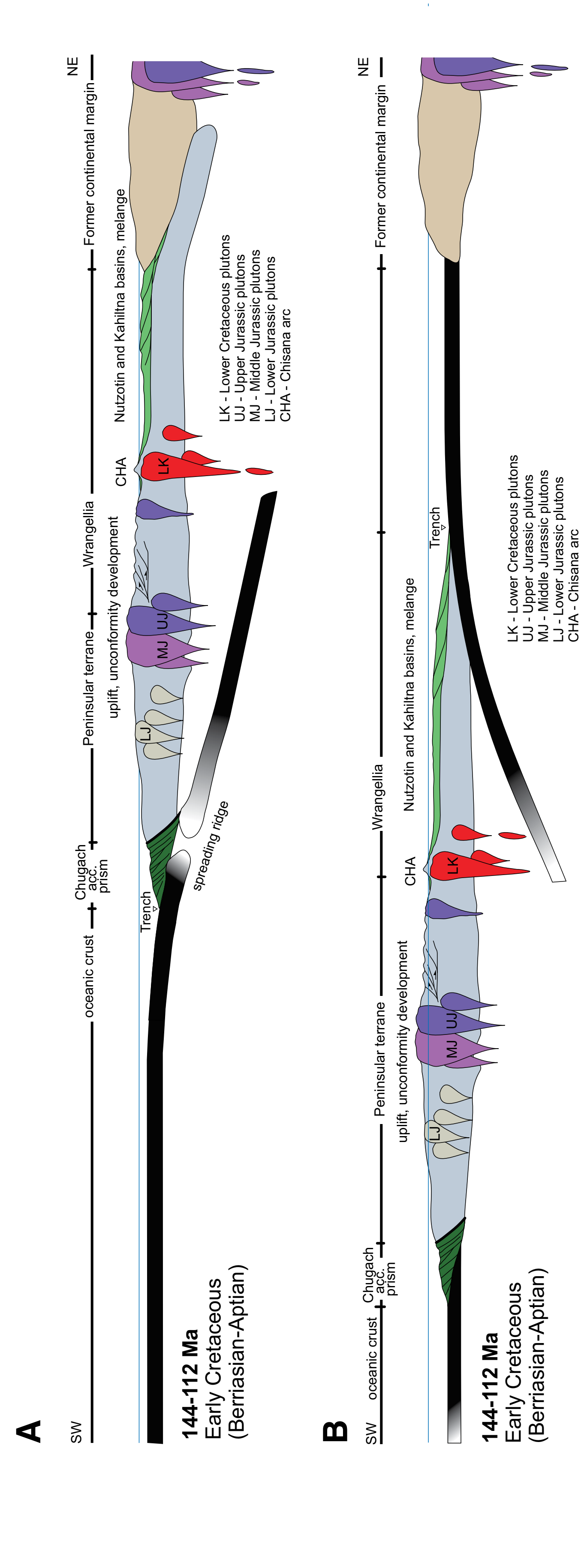

Figure 2. Schematic cross sections showing inferred tectonic framework of the south-central Alaska segment of the Insular terrane during Late Jurassic–Early Cretaceous time. (A) East-dipping model. Note inboard-dipping subduction beneath the Wrangellia-Peninsular terrane (i.e., Insular terrane) based on accretionary complex, forearc basin, magmatic arc elements, narrowing/closure of remnant ocean basin, and regional shortening/uplift during Early Cretaceous collision/accretion of the terrane. (B) West-dipping model, based on ideas presented in Sigloch and Mihalynuk (2017). This model does not explain the position of the Chugach accretionary complex relative to the arc rocks or the vergence of deformation within the marginal basins such as the Kahiltna. Modified from Trop and Ridgway (2007).

and accumulated outboard of the eastern Coast Mountains batholith. Western facies of the Gravina belt are interpreted to have been juxtaposed against eastern facies of the Gravina belt by Early Cretaceous sinistral strike-slip followed by mid-Cretaceous structural imbrication (Monger et al., 1994). Nowhere along British Columbia or southeast Alaska have direct remnants of subduction been observed within the basinal strata or along these thrusts.

Farther to the south, eastern facies strata of the Gravina belt extend into the Tyaughton-Methow basin (M on Fig. 1), which also consists of Upper Jurassic–Cretaceous marine strata and subordinate volcanic rocks. These basins are interpreted to record east-dipping subduction during Late Jurassic–Early Cretaceous time, followed by arrival of the Insular terrane along the Cordilleran margin during Albian time (e.g., Surpless et al., 2014). These relations suggest that most basin strata formed along an east-dipping subduction zone constructed on most of the western margin of the North American continent. Deep exhumation and strike-slip faulting obscure details (Figs. 1A and 1B), but there is no evidence to support the interpretation of Sigloch and Mihalynuk (2017) that these basins formed in a west-dipping subduction zone.

Evidence from Northern Alaska

The only part of the northern Cordillera that has a clear geologic signal of post-mid Jurassic outboard (away from continental margin) subduction is in northernmost Alaska (e.g., Moore et al., 1994). There, in the Brooks Range, structural and metamorphic evidence shows subduction of the continental margin beneath a Late Jurassic–earliest Cretaceous island arc, the Koyukuk terrane (Box and Patton, 1989). Fragments of an ocean basin were emplaced on the continental margin as the Angayucham complex during collision at ca. 145–135 Ma (Roeske et al., 1989; Lemonnier et al., 2016). Possible tectonic connections, if any, between the northern and southern Alaska Mesozoic arcs are highly uncertain, particularly given that this collision occurred prior to the opening of the Canada basin when the orogen faced north, not south (Figs. 1A and 1B). Thus, extrapolating this outward-dipping subduction-collision system to all of the Cordilleran margin (e.g., Sigloch and Mihalynuk, 2017) is not warranted.

Summary of the Geologic Data

The most marked differences in the models (Fig. 1) are (1) the inferred polarity of subduction zones during Late Jurassic–Early Cretaceous time; and (2) the nature of the suture zone inboard of the WCT. The upper-plate geology preserves abundant lines of evidence for an east-dipping subduction zone beneath the outboard margin of WCT during Jurassic–Late Cretaceous time as well as south to north closure of a marine basin between the WCT and North America along an east-dipping megathrust. There is virtually no evidence for west-dipping subduction anywhere along the inboard margin of the WCT.

DISCUSSION AND CONCLUSIONS

Alternative Explanation of Geophysical Observations

Although we have emphasized the geologic record relative to the WCT here, the record of east-dipping subduction during Late Jurassic through Late Cretaceous time is even better established along the continental margin of Oregon, California, and northwestern Mexico by the Sierra Nevada, Great Valley, and Franciscan assemblages. Any tectonic model calling on west-dipping subduction during this time interval must address how these iconic tectonic relations have been misinterpreted by generations of geologists (e.g., Dickinson, 1974). Ribbon continent reconstructions of western North America (e.g., Johnston, 2008) provide alternate views, but represent even more glaring contradictions to generations of geologic studies (see discussion in Sigloch and Mihalynuk, 2017).

It is important to note that there is evidence of west-dipping subduction in the Cordillera, but it is clearly pre-Late Jurassic and does not involve the WCT (Monger, 2014). Instead, vast areas that comprise the terranes inboard of the WCT show evidence of Permo-Triassic ocean basin closure along a west-dipping subduction interface that existed until Early–Middle Jurassic time. Widespread ophiolitic rocks associated with the system, and their emplacement over rocks that were clearly part of the North American passive margin from southern British Columbia (e.g., Slide Mountain terrane; Roback et al., 1994) to Alaska (e.g., Seventy Mile terrane; Dusel-Bacon et al., 2006), attest to a collision along a west-dipping subduction zone. We follow Monger (2014) in suggesting that this event provides a likely explanation of the geophysical observations of Sigloch and Mihalynuk (2017). A scenario that incorporates these earlier events as an explanation of the tomographic anomalies is provided in GSA Data Repository Fig. DR1[3].

Reconciling the Top-Down Record with the Bottom-Up Record: Implications for Whole-Earth Processes

Reconciling these issues is an important problem because it relates to whole-earth processes of mantle convection and past plate motion. We suggest that a challenge to the broader community is providing clear tests of the hypothesis that the deep anomalies are indeed subduction zone remnants, which will require clear correlations to the geologic record. Conversely, assuming the interpretation of the deep anomalies as subducted lithosphere is correct, the community must develop tectonic models that fit both the deep geophysical data and the geologic record. Resolving this conflict is a fundamental tectonic problem that requires integrated analysis between geologists and mantle observers/modelers.

The diversity of tectonic models (Fig. 1) places the community in a quandary. New models based on geophysics can stir debate, but these insights must be consistent with the geologic record and what the tomography data actually show (e.g., Liu, 2014). Nonetheless, among a larger group of northern Cordilleran geologists, the evidence from surface geology seems overwhelmingly opposed to the tomography-based conclusions. How then can we proceed? One approach is to assemble working groups with broad knowledge that tackle a problem by integrating information from a wide range of approaches and attempt to arrive at a solution that honors all observations. Alternatively, new insights might arise from technological advances (e.g.,

[3]GSA data repository item 2019259, Figure DR1, showing the tectonic models discussed in the text in a global projection, is online at www.geosociety.org/datarepository/2019.

Walker et al., 2019) that require abandoning existing hypotheses and exploring fundamentally different interpretations.

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