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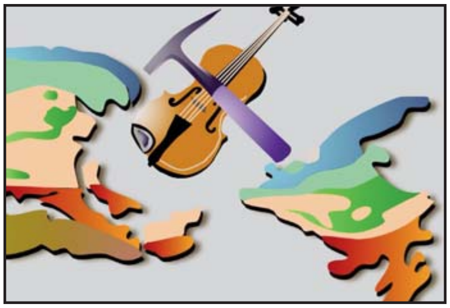
Résumé de l'article

Les indications géologiques, en particulier la présence de deux marges de plateforme passives, de déformations adjacentes non-conformes entre l'Amérique du Nord et les terranes extérieurs, ainsi que l'absence de gisements de rift, permet de croire que l'Amérique du Nord était la plaque sous-jacente durant les événements de Sevier et de Laramide et que la subduction plongeait vers l'ouest sous le continent rubané de la Cordillères (Rubia). Les terranes du continent rubané composite, maintenant au sein de la Cordillère canadienne, sont entrés en collision avec l'ouest de l'Amérique du Nord durant l'événement Sevier (125-105 Ma), et ont été transportés vers le nord durant l'événement Laramide (~80–58 Ma), laquelle a affecté la Cordillère, de l'Amérique du Sud à l'Alaska. Une nouvelle tomographie haute résolution du manteau sous l'Amérique du Nord montre la présence d'un gigantesque mur de plaques vertical qui s'étend sur 1 000 km, marque le site d'une subduction de longue haleine, et offre une validation indépendante du modèle d'une subduction à pendage vers l'ouest. D'autres chercheurs ont analysé les trajectoires paléogéographiques et conclu que la collision initiale s'est produite au Canada vers 160 Ma – un moment et un endroit sans épaississement par déformation sur la plateforme d'Amérique du Nord – et plus tard plus à l'ouest, là où la subduction n'était vraisemblablement pas vers l'ouest, mais vers l'est. Cela dit, en considérant une trajectoire paléogéographique de l'Amérique du Nord corrigée longitudinalement, avec la position géologique la plus probable de la déformation initiale, la position de la portion ouest de l'Amérique du Nord par rapport aux restes de la super-plaque explique alors facilement la chronologie et l'étendue des épisodes Sevier et Laramide.

HAROLD WILLIAMS SERIES



Geology, Mantle Tomography, and Inclination Corrected Paleogeographic Trajectories Support Westward Subduction During Cretaceous Orogenesis in the North American Cordillera

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SUMMARY

Geological evidence, including the presence of two passive margin platforms, juxtaposed and mismatched deformation between North America and more outboard terranes, as well as the lack of rift deposits, suggest that North America was the lower plate during both the Sevier and Laramide events and that subduction dipped westward beneath the Cordilleran Ribbon Continent (Rubia). Terranes within the composite ribbon continent, now present in the Canadian Cordillera, collided with western North America during the 125–105 Ma Sevier event and were transported northward during the ~80–58 Ma Laramide event, which affected the Cordillera from South America to Alaska. New high-resolution mantle tomography beneath North America reveals a huge slab wall that extends vertically for over 1000 km, marks the site of long-lived subduction, and provides independent verification of the westward-dipping subduction model. Other workers analyzed paleogeographic trajectories and concluded that the initial collision took place in Canada at about 160 Ma – a time and place for which there is no deformational thickening on the North American platform – and later farther west where subduction was not likely westward, but eastward. However, by utilizing a meridionally corrected North American paleogeographic trajectory, coupled with the geologically most reasonable location for the initial deformation, the position of western North America with respect to the relict superslab parsimoniously accounts for the timing and extents of both the Sevier and Laramide events.

SOMMAIRE

Les indications géologiques, en particulier la présence de deux marges de plateforme passives, de déformations adjacentes non-conformes entre l'Amérique du Nord et les terranes extérieurs, ainsi que l'absence de gisements de rift, permet de croire que l'Amérique du Nord était la plaque sous-jacente durant les événements de Sevier et de Laramide et que la subduction plongeait vers l'ouest sous le continent rubané de la Cordillères (Rubia). Les terranes du continent rubané composite, maintenant au sein de la Cordillère canadienne, sont entrés en collision avec l'ouest de l'Amérique du Nord durant l'événement Sevier (125-105 Ma), et ont été transportés vers le nord durant l'événement Laramide (~80–58 Ma), laquelle a affecté la Cordillère, de l'Amérique du Sud à l'Alaska. Une nouvelle tomographie haute résolution du manteau sous l'Amérique du Nord montre la présence d'un gigantesque mur de plaques vertical qui s'étend sur 1 000 km, marque le site d'une subduction de longue haleine, et offre une validation indépendante du modèle d'une subduction à pendage vers l'ouest. D'autres chercheurs ont analysé les trajectoires paléogéographiques et conclu que la collision initiale s'est produite au Canada vers 160 Ma – un moment et un endroit sans épaississement par déformation sur la plateforme d'Amérique du Nord – et plus tard plus à l'ouest, là où la subduction n'était vraisemblablement pas vers l'ouest, mais vers l'est. Cela dit, en considérant une trajectoire paléogéographique de l'Amérique du Nord corrigée longitudinalement, avec la position géologique la plus probable de la déformation initiale, la position de la portion ouest de l'Amérique du Nord par rapport aux restes de la super-plaque explique alors facilement la chronologie et l'étendue des épisodes Sevier et Laramide.

INTRODUCTION

Ever since the seminal papers by Warren Hamilton (Hamilton 1969a, b), in which he suggested that Pacific oceanic

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lithosphere was subducted beneath western North America to form the voluminous Cordilleran type magmatic belts such as the Peninsular Ranges, Sierra Nevada, Idaho, and Coast batholiths, most Cordilleran geologists have embraced models predicated upon long-lived eastward subduction (Burchfiel and Davis 1972, 1975; Price 1981; Dickinson 2004; Colpron et al. 2007; Ingersoll 2008). Over the years a few workers (Moores 1970; Mattauer et al. 1983; Chamberlain and Lambert 1985; Lambert and Chamberlain 1988; Moores 1998) proposed alternative models involving collision of North America with various arcs above westward-dipping subduction zones but they failed to garner traction in the community. Some more recent models for Cordilleran development, created to better explain the overall development of the orogen, posit that the leading edge of North America was subducted to the west beneath an exotic ribbon continent during Cretaceous orogenesis (Johnston and Borel 2007; Johnston 2008; Hildebrand 2009, 2013). Testing these models is difficult because there were no alternating magnetic anomalies produced during the lengthy Cretaceous superchron and huge tracts of the easternmost floor of the Pacific Ocean basin were subducted (Engebretson et al. 1985; Atwater 1989). Thus, magnetic anomalies and hot spot tracks are not available to quantitatively reconstruct Cretaceous plate motions.

Over the past several decades there have been significant advances in three-dimensional seismic tomographic imaging of the Earth's interior (Grand et al. 1997; Tanimoto and Lay 2000). With improvements in computing power and high-resolution seismic arrays, such as USArray (Williams et al. 2010), these advances have now reached a level where they can be integrated with geological models based on surface geology (Sigloch 2011; Sigloch and Mihalynuk 2013). Moreover, the seismic tomography can be used in consort with recently developed kinematic models for plate motions in deep-mantle reference frames based on seafloor-spreading history, hotspot migration, paleomagnetism, and moving continents (Müller et al. 1993; O'Neill et al. 2005; Torsvik et al. 2008a, b; Doubrovine et al. 2012; Shephard et al. 2012; Seton et al. 2012) to constrain the tectonic development of orogenic belts. My goal here is to provide a brief, but modern treatment of the geology, then to show how existing plate trajectories – once modified to account for compaction errors – fit remarkably well with the geology, both spatially and temporally.

GEOLOGY

A cursory glance at a geologic or tectonic map of the Cordillera (Fig. 1) reveals that it is composed of a myriad of different terranes (Coney et al. 1980), many of which are oceanic. These terranes and their spatial distribution imply a regime similar to the present-day SW Pacific, where arcs, continental fragments, spreading ridges, and cratons interact in complex ways (Hamilton 1979). Terrane amalgamation in the Jurassic formed a superterrane, or ribbon continent, that I named Rubia (Hildebrand 2009, 2013). Because the ribbon continent is much more extensive than I had originally realized, extending at least from Alaska well into South America, it is probably best that it be called the Cordilleran Ribbon Continent, a name first suggested to me by Ted Irving. In my model then, the leading edge of western North America was attached to a slab that subducted to the west beneath the Cordilleran Ribbon Continent.

A major problem with the existing eastward subduction, or backarc, model is that there are two different passive margin platforms in western North America: (1) the North American platform, that formed in the Cambrian and which is characterized by a Middle Cambrian carbonate reef complex; and (2) a more westerly carbonate platform – known as the Antler platform in the US and the Cassiar platform in Canada – that formed during the Neoproterozoic and which contains a conspicuous Early Cambrian carbonate bank dominated by *Archeocyathids* and oolite shoals (Johnston 2008; Hildebrand 2009). The western platform was involved in several orogenic events: (1) initially during the latest Devonian-early Mississippian when rocks of the Roberts Mountain allochthon were thrust upon it (Roberts et al. 1958; Miller et al. 1992); (2) between 260–253 Ma when the Slide Mountain ocean was subducted during the collision of the Yukon-Tanana terrane (Murphy et al. 2006; Beranek and Mortensen 2011); (3) at 250 Ma when the Golconda allochthon was emplaced on the western margin of the Roberts Mountain allochthon (Silberling and Roberts 1962); and (4) at both 187–185 Ma and 173 Ma, when Kootenay terrane, which contains Cassiar platform, or equivalents, in southern Canada, collided with Quesnellia to the west (Nixon et al. 1993) and then with rocks of the Belt-Purcell-Windermere block to the east, respectively (Murphy et al. 1995; Colpron et al. 1996). All of these terranes plus others, such as the complex group of collided Jurassic arcs and intervening mélange terranes of western Nevada, the Sierra Nevada, Klamaths, and British Columbia, plus the Insular composite terrane of coastal British Columbia and Alaska, formed part of the Cordilleran Ribbon Continent (Hildebrand 2009, 2013). The evidence suggests that it was mostly assembled by 160 Ma, but ultimately amalgamated by 100 Ma, when a basin of unknown nature and width that separated the eastern and western halves of the Peninsular Ranges batholith, the Sierra Nevada, and the Coast Plutonic complex, closed (Kistler 1990; Kimbrough et al. 2001; Lackey et al. 2008; Gehrels et al. 2009; Hildebrand 2013). The North American platform terrace was unaffected by any of these events; either the more outboard collisions were sufficiently small or local that they did not affect the North American margin, or, more likely given the number, variety, and extent of terranes, there was an intervening ocean basin (Johnston and Borel 2007; Johnston 2008; Hildebrand 2009, 2013). That the North American platform terrace was unaffected by these events forms a key part of the evidence that the Cordilleran Ribbon Continent and North America were separate entities until they collided – initially during the Sevier event and later during Laramide terminal collision.

Other perplexing features of the Cordillera are the lack, along its entire length, of rift-related volcanic rocks and evaporites (Hildebrand

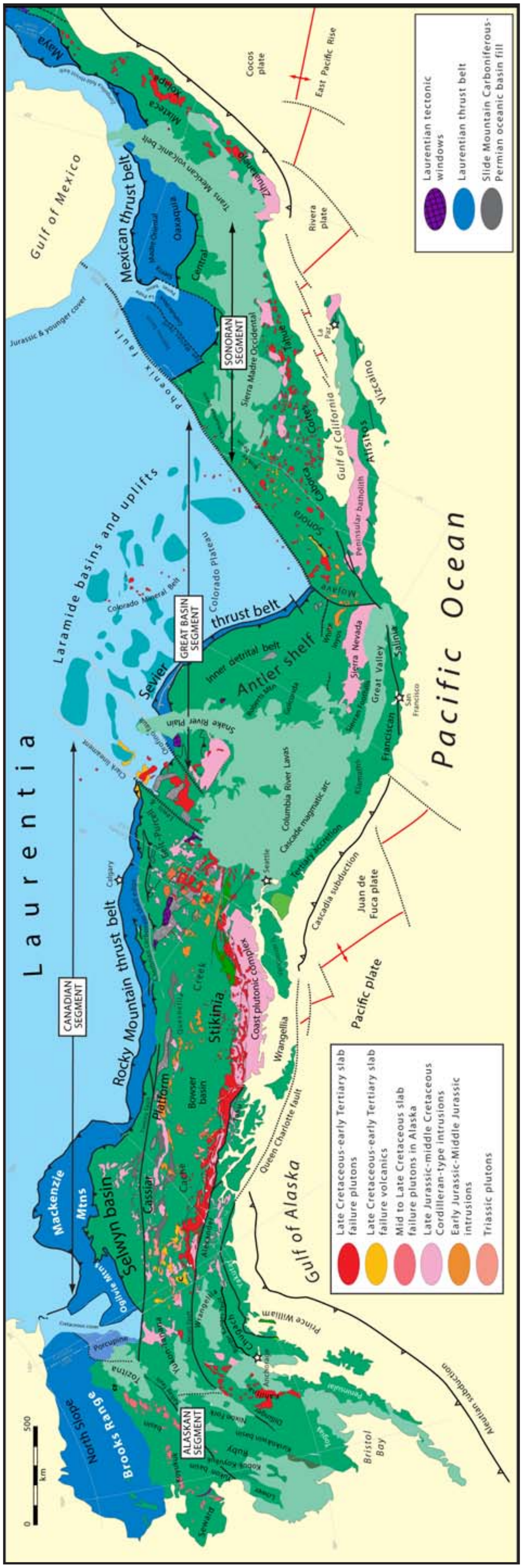

Figure 1. Geological sketch map illustrating the extent of the Cordilleran Ribbon Continent (shades of green) within North America and the main sectors of the orogen. Modified from Hildebrand (2013). Many terranes within the ribbon continent are labeled but not otherwise distinguished.

2013), both common to rift facies worldwide. Some workers (Lund 2008; Dehler et al. 2010; Balgord et al. 2013) suggest that Neoproterozoic rocks of the Windermere Supergroup and its equivalents are rift rocks, but evaporites are unreported, volcanic rocks are very sparse, and overall the rocks are 100–200 Myr older than passive margin subsidence of the North American margin (Bond and Kominz 1984). The lack of such rocks along the entire length of the Cordillera suggests that the rift rocks, along with outer rise-slope sedimentary rocks, which are also missing from North America, were not simply displaced by strike-slip faults, but instead torn from the margin during slab failure – a feature readily accounted for in the westerly subduction model, in which North America was attached to a westerly subducting slab, but difficult to reconcile in easterly dipping models (Hildebrand and Bowring 1999; Hildebrand 2009, 2013).

Sevier Event

The oldest Mesozoic deformational thickening known to affect the North American platform terrace was the Sevier event (Armstrong 1968), which was confined to the Great Basin sector of the orogen, located between the Lewis and Clark line (Wallace et al. 1990) to the north and the Phoenix fault (Hildebrand 2009), located along the southern margin of the Colorado Plateau to the south (Fig. 1). The event consisted of the emplacement of huge thrust sheets containing >10 km thick sections of Neoproterozoic–Paleozoic platformal sedimentary rocks, that apparently originated outboard of the western edge of the North American platform terrace (Sheldon 1963; Armstrong and Oriel 1965; Picard et al. 1969; Rose 1977, during the Aptian-Albian between 125–105 Ma (Hildebrand 2013). The folds and thrust faults are easterly vergent and shed coarse clastic debris eastward into an adjacent foredeep (Armstrong 1968; DeCelles 2004; DeCelles and Coogan 2006; Yonkee and Weil 2011). The initiation of thrusting is dated to be between about 124 and 120 Ma based on dated ash beds in the basal foredeep of Utah (Greenalgh and Britt 2007); detrital zircons in the foredeep (Britt et al. 2007), a 119.4 ± 2.6 Ma

U–Pb date of uraniferous carbonate from the forebulge, and a good match between $\delta^{13}C_{org}$ excursions in early terrestrial foredeep sedimentary rocks and well-dated Albian features of the global carbon isotope chemostratigraphy (Ludvigson et al. 2010).

Major thrusting of the Sevier event stopped during the mid-Albian at about 105 Ma, as documented by alluvial fan and fluvial sedimentary rocks of the Canyon Range wedge-top basin that unconformably overstepped the Canyon Range thrust (Lawton et al. 2007). Farther north, within the Wyoming Salient, conglomerates of the 120–110 Ma Gannett Group recorded major slip on the megathrust sheets (DeCelles et al. 1993; Yonkee and Weill 2011). There, zircon fission track and ^{40}Ar/^{39}Ar ages of muscovite, plus westward-coarsening conglomerates of the Bear River and Aspen formations in the salient, indicate that the thrust sheets were uplifted and exhumed mainly during the Cenomanian-Turonian (Yonkee and Weill 2011). In my model thrusting presumably stopped and exhumation began when the westward-dipping subducting slab attached to North America failed (Hildebrand 2013). A Santonian to Paleocene thin-skinned fold-thrust belt lies farther east (DeCelles 1994; Yonkee and Weill 2011). It is separated from the western belt in northern Utah and southern Idaho by the Wasatch anticlinorium, a regional culmination cored by allochthonous Paleoproterozoic crystalline basement (Yonkee et al. 1997; Yonkee et al. 2000; Yonkee and Weill 2011; Shervais et al. 2013). The eastern fold-thrust belt is interpreted to have formed during the younger Laramide event. This interpretation – different from that made by most workers who consider that the Sevier event includes both an older Aptian to mid-Albian phase in the west and a younger phase of late Cretaceous–Paleocene shortening to the east (DeCelles 2004; Yonkee and Weill 2011) – is based upon the cessation of thrusting in the west at around 105 Ma, the 100–90 Ma exhumation of the western thrust belt, and the ~15–20 Myr gap between thrusting in the western and eastern thrust belts.

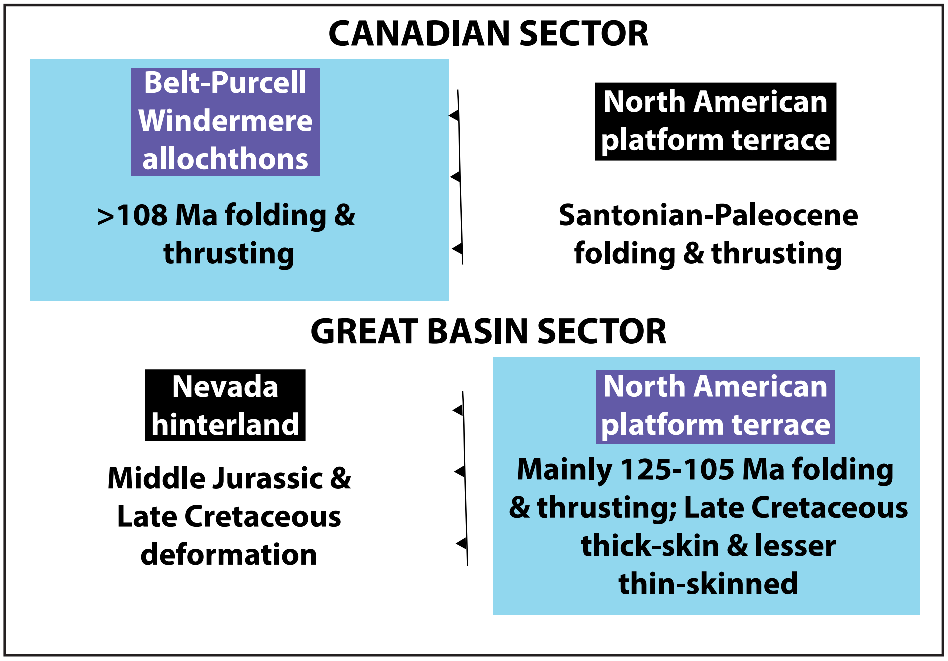

Figure 2. Graphical illustration of mismatched deformational ages for the Great Basin and Canadian sectors of the Cordilleran orogen as discussed in the text. In the Great Basin area, rocks of the North American platform terrace were deformed and thrust eastward during the 125–105 Ma Sevier event, yet rocks to the west show no evidence of this deformation. The opposite holds true for the Canadian sector where rocks of the North American platform terrace have a well-developed Santonian-Paleocene Laramide fold-thrust belt but rocks to the west have Sevier-age deformation. This and other data suggest that the arc and hinterland to the Sevier event are now resident in the Canadian Cordillera.

As the region of younger Laramide thick-skinned thrusting coincides longitudinally with that affected by the Sevier event, there might be a simple causal relationship between the two. Because the oceanic lithosphere and thinner transitional rift crust of western North America were torn off and subducted during slab failure only in the Great Basin area, it may have been that during the younger Laramide event, when old and dense oceanic lithosphere was still connected to North America both to the N and S, and thus driving convergence with the ribbon continent, that the part of the North American craton within the Great Basin region was too buoyant to be pulled much beneath the ribbon continent. Ultimately, the bending and compressive stresses led to a wide zone of deformation that affected the entire crust and generated the classic thick-skinned deformation to the east.

In the Great Basin region to the west, neither deformation nor metamorphism in the 125–105 Ma range have been reported (Fig. 2), but instead deformation occurred in the Jurassic (Elko) and Upper Cretaceous (Laramide) as described by Camilleri et al. (1997). North of the Lewis and Clark line within the Canadian sector of the orogen, the reverse situation exists (Fig. 2). There, the deformation on the North American platform started during the Upper Cretaceous, as documented by the presence of Santonian-Campanian marine shales in the footwall syncline of the Borgeau thrust, which in the southern Canadian Rockies is the westernmost major thrust sheet to affect the platform terrace (Price 2013); whereas just to the west, where Paleozoic sedimentary rocks sit atop the metasedimentary rocks of the Mesoproterozoic Purcell group, thrusts were shown to predate 108 Ma as they are cut by syn- to post-kinematic plutons of the Bayonne suite (Logan 2002; Larsen et al. 2006). Likewise, within the Monashee Mountains of southern British Columbia (Fig. 3), rocks of the Selkirk allochthon contain three periods of kyanite growth: 162–143 Ma, 130–88 Ma, and 82–60 Ma (Gervais and Hynes 2013), which are reasonably interpreted to corre-

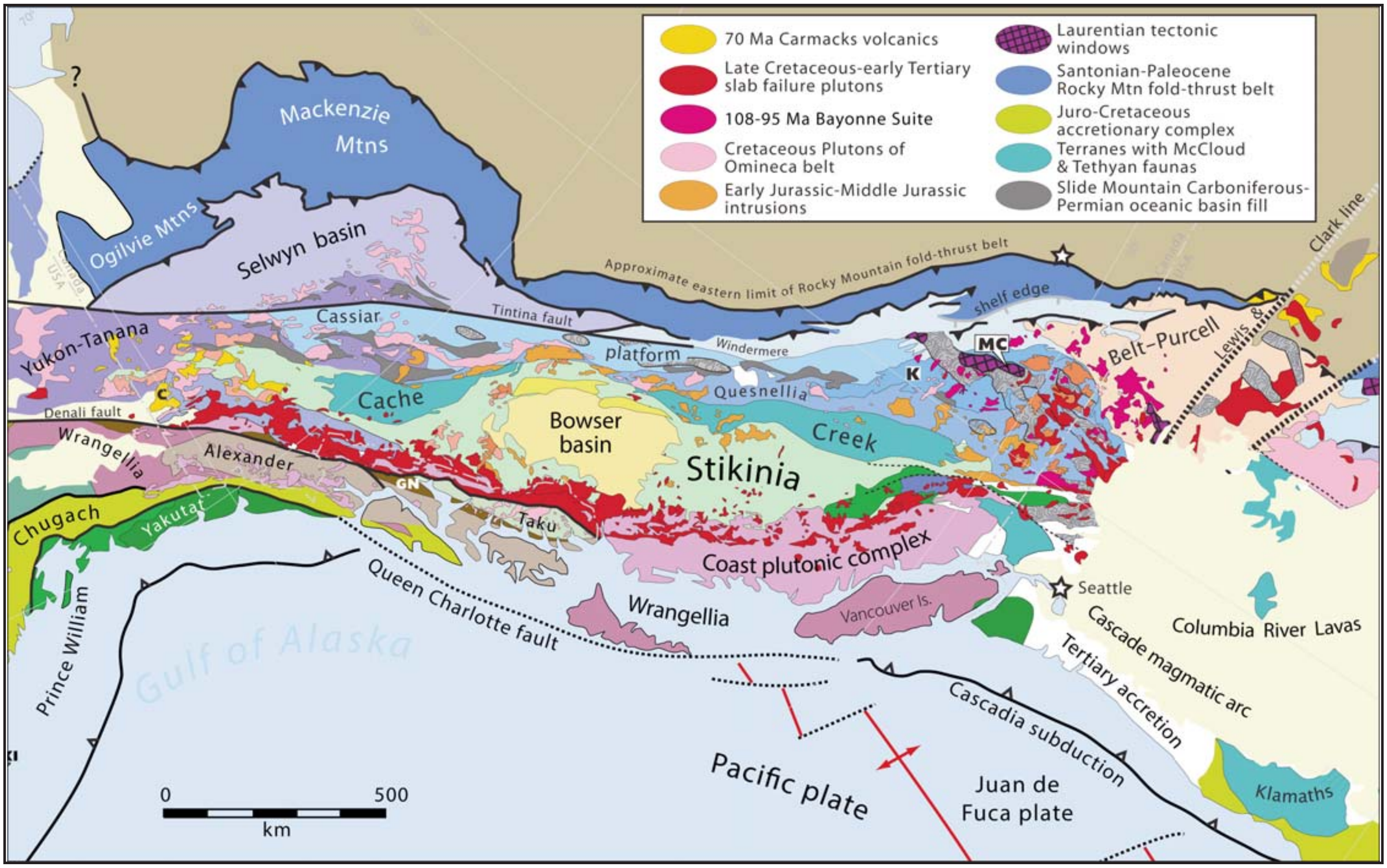

Figure 3. Geological map showing major terranes and plutonic suites of the Canadian Cordillera modified from Hildebrand (2013). In the model presented here, rocks as far north as the Yukon-Tanana terrane and Selwyn basin collided with western North America during the Sevier event in the Great Basin sector of the US and migrated meridionally northward during and after the Late Cretaceous–Early Tertiary Laramide event. The ~70 Ma Carmacks volcanic rocks yielded paleolatitudes near San Francisco as discussed in the text. C–Carmacks volcanic rocks; GN–Gravina-Nutzotin-Dezadeash basin; K–Kootenay terrane; MC–Monashee complex.

spond to the Elko, Sevier and Laramide deformational/thickening events. Based on the age of the youngest rocks deformed, thrusting within the Selwyn basin to the north occurred after the latest Jurassic, and based on ^{40}Ar/^{39}Ar in muscovite from greenschist grade rocks, had ceased by about 104 Ma (Mair et al. 2006).

Thus, Hildebrand (2013) argued that the western parts of the Sevier belt are located within the Canadian Cordillera and that plutons of the eastward-younging Omineca crystalline belt of Monger et al. (1982) represent rocks of the magmatic arc on the terrane that docked with North America to create the event. In this case, eastward rollback of the old and dense subducting slab produced the progressive eastward younging of arc magmatism (Fig. 4). The bulk of the plutonic rocks intruded the belt prior to collision between about 125 Ma and 105 Ma – similar to early magmatism in Cordilleran batholiths of western North America – and were followed by the intrusion of small metalliferous post-thrusting bodies ranging in age from about 105 to 92 Ma likely generated when asthenosphere upwelled through the torn slab during slab failure (Logan 2002; Hart et al. 2004a; Johnston 2008; Rasmussen 2013). Other Cordilleran batholiths of North America, such as the Coast plutonic complex of British Columbia, the Sierra Nevada batholith of California, and the Peninsular Ranges batholith of Baja California, have many typical Cordilleran-type plutons in the 100–82 Ma range (Hildebrand 2013).

In this model, rocks as far north and east as those of the Selwyn Basin were located well to the south in the Great Basin area and migrated north during and following the Late Cretaceous–Early Tertiary Laramide event (Gladwin and Johnston 2006; Enkin 2006; Kent and Irving 2010). Supporting this conclusion are robust paleomagnetic poles from the ~70 Ma Carmacks volcanic rocks (Johnston et al. 1996; Enkin et al. 2006a), which although much younger, were located in the same block as the plutonic suites (Figs. 3, 5), and were erupted at the approximate latitude of San Francisco. Even though some workers attempt to minimize the significance of paleomagnetic data indicating meridional migration of Cordilleran terranes in order to bolster a static North American model for the Selwyn Basin (Nelson et al. 2013), the data consistently show more than 1000 km of northward migration (Beck 1991; Enkin 2006; Kent and Irving 2010; Hildebrand 2013) and are supported by other data sets, such as

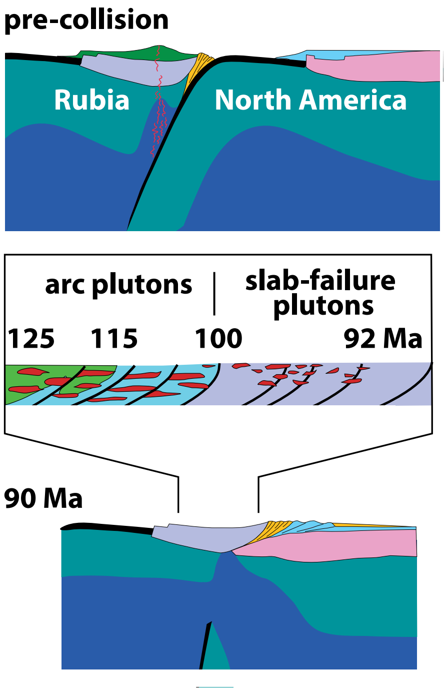

Figure 4. Schematic plate model for the Sevier collision and both arc and slab failure plutonism with elements from Hildebrand (2013) and Johnston (2008).

matching of unique piercing points and leaf margin studies (Fig. 6), and the northerly migrating Laramide foredeep (Fig. 7).

Following thrust emplacement and slab failure, consequent upward migration and partial melting of asthenosphere led to mafic magmas that invaded the crust of both Selwyn basin and Yukon-Tanana terrane (Fig. 4), which were joined between 260–253 Ma (Beranek and Mortensen 2011). Slab failure magmatism commonly overlaps the terminal stages of deformation and is highly metalliferous (Solomon 1990; McDowell et al. 1996; de Boorder et al. 1998; Cloos et al. 2005; Hildebrand 2009, 2013). Within Selwyn basin and Yukon-Tanana terrane the slab failure magmatism led to a swarm of small 99–92 Ma, post-kinematic, plutons with associated Au, Cu, Bi, W, Zn, Sn, Mo, and Sb mineralization – known variously as the Tombstone-Mayo-Tungsten-Livengood suites (Fig. 5) – that were emplaced over at least 1000 km of strike length from east-central Alaska across Yukon to the southwestern Northwest Territories (Anderson 1987; Newberry et al. 1990, 1996; Reifenstuhl et al. 1997a, b; Hart et al. 2004a, b; Rasmussen 2013; Pigage et al. 2014), as well as the extensive syn- to post-kinematic Bayonne intrusive suite (Fig. 3) in the southern Canadian Cordillera (Logan 2002). These rocks were all located within the Great Basin sector when they were emplaced, as northward migration did not start until the Laramide event (Hildebrand 2013).

Laramide Event

The second event to have affected the North American platform was the Late Cretaceous–Early Tertiary Laramide event, which is interpreted to represent terminal collision of the Cordilleran Ribbon Continent, with North America (Hildebrand 2013). I consider the Laramide as an event, not simply a structural style, and therefore it is variable along strike. The event, which is perhaps best known for its thick-skinned thrusting within the Great Basin-Colorado Plateau and Alaskan sectors (Hamilton 1988; Dickinson et al. 1988; Moore et al. 1997), is also represented by late Cretaceous thin-skinned thrust belts throughout Alaska, the Canadian Rockies, and eastern Mexico (Coney 1971; Hildebrand 2013). The Cordilleran Ribbon Continent continues southward through the Antilles to South America where the Great Arc of the Caribbean and the Caribbean-Columbia oceanic plateau were accreted to northwestern South America above a westward dipping subduction zone at about 75 Ma (Kennan and Pindell 2009).

In the Maya block (Fig. 1) north of the Guatemalan suture complex, a west-facing Cretaceous carbonate platform was drowned during the uppermost Campanian, buried by orogenic flysch during the Maastrichtian-Danian, and overthrust by peridotite nappes, while rocks of the lower plate crystalline basement were metamorphosed to eclogite at 76 Ma (Fourcade et al. 1994; Martens et al. 2012). Throughout eastern Mexico, a Late Cretaceous east-verging thrust belt that involved a west-facing carbonate platform and overlying foredeep marks the arrival of the Guerrero superterrane, a southern segment of the Cordilleran Ribbon Continent (Busch and Gavela 1978; Eguilez de Antuñano et al. 2000; Centeno-Garcia 2011; Hildebrand 2013). Within the US Southwest, Laramide deformation and metamorphism are ubiquitous in the Sonoran-Mojave desert, the Sierra Nevada, and the Transverse ranges (May and Walker 1989). Folding and thrusting are also known from the hinterland belt of the Great Basin sector, exposed in Paleocene core complexes (Camilleri 1992). The entire Rocky Mountain fold-thrust belt of the Canadian sector (Price 1981) and its Late Cretaceous–Early Tertiary foredeep must be younger than Santonian, the age of marine mudstones in the footwall syncline to the Bourgeau thrust, the westernmost of the large thrusts that cut the North American platform terrace (Larson et al. 2006; Price 2013). Within Alaska, sedimentary rocks of the Kahiltna Basin were folded and thrust northward coincident with kyanite-grade metamorphism and the development of the Campanian-Maastrichtian Cantwell thrust-top basin (Ridgway et al. 2002; Trop and Ridgway 2007). The hypsometry of the modern Brooks Range was caused by thick-skinned Laramide thrusting (Moore et al. 1997). During and after terminal Laramide collision there was a northward migration of the Cordilleran Ribbon Continent (Hildebrand 2013). Most, if not all, of the terranes now present within the Canadian Cordillera were translated from the Great Basin and Sonoran sectors of the orogen (Enkin 2006; Kent and Irving 2010).

Overall, my preferred model for the geological development of the North American Cordillera outside Alaska is best viewed as the attempted, but ultimately abortive, subduction of North America beneath Rubia, the Cordilleran Ribbon Continent amalgamated mostly during the Mesozoic (Hildebrand 2013). The initial collision of the ribbon continent with North America occurred at 125 Ma, was localized in the Great Basin sector of the orogen, probably because that area was a promontory on western North America, and led to slab failure at 105 Ma, followed by exhumation and the emplacement of slab failure plutons between 105 and 92 Ma (Fig. 4). Terminal collision of the ribbon continent with North America occurred some 40 Myr later at 80 ±5 Ma, and resulted in deformation over the length of North

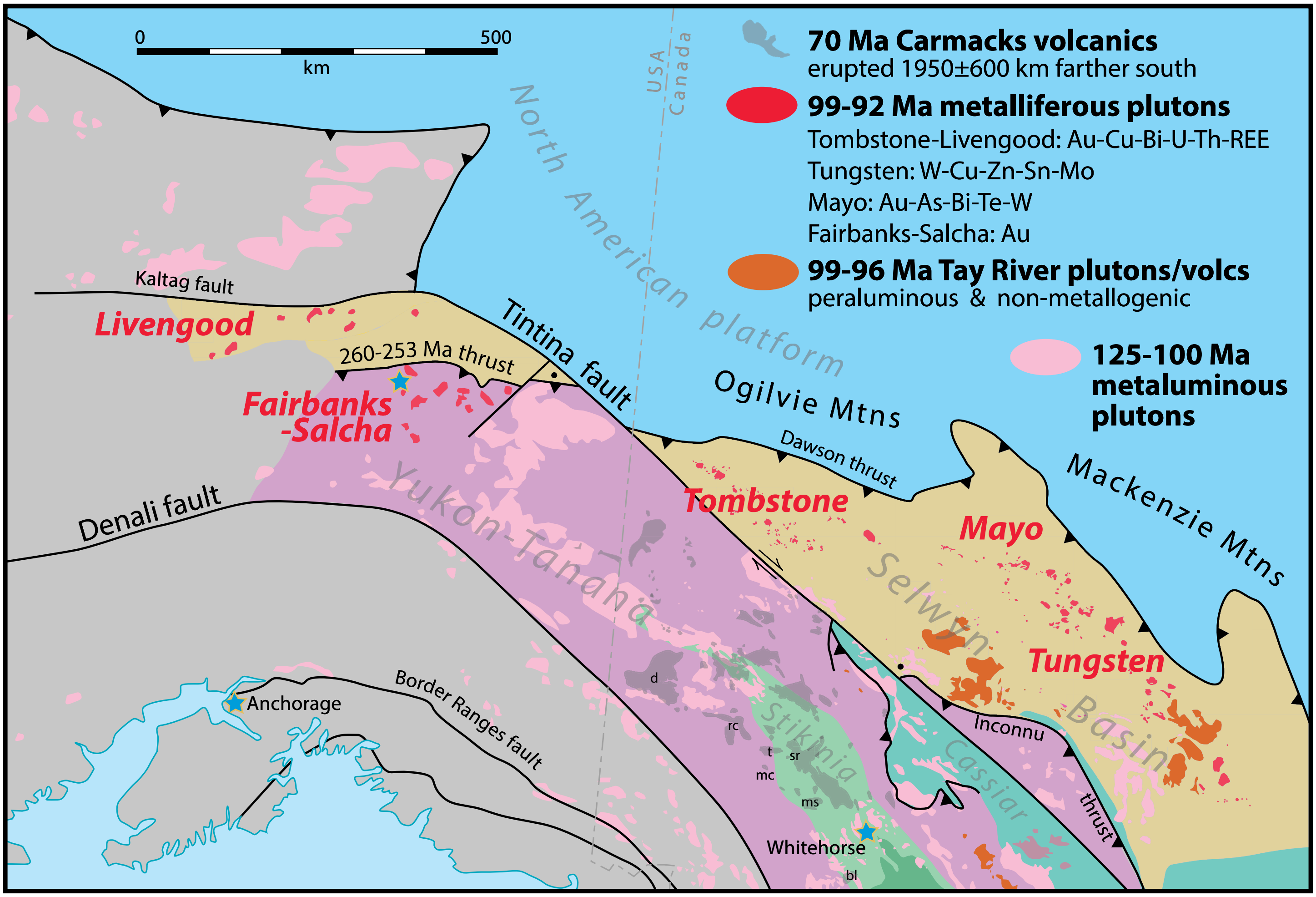

Figure 5. Geological sketch map showing the distribution of post-Sevier metalliferous slab-failure plutons now located within northern Canada and Alaska (Hart et al. 2004a, b; Rasmussen 2013) interpreted to result from failure of the west-dipping North American oceanic plate. Note the abundant remnants of 70 Ma Carmacks volcanic rocks, which in multiple studies, yielded paleolatitudes of San Francisco (Johnston et al. 1996; Enkin et al. 2006a). As rocks of Selwyn basin, Cassiar platform, and Yukon-Tanana terrane were joined together at 260–253 Ma (Beranek and Mortensen 2011) they are all interpreted to have been located within the Great Basin-Sonora segments of the orogen at 70 Ma and migrated to their present northerly latitude mostly during the early Tertiary. Dots adjacent to the Tintina fault are approximate pre-fault piercing points (Gabrielse et al. 2006). Other Late Cretaceous–Paleocene magmatic complexes commonly have associated mineralization and, along with the Carmacks, are probably slab failure rocks related to the accretion of Wrangellia to the western margin of the Intermontane superterrane during the Laramide event. Labeled complexes from Morris et al. (2014): d–Donjek; rc–Rhyolite Creek; bl–Bennett Lake; ms–Mount Skukum; mc–Mount Creedon; sr–Sifton Range; t–Tlansanlin.

America. Breakoff of the remainder of the Panthalassic slab attached to North America led to the end of compressional deformation, subduction of North American rift and outer-slope passive margin deposits, exhumation, and a widespread Late Cretaceous–Early Tertiary firestorm of magmatism (Fig. 1). In the case of subduction of very old and dense oceanic lithosphere and thick Precambrian cratonic lithosphere, such as between Cambrian Panthalassic lithosphere and that of cratonic North America, slab failure might be difficult and slow. This would lead to a broad orogen and higher grades of metamorphism in the downgoing plate because it was pulled to great depth prior to slab failure (Duretz et al. 2013). Let's now turn to the geophysics and plate trajectories to see what they tell us about subduction polarity and timing of events.

GEOPHYSICS

Seismic Tomography

Tomographic analysis of the mantle beneath North America is illuminating for it shows 'fast' regions in the mid-mantle, readily interpreted as folded relict oceanic slabs (Grand et al. 1997). The largest of these anomalies is a steeply inclined slab wall in the transition zone and lower mantle that extends for over 40° of latitude in eastern North America (Sigloch 2011; Sigloch and Mihalynuk 2013). Another 'slab' farther west and as deep as 1800 km rises westward to connect with the Cascadia subduction and thus represents the Farallon slab at depth, so the separate eastern slab cannot be the Farallon slab (Sigloch et al. 2008; Sigloch and Mihalynuk 2013). The

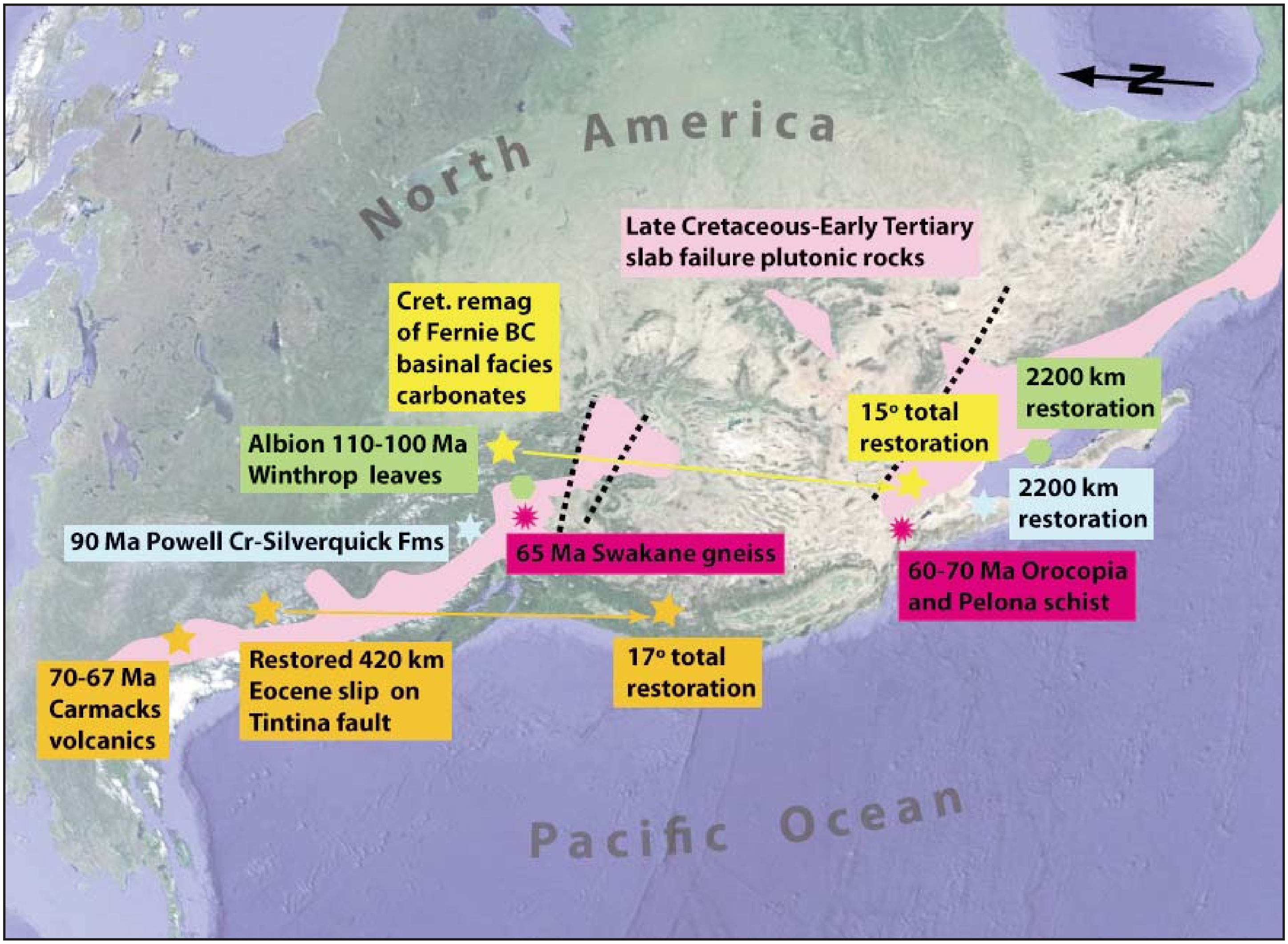

Figure 6. Various elements of western North America illustrating possible piercing points and selected paleomagnetic data documenting large-scale northward migration during and after the Laramide event. 70–67 Ma Carmacks volcanic rocks have 17º northward rotation (Enkin et al. 2006a); 90 Ma Powell Creek and Silverquick formations have 2200 km northward migration (Enkin et al. 2006b); Cretaceous remagnetized basinal carbonate just west of the North American platform terrace show 15º northward movement (Enkin et al. 2000); Albion leaf margin data in Winthrop Formation of Methow basin show some 2200 km migration (Miller et al. 2006). The 65 Ma Swakane gneiss (Matzel et al. 2004) is remarkably similar to the 70–60 Ma Orocopia and Pelona schists (Jacobson et al. 1996) and were likely part of the same belt; Late Cretaceous-Early Tertiary slab failure plutonic rocks were likely contiguous (Hildebrand, 2009; 2013). Note that older sites show greater separation than younger sites, which suggests that northward meridional migration had started by ~85 Ma. Map base from Google Earth®.

extensive eastern slab forms a vertical wall within the mantle from about 800 to at least 1800 km depth (Grand et al. 1997; Sigloch and Mihalynuk 2013). During the opening of the Atlantic Ocean, at least during the Jurassic–Early Cretaceous periods, North America was moving westward from a more or less fixed Africa (Coney 1971; Torsvik et al. 2008a; Steinberger and Torsvik 2008; Seton et al. 2012). This implies that the slab wall formed during westward-dipping subduction because if the slab was easterly dipping beneath western North America – as generally assumed by most workers to have been the case since at least the Triassic – the trench would have migrated westward and, as long as the slab sank vertically, left an inclined slab at depth which dips toward older trench positions. In other words, westward rollback of an eastward-dipping slab could not have produced a vertical slab wall. Only a more or less fixed trench can produce such a wall and so it fixes the paleo-position of the trench (van der Meer et al. 2010; Sigloch and Mihalynuk 2013).

During the mid-Cretaceous there were two places to put a subduction zone west of North America as most of the terranes within the Cordillera were joined by about 160 Ma (Hildebrand 2013): (1) in the basin along the western side of the Intermontane (Yukon-Tanana) superterrane; and (2) along the western side of North America. However, only case (2) could have been a westward-directed subduction zone as arc magmatism was continuous from the Triassic to 100

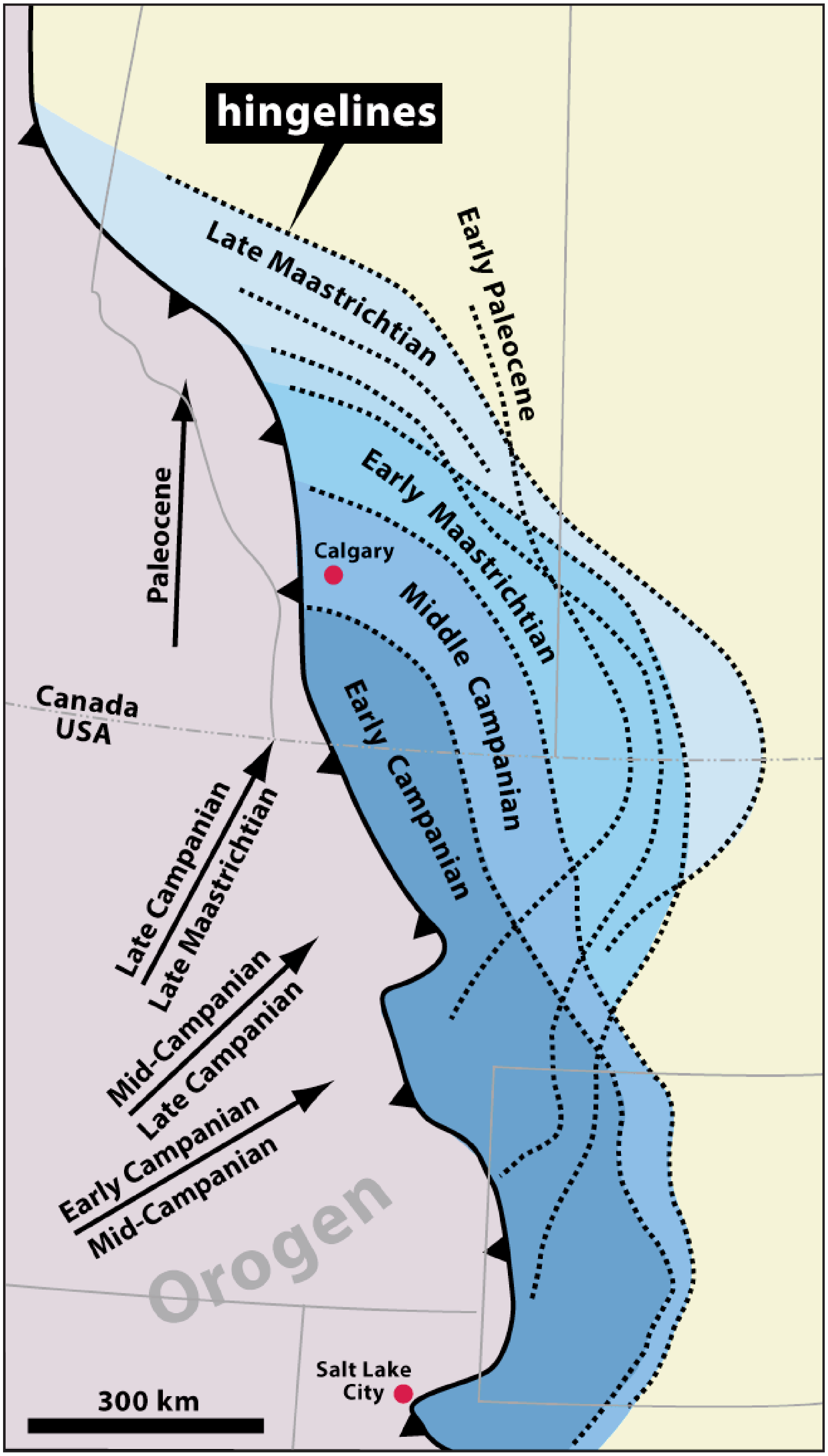

Figure 7. Northward migration of the Laramide foredeep during Campanian–Paleocene transpressional deformation. Modified from Catuneanu et al. (2000).

Ma in the Intermontane superterrane (Gehrels et al. 2009), and because the thrusting related to the 100 Ma closure of the Gravina-Dezadeash-Nutzotin basin to the west involved westward vergent folds and thrusts (Journeay and Friedman 1993; Rubin et al. 1990), subduction was eastward at this time. In fact, using this scenario some workers (Hart et al. 2004a; Rasmussen 2013) attribute all of the plutonism within the Omineca Belt to eastward subduction located west of Yukon-Tanana. In any case, it could not have been the subduction zone that formed the tomographic anomaly as its relict in the mantle would have been inclined eastward, not vertical. Therefore, the subducted slab wall was connected to western North America, and it must be the Panthalassic slab, formed when Rodinia broke into pieces and drifted apart (Li et al. 2008; Evans 2009).

Plate Trajectories and Paleomagnetism

As pointed out by Sigloch and Mihalynuk (2013), a vertical slab wall effectively fixes the position of the trench when active, and because its upward truncation represents the collision and related slab failure, the correct paleogeographic model should match the collision zone with the slab wall at the appropriate time as deduced from geological arguments. One can use Gplates (Boyden et al. 2011; Gurnis et al. 2012; Williams et al. 2012) as did Sigloch and Mihalynuk (2013) to compare the location of the eastern vertical slab with the predicted paleogeographic trajectories for North America from 140 Ma to present as deduced from the five separate models of Shephard et al. (2012): (1) a hybrid hotspot model, which uses moving hotspots in both the Atlantic and Indian oceans from 100 Ma to the present (O'Neill et al. 2005), and fixed hotspots for older ages (Müller et al. 1993); (2) a fixed hotspot reference frame model (Müller et al. 1993); (3) a hybrid model utilizing moving hotspots after 100 Ma (O'Neill et al. 2005) and a paleomagnetic model utilizing a fixed position for Africa from 140 Ma to 100 Ma (Torsvik et al. 2008a); (4) another hybrid model that uses the migrating Afro-Indian hotspots but for times prior to 100 Ma uses a TPW-corrected paleomagnetic

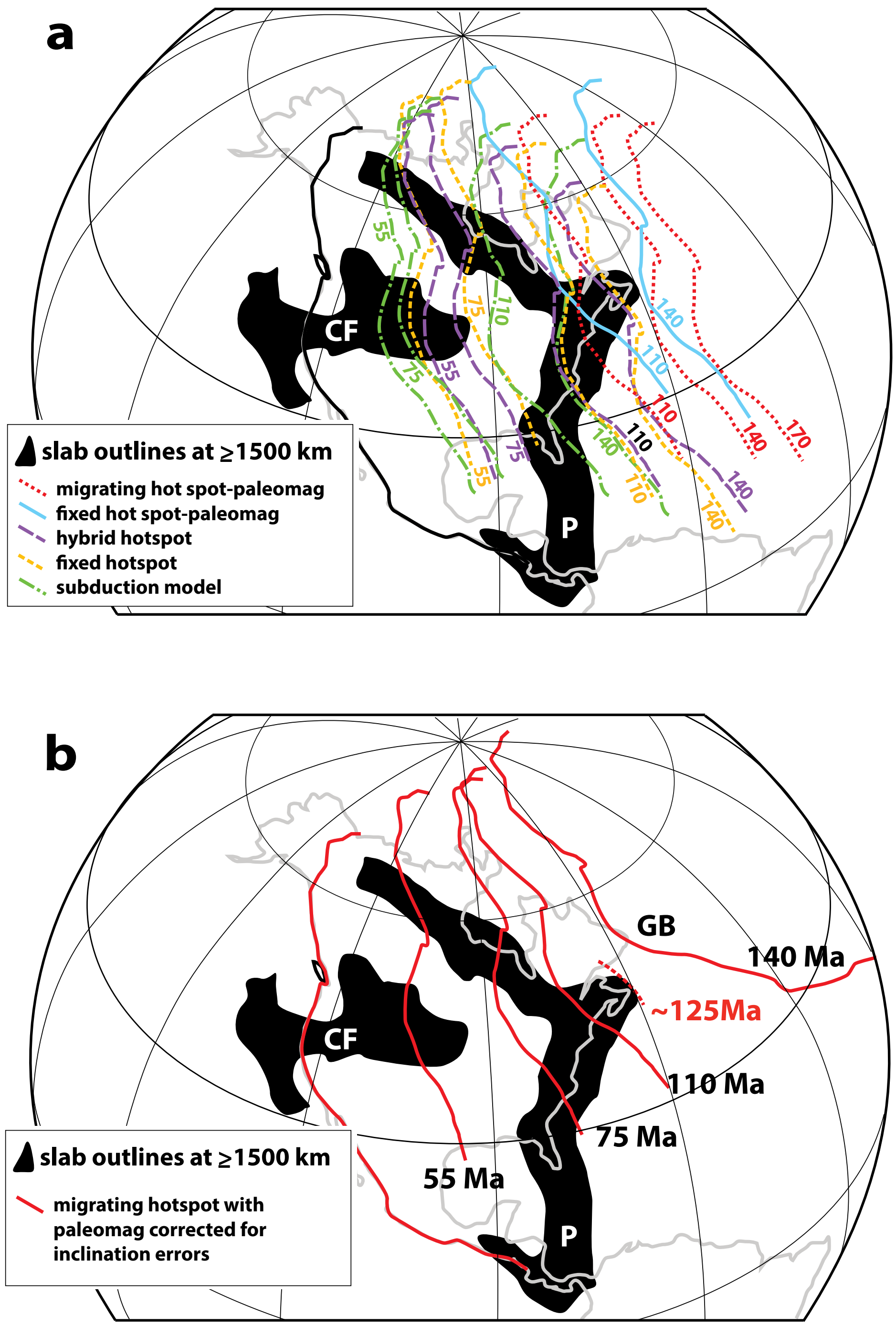

Figure 8. (a) Sketch map (modified from Sigloch and Mihalynuk 2013), illustrating the approximate relative positions of North America at different times using the five paleogeographical models discussed in the text relative to the tomographically imaged slabs beneath North America. Note that both models using the migrating and fixed hotspot plus paleomagnetics approximate the timing of North America's arrival at the trench defined by the eastern Panthalassic slab, but that the paleolatitude is poorly matched with the Great Basin area where the Sevier event occurred. (b) By correcting the migrating hotspot model with paleolatitudes derived by accounting for inclination errors (Kent and Irving 2010), the Great Basin area encountered the trench between 140 and 110 Ma, approximating the 125 Ma age for the initiation of the Sevier event. CF–Cascadia-Farallon slab; P–Panthalassic slab; GB–Great Basin area of North America.

framework that also assumes no longitudinal motion of Africa (Steinberger and Torsvik 2008; Seton et al. 2012); and (5) an entirely different type of model that matches subducted slabs with subduction zones (van der Meer et al. 2010).

Uncertainty pervades nearly every aspect of the reconstructions, including possible errors in properly locating and dating hotspots, the shape of the North American margin, error envelopes in paleomagnetic pole locations and ages, errors in assigning movement to hotspots, and in the case of the subduction model, mistakes in matching mantle anomalies with subduction zones once the subducting slab has broken. To these can be added the errors in understanding the original upper mantle dip of the subducting slab and how it changed with time. The results must be considered qualitative as the aggregate uncertainties are impossible to quantify at this time. Even so, the results may be useful to sort out different tectonic models and because the idea is to see which model best matches the known geology, it should provide geological feedback to discern the most plausible of the competing paleogeographic models.

As can be seen on Figure 8a, western North America coincides with the eastern V, or promontory, of the mid-mantle anomaly between 140 and 110 Ma in the two models (#3 and #4) that utilize a pre-100 Ma paleomagnetic framework. In the other three trajectories the western margin of North America arrived at the trench prior to 140 Ma, a period when there is no known deformational thickening on the North American platform. The non-TPW-corrected paleomagnetic model (#3) is probably the best fit but the paleolatitudes are too far south for a good fit with the known geology. However, as pointed out by Kent and Irving (2010) the majority of the paleolatitudes from North America and other continents used by Torsvik et al. (2008a) were determined from sedimentary rocks and thus subject to inclination errors that yielded paleolatitudes that were too low. By using the paleomagnetic determinations from igneous rocks and inclination-corrected poles from sedimentary rocks of Kent and Irving (2010) to correct the non-

TPW paleolatitudes, the fit is reasonable and places the V of the mid-mantle Panthalassic anomaly within the Great Basin sector (Fig. 8b).

Thus, by utilizing paleogeographic trajectories determined from migrating hotspots and paleomagnetism, corrected for inclination errors, the eastward V of the mid-mantle anomaly coincides with the Great Basin region of western North America between 140 Ma and 110 Ma, which based on (1) 124 Ma ash beds within the Buckhorn conglomerate, a unit at the base of the Sevier foredeep (Greenhalgh et al. 2006); (2) detrital zircons within the foredeep atop the North American platform terrace (Britt et al. 2007; Ludvigson et al. 2010); (3) a 119 ±2.6 Ma U–Pb age of a uraniferous carbonate farther east in the thinner forebulge section to the east; and (4) a compelling match between $\delta^{13}C_{org}$ excursions in early terrrestrial foredeep sedimentary rocks with well-dated Albian features of the global carbon isotope chemostratigraphy (Ludvigson et al. 2010), all indicate that North America entered the trench between 125 Ma and 120 Ma (Hildebrand 2013). Given all the uncertainties, this is a good match.

As noted earlier, Sevier deformation lasted until 105 Ma and was followed by slab failure within the Great Basin segment and the consequent emplacement of a suite of 105–92 Ma metalliferous slab failure plutons (Hildebrand et al. 2013). The northern and southern margins of the Sevier belt were almost certainly truncated by Subduction Transform Edge Propagator (STEP) faults (Govers and Wortel 2005) because the adjacent North American platform terrace to the north lacks Sevier-age deformation (Hildebrand 2013). The geology to the south is less well known but the thrust belt is Laramide in age so STEP faults are interpreted here to delineate the northern and southern margins of the promontory in the mid-mantle anomaly.

The consequences of the Laramide collision were large. Not only did subduction between the ribbon continent and North America end, but (1) eastward-directed subduction along the western side of the ribbon continent shut down and rocks of the Franciscan accretionary complex were rapidly exhumed; (2) nearly the entire Cordilleran Ribbon Continent started to migrate northward along the margin of North America; (3) nearly all of the remaining rift and outer slope deposits of the North American margin were recycled into the mantle; and (4) a huge magmatic bloom of Late Cretaceous–Early Tertiary plutons, was emplaced more or less along the collision zone within the then conjoined Canadian and Sonoran segments (Hildebrand 2009, 2013). The 80-Ma terminal collision aligns quite well with the main bulk of the mantle slab anomaly (Fig. 3), except for deviations within the Canadian sector, which were possibly caused by anticlockwise rotation of northern Alaska during the opening of the Canada Basin between 134 Ma and 84 Ma (Helwig et al. 2011).

The model presented here differs from the conjectures of Sigloch and Mihalynuk (2013) in that they argued for initial accretion much earlier, at about 160–155 Ma, when they believe the Intermontane superterrane collided with North America above an eastward-dipping subduction zone. In their model the slab wall represents a younger westward dipping subduction zone located west of the Intermontane superterrane. However, because the Sevier event at 125 Ma represents the first deformational thickening of the North American platform terrace, and because it occurred only in the Great Basin sector, their model does not match the known geology. They inferred that clastic sedimentary rocks of the Fernie and Kootenay basin of the southern Canadian Rockies represent orogenic sediments related to the collision of the Intermontane superterrane (Monger et al. 1982), but those basinal rocks contain no exotic debris (Gibson 1985; Ross et al. 2005), do not thicken westward (Hamblin and Walker 1979; Price and Fermor 1985), and thrust faults do not cut rocks of either group until the Santonian-Campanian (Larson et al. 2006), some 70–80 Myr later. Additionally, there are no arc rocks of the appropriate age on North America. Another problem with collision at that time and place is that geologists have had to invent a drainage divide to separate the open-ocean phosphorites, that directly underlie rocks of the Fernie Group of North America, from the Kootenay terrane, now located just to the west, which experienced plutonism, large-scale recumbent folding and exhumation from pressures of 6 kb to 2 kb at that time (Colpron et al. 1996; Ross et al. 2005; Evenchik et al. 2007).

Sigloch and Miyalynuk (2013) also suggested that following westward subduction leading to the formation of the Red Ant schist at 170 Ma in the Sierra Foothills belt of California (Fig. 1), that subduction flipped to eastward dipping and started Franciscan subduction at 160 ±5 Ma, yet there is scant evidence – in the form of a few high grade ~160 Ma knockers of unknown provenance – for Franciscan sedimentation at that time, especially considering that the oldest and structurally highest Franciscan rocks, the South Fork Mountain schist, contain detrital zircons dated at 131 Ma (Dumitru et al. 2010). There are also two different arc complexes west of the Red Ant schist – the Slate Creek-Combie arc, accreted at 170 Ma, and the Smartville-Foothills arc, accreted at 160 Ma – both of which appear to have been located above westerly dipping subduction zones (Hildebrand 2013). It's also unlikely that the Franciscan, Coast Range ophiolite, and Great Valley forearc basin, which appear to form a linked triad (Dickinson 1976), were located west of the Sierra Nevada prior to 100 Ma as (1) the detrital zircon populations within rocks of the Great Valley Group are incompatible with their present location west of the Sierra Nevada (Wright and Wyld 2007); and (2) rocks of the Great Valley forearc basin show no evidence of an intense deformational event that occurred in the Sierra Nevada at 100 Ma (Hildebrand 2013).

Finally, as discussed earlier in this contribution, prior to the 100 Ma closure of the Nutzotin-Gravina-Dezadeash ocean basin to the west, the subduction zone there was likely eastward-dipping, based on the westward vergence of collisional thrusts formed during closure of the basin, and the occurrence of a long-lived arc on the Intermontane superterrane to the east (Rubin et al. 1990; Journeay and Friedman 1993; Gehrels et al. 2009). The only place to put a westward-dipping subduction zone during the 160 Ma to 80 Ma period would have been between the Cordilleran Ribbon Continent and North America, far inboard of that hypothesized by Sigloch and Mihalynuk (2013).

Overall, the model by Sigloch and Mihalynuk (2013) makes a compelling argument for westerly subduction, but it fails to link the subduction to known geology of the North American Cordillera. As shown here, the paleomagnetically corrected plate trajectories in a fixed mantle framework and the relict slab imaged by seismic tomography coincide in the Great Basin sector between 140 and 110 Ma, which fits the 125 Ma initiation of the Sevier event as determined from geological observations.

CONCLUSIONS

North America was migrating westward during Late Jurassic–Early Cretaceous opening of the Atlantic Ocean, making it impossible to create the vertical slab wall beneath eastern North America by an eastward-dipping scheme: only a west-dipping slab subducting into a more or less fixed trench position can create the observed vertical wall (Sigloch and Mihalynuk 2013). The intersection of the relict slab position, which fixes the trench in space, and the expected position of western North America during the Sevier and Laramide events fixes the approximate time at which the western margin of North America arrived at the trench. When combined, the consistency of the modeled position of the margin at 125–120 Ma and 80–75 Ma and the relict slab supports the hypothesis that a westerly dipping oceanic slab pulled the western margin of North America into the trench during the Sevier and Laramide events. The Sevier sector of the slab failed at 105 Ma and produced a 99–92 Ma suite of metalliferous plutons now found in northern Canada and eastern Alaska. Prior to the Laramide event the Cordilleran Ribbon Continent migrated sinistrally with respect to North America (Kent and Irving 2010), but during and following the terminal Laramide collision, the interactions between North America and the ribbon continent were dextral and terranes within the ribbon continent then located within the Great Basin and Sonoran sectors of the orogen migrated northward into the Canadian sector where they reside today. Voluminous slab failure magmatism accompanied Laramide slab failure in the Canadian and Sonoran sectors (Hildebrand 2009, 2013). The failure of the slab likely occurred within the region of previously extended and broken crust and so the rift and outer slope deposits were torn from North America and recycled into the mantle. Overall, the geology, meridionally-corrected plate trajectories in a fixed mantle framework, and the seismic tomography are consistent with a long-lived westward subduction model that ultimately led to the collision of the Cordilleran Ribbon Continent with North America, initially during the Sevier event of the Great Basin sector, and finally over the length of North America during the Laramide event.

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