The odyssey of the Cache Creek terrane, Canadian Cordillera: Implications for accretionary orogens, tectonic setting of Panthalassa, the Pacific superwell, and break-up of Pangea

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Abstract

The Cache Creek terrane (CCT) of the Canadian Cordillera consists of accreted seamounts that originated adjacent to the Tethys Ocean in the Permian. We utilize Potential Translation Path plots to place quantitative constraints on the location of the CCT seamounts through time, including limiting the regions within which accretion events occurred. We assume a starting point for the CCT seamounts in the easternmost Tethys at 280 Ma. Using reasonable translation rates (11 cm/a), accretion to the Stikinia–Quesnellia oceanic arc, which occurred at about 230 Ma, took place in western Panthalassa, consistent with the mixed Tethyan fauna of the arc. Subsequent collision with a continental terrane, which occurred at about 180 Ma, took place in central Panthalassa, >4000 km west of North America yielding a composite ribbon continent. Westward subduction of oceanic lithosphere continuous with the North American continent from 180 to 150 Ma facilitated docking of the ribbon continent with the North American plate.

The paleogeographic constraints provided by the CCT indicate that much of the Canadian Cordilleran accretionary orogen is exotic. The accreting crustal block, a composite ribbon continent, grew through repeated collisional events within Panthalassa prior to docking with the North American plate. CCT's odyssey requires the presence of subduction zones within Panthalassa and indicates that the tectonic setting of the Panthalassa superocean differed substantially from the current Pacific basin, with its central spreading ridge and marginal outward dipping subduction zones. A substantial volume of oceanic lithosphere was subducted during CCT's transit of Panthalassa. Blanketing of the core by these cold oceanic slabs enhanced heat transfer out of the core into the lowermost mantle, and may have been responsible for the Cretaceous Normal Superchron, the coeval Pacific-centred mid-Cretaceous superplume event, and its lingering progeny, the Pacific Superswell. Far field tensile stress attributable to the pull of the slab subducting beneath the ribbon continent from 180 to 150 Ma instigated the opening of the Atlantic, initiating the dispersal phase of the supercontinent cycle by breaking apart Pangea. Docking of the ribbon continent with the North American plate at 150 Ma terminated the slab pull induced stress, resulting in a drastic reduction in the rate of spreading within the growing Atlantic Ocean.
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1. Introduction

Accretionary orogens form at long-lived convergent margins, and consist of a complex collage of accreted crust and lithosphere (terranes), that include arcs, oceanic plateaus, and seamounts. Such orogens host the bulk of the Earth's orogenic gold and volcanogenic massive sulphides deposits, are stitched together and on-lapped by post-tectonic granitoid intrusions and sedimentary basins, respectively, and are commonly inferred

to be the sites of construction of continental lithosphere [1,2]. Establishing the processes responsible for the development and evolution of accretionary orogens, and quantifying the rate of continental growth within such orogens remains, therefore, of significant tectonic and economic interest.

The Canadian Cordillera (Fig. 1) developed along the west margin of the Pangea supercontinent (Fig. 2) during its break-up, faced east toward the Panthalassa superocean, and is commonly cited as a prime example
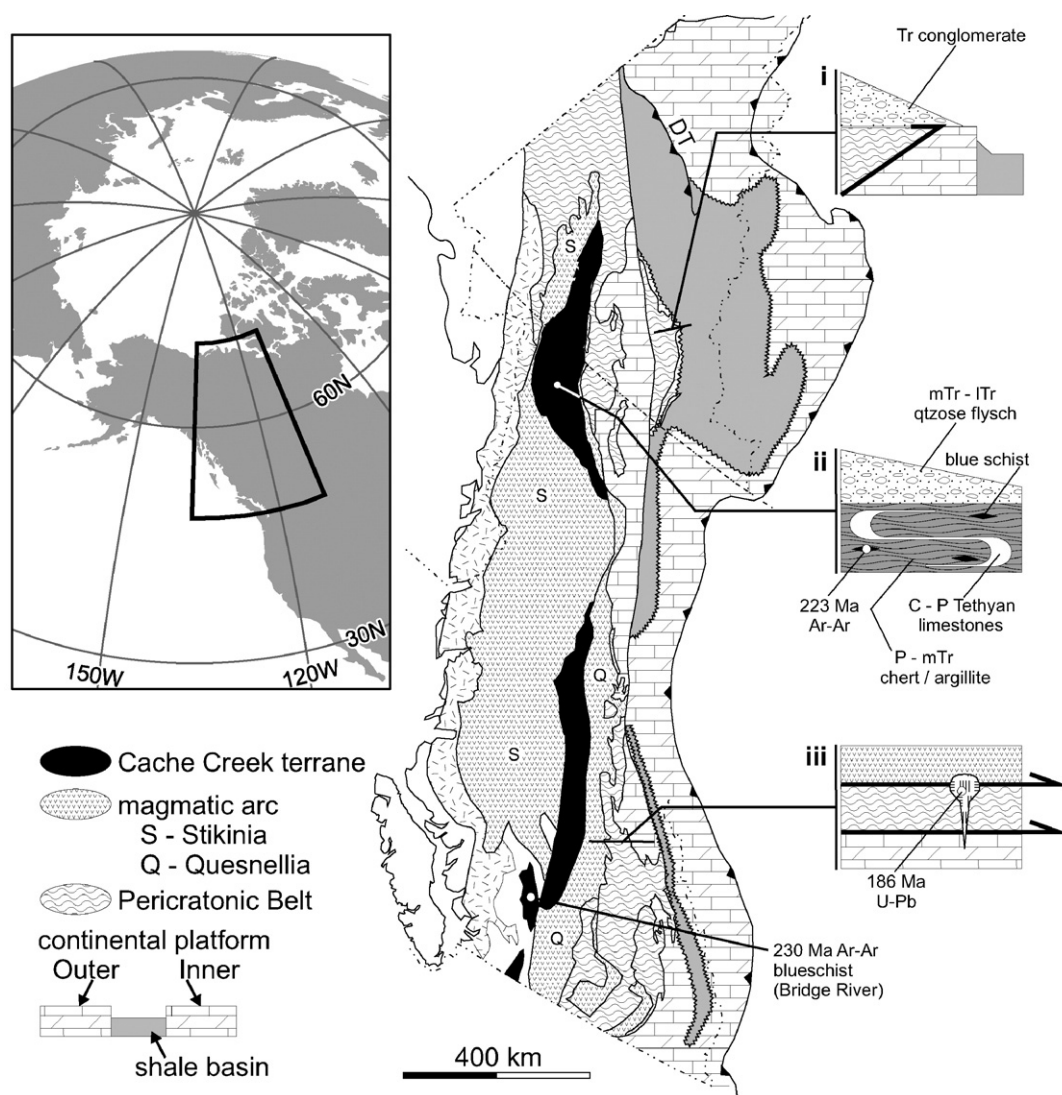

Fig. 1. Tectonic map of the Canadian Cordillera, location indicated on index map at top left. Schematic cross-sections at right show (i) Triassic conglomerate unconformably overlying the thrust that places pericratonic belt crystalline rocks on top of the outboard continental platform; (ii) Middle Triassic and younger arc flysch, interpreted to be derived from Stikinia, unconformably overlying folded and metamorphosed (blueschist facies) Cache Creek strata; and (iii) 186 Ma plutons intruding and stitching together previously imbricated strata of the Quesnellia arc terrane, the pericratonic belt and the outboard continental platform. Cooling ages from Cache Creek and correlative blueschists indicated (references in text). DT — Dawson thrust.
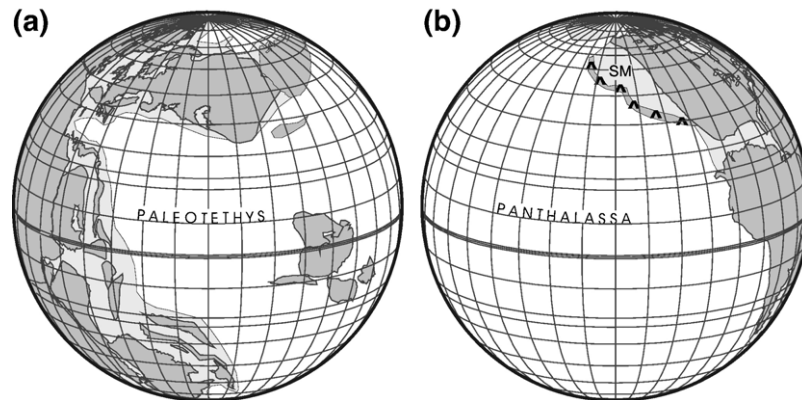
Fig. 2. Permian paleogeography, after Stampfli and Borel [78], with continental regions in grey and light grey. (a) The northern Laurasian and southern Gondwanan components of Pangea separated by the eastward widening Paleotethys. Continental blocks that now form South China occurs along the eastern margin of Tethys and separate it from Panthalassa to the east. (b) The opposite side of the Earth, showing Panthalassa and the west margin of Pangea. The commonly interpreted location of the Stikinia–Quesnellia arc, taken from Mihalynuk et al. [16], is indicated by a grey band ornamented with inverted V symbols (volcanoes) and is separated from the continent by the 0 to 1500 km wide Slide Mountain (SM) marginal basin.

of an accretionary orogen [3,4]. Hence the orogen provides us with a record of plate margin processes involved in the break-up phase of a supercontinent cycle, and presents us with an opportunity to better understand the processes involved in supercontinent dispersal and superocean tectonics. The Pacific basin is the remains of Panthalassa, and its current geometry and character may, therefore, owe much to the geometry and fate of the oceanic plates that floored Panthalassa. Oceanic terranes preserved within the Cordillera may, therefore, provide us with constraints on the tectonics and evolution of the Panthalassa superocean, and clues as to current tectonic setting and thermal structure of the Pacific basin.

The Cache Creek terrane is an accretionary complex within the Canadian Cordillera. The complex includes the uppermost portions of upper Paleozoic seamounts and oceanic plateau. Sedimentary rocks deposited on these seamounts are characterized by Tethyan fauna [5], implying an origin within the Tethys, the internal ocean that separated the northern (Laurasia) and southern (Gondwana) portions of Pangea, and which opened eastward into the westernmost portion of Panthalassa (Fig. 2). The Cache Creek seamounts, therefore, originated on the opposite side of Panthalassa from the Cordilleran accretionary orogen. Their odyssey, crossing the Panthalassa superocean, has never been explored as a constraint on Panthalassan tectonics, and is the focus of our paper.
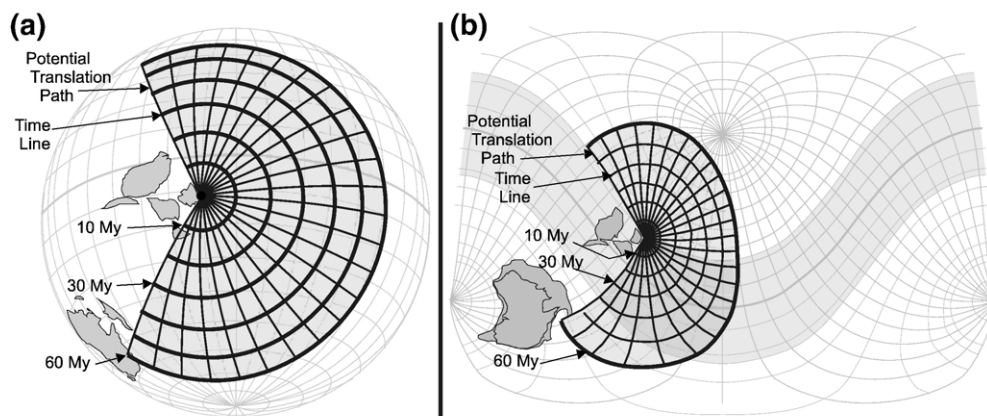

Fig. 3. Potential Translation Path plots, constructed using GMAP [79], on (a) an orthogonal projection, and (b) a Mercator projection. Potential Translation Paths are shown as portions of great circles radiating out from an assumed starting point. Small circles perpendicular to the Potential Translation Paths are time lines that show the maximum possible distance travelled at a given rate (11 cm/a) in 10 m.y. increments. Together, the translation paths and time lines define a velocity net that is shaded in grey.

We review stratigraphic, geochemical and faunal data that pertain to the origin and accretion history of the Cache Creek seamounts. Potential Translation Path (PTP) plots (Fig. 3) are introduced as a means of placing quantitative constraints on the location of the Cache Creek seamounts through time, including limiting the regions within which accretion events occurred. The translation path of the Cache Creek seamounts (1) yields new insights into the accretionary history of the Cordilleran orogen, (2) aids us in better understanding the plate tectonics of Panthalassa and the role of the superocean in shaping our post-Pangea Earth, and (3) provides us with a means for investigating the role of the Cordillera in the break-up of Pangea.

2. Terranes and terrane relationships

The four main terranes of the Canadian Cordillera, from west to east, are (1) the Cache Creek accretionary complex, (2) the Stikinia–Quesnellia arc, (3) the pericratonic belt, and (4) passive margin sequences of the Cordilleran Foreland (Fig. 1) (we ignore the more outboard terranes located along the west margin of the orogen). Here we briefly describe each of these four main terranes and indicate the nature and timing of links between each of the terranes.

2.1. Cache Creek terrane

The Cache Creek terrane (Fig. 1) and correlative sequences is an accretionary complex that includes melange belts, mafic–ultramafic volcanic–plutonic complexes, and large intact stratigraphic sequences (up to 75 km long by 40 km wide and 1 to 2 km thick) that consist mostly of shallow water reefal carbonates. The reefal carbonates commonly stratigraphically overlie basalt. Geochemical studies indicate that these basalts are alkalic, compositionally resembling Hawaiian basalts in major and trace elements, and are geochemically classified as Ocean Island basalts or within-plate tholeiites [6–8]. The within-plate character of the basalts is consistent with interpretation of the Cache Creek terrane as consisting of off-scraped seamounts and oceanic plateau with fringing carbonate reefs and banks [9]. The seamounts are assumed to have originated above a hotspot or mantle plume within an ocean basin setting [8]. The seamount basalts are characterized by a DUPAL isotopic signature [10], with elevated $^{208}Pb/^{204}Pb$ (37.8–38.6) relative to $^{206}Pb/^{204}Pb$ (18.1–19.1) and moderate åNd(T) of ∼5 [7]. The Cache Creek terrane is overthrust by and lies in the forearc region of the Stikinia and Quesnellia arcs (Fig. 1), and is

interpreted as the accretionary prism that developed during subduction beneath the arcs [11].

Sedimentary rocks of the Cache Creek terrane are characterized by fauna that are exotic with respect to other terranes of the Cordillera and to autochthonous North American strata. The distinct Cache Creek fauna range in age from Upper Carboniferous into the Triassic, and are characterized by the distinct Permian Veerbeekinid (Yabeina) fusulinids [5] that are known elsewhere only from the Tethyan domain of southern Asia. The benthic nature of the fusulinids allows for only limited distribution by currents, and effectively restricts the seamounts to having originated adjacent to other crustal blocks characterized by similar fauna. Additional Eurasian or Tethyan fauna observed in sedimentary rocks of the Cache Creek seamounts include Upper Carboniferous to Triassic sponges, corals, spongiomorphs, brachiopods, bryozoans and other tropical reef organisms [12], as well as conodonts and radiolarian [13]. Based on the Tethyan faunal character, the Cache Creek seamounts are interpreted to have originated within or immediately adjacent to the Tethyan ocean that separated the southerly Gondwanan and northerly Laurasian portions of the supercontinent Pangea (Fig. 2)[5]. Deposition of Upper Carboniferous to Lower Triassic shallow water limestones [14] requires that the Cache Creek terrane remained within the tropics throughout this period.

2.2. Stikinia–Quesnellia

The Cache Creek terrane accretionary complex is structurally juxtaposed against the Stikinia (to the west) and Quesnellia (to the east) volcanic arc terranes. Though now on opposite sides of Cache Creek terrane, Stikinia and Quesnellia share a common Paleozoic to early Mesozoic history and are inferred to have originated as a single, continuous magmatic arc that lay to the east of the Cache Creek terrane [15,16]. Migration of Stikinia to a position outboard (west) of the Cache Creek terrane is inferred to have occurred during syn- to post-accretion deformation, either as a result of strike-slip displacement [15] or by oroclinal bending [16].

Devonian to Permian carbonate deposition and arc magmatism characterize the Stikinia–Quesnellia magmatic arc [9,17–20]. A basal quartzose turbidite sequence suggests proximity to a continental domain in the Devonian [19,21]. A restricted, condensed sequence of argillite, chert and conglomerate characterizes the Upper Permian to Middle Triassic, deposition of which was followed in the Upper Triassic by arc magmatism and coral reef formation [18,22].

Stikinia–Quesnellia lack the distinctly Tethyan fauna that characterizes the Cache Creek terrane, and have considerably lower fusulinid species diversity. Permian strata are characterized by schwagerinid fusulinids and additional fauna that are similar to those found in the McCloud Limestone of northern California and Nevada [23]. The McCloud Fauna is distinct from the fauna of coeval North American strata. The degree of separation required to produce this faunal provincialism is commonly assumed to have been <1000 km [24,25], and the arcs are inferred to have been separated from the autochthon by a marginal basin [16] or to be autochthonous on North American basement [26](Fig. 2).

Exotic fauna of Eurasian affinity locally characterizes Stikinia and Quesnellia, however, and may point to a more distant origin for the arc. Conodonts of exclusively Eurasian derivation characterize Upper Devonian and Lower Carboniferous strata of Quesnellia and Stikinia, respectively [27]. Permian and Triassic strata are of a mixed faunal realm that includes corals, conodonts and radiolaria that are otherwise unknown outside Tethys [28,29].

Paleomagnetic data constraining the Permian through Jurassic paleolatitude of Stikinia–Quesnellia are limited. Reversed polarity recorded by Permian strata implies a northern hemispheric origin, because during much of the Permian the earth's magnetic field resided in a reversed polarity superchron [30]. Late Triassic and Early Jurassic volcanic rocks yield paleolatitudes, relative to autochthonous North America, that are similar to their current latitude, leading to the suggestion that Stikinia–Quesnellia has been fixed to North America since the Triassic [31]. Stikinia–Quesnellia is, however, characterized by Carnian and Norian sponge reefs that are otherwise unknown outside of tropical Tethyan sequences [28,29], implying that the arc lay within the tropics between 220 and 200 Ma.

The Cache Creek seamounts lay on and were conveyed by the slab subducting beneath Stikinia–Quesnellia into the arc. Lower Triassic or earlier accretion of the seamounts [16] is recorded by (1) the on-lap of Lower Triassic and younger arc-derived quartzose flysch onto the Cache Creek carbonates [32,33], (2) post-Upper Permian but pre-Upper Triassic isoclinal folding of Cache Creek strata and associated bedding-parallel foliation development, and (3) blueschist facies metamorphism [11,32]. Blueschist cooling ages of between 220 and 230 Ma [34,35] are consistent with exhumation following Lower Triassic entry into a subduction zone. Upper Permian to Lower Triassic quiescence within the Stikinia–Quesnellia arc may be an upper plate response to seamount and plateau accretion. Locally the Cache

Creek accretionary complex includes Lower Jurassic chert [14,36] implying continued subduction subsequent to seamount accretion. Blueschist facies metamorphism of Cache Creek terrane rocks that yield ages as young as Lower Jurassic [37] further implies continued subduction and exhumation. Seamount accretion did not, therefore, terminate subduction beneath Stikinia–Quesnellia.

2.3. Pericratonic belt

A series of pericratonic assemblages lie adjacent to and are structurally juxtaposed against the inboard (continentward) margin of the Stikinia–Quesnellia arc [16]. Locally referred to as the Nisling, Yukon–Tanana and Kootenay terranes, these assemblages are characterized by quartzose rocks and are assumed to have originated as a continental margin. Voluminous Late Devonian, Mississippian, and Permian volcanic and plutonic suites imply subduction beneath the margin and the development of an Andean-type magmatic arc in the middle to upper Paleozoic [38]. Residence adjacent to a subduction zone is further indicated by the presence of blueschists and eclogites yielding cooling ages ranging from the Carboniferous to the Triassic [39]. Imbricated with and lying along the eastern margin of the pericratonic belt are dismembered Upper Devonian to Permian ophiolite, referred to as the Slide Mountain terrane, that is inferred to have originated within a marginal basin that developed landward of the Andean arc assemblages [40](Fig. 2).

The pericratonic belt is overthrust by Stikinia–Quesnellia. 186 Ma plutons intrude and stitch together Stikinia–Quesnellia and the pericratonic terranes [41], limiting imbrication to the Early Jurassic or earlier. A magmatic arc (Stuhini–Nicola) consisting of isotopically juvenile mafic volcanic rocks [42], that developed on Stikinia–Quesnellia (and on the previously accreted Cache Creek seamounts) in the Upper Triassic contrasts with coeval quiescence in the pericratonic belt, implying separation of these terranes until the end of the Triassic. The Stuhini–Nicola arc probably provides a record of closure of an oceanic basin separating Stikinia–Quesnellia and the pericratonic belt, with final closure and collision occurring in the latest Triassic–earliest Jurassic. Pliensbachian molasse shed off the collision zone includes clasts of ultra-high pressure garnet peridotite unroofed from depths of 100 to 150 km depth [43] indicating that the arc-pericratonic belt collision was thick-skinned. Rare Upper Triassic magmatism in the pericratonic belt, for example the Teslin–Taylor Mountain batholith in Alaska [44], and mapped stratigraphic relationships between Quesnellia and the pericratonic belt [26,45] may imply that separation of Stikinia–
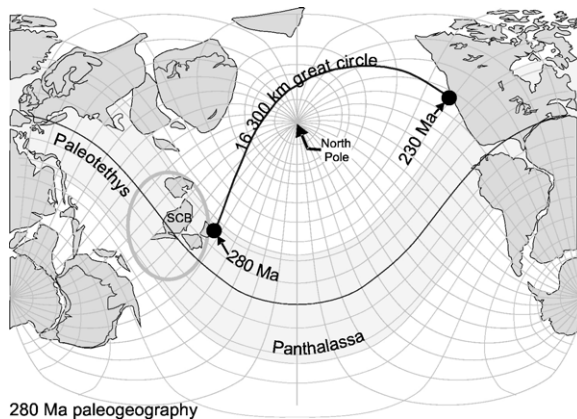
Fig. 4. Paleogeographic map for 280 Ma showing the shortest route between the easternmost Tethyan domain, at left, and the west coast of North America, at right — a 16 300 km long great circle route across Panthalassa. In this and in all subsequent PTP plots the paleogeographic positioning of the main continental blocks (shown in grey) is taken from Stampfli and Borel [78]. Light grey shading indicates the tropical belt. The grey ellipse encloses the South Chinese blocks (SCB) that lie along and define the eastern limit of the Tethyan domain and indicates the region in which we interpret the Cache Creek seamounts to have originated. The seamounts departed the Tethyan domain in the Permian (280 Ma or later) and accreted to the Stikinia–Quesnellia arc at 230 Ma. This PTP requires impossibly high translation rates (>32 cm/a).

Quesnellia and the pericratonic belt varied along strike and consisted of discontinuous marginal basins.

2.4. Foreland passive margin

Non- to weakly metamorphosed Paleozoic to Middle Jurassic shallow water carbonates and deeper water argillaceous sediments, locally underpinned by Meso- and Neoproterozoic clastic and carbonate sequences, dominate the Cordilleran Foreland. The passive margin assemblages can, based on the distribution of Paleozoic carbonates and shales, be divided into an internal or landward carbonate belt (the Rocky Mountain or Mackenzie platform), a medial shale basin (Selwyn basin/ Kechika Trough), and an outer or oceanward carbonate belt (Cassiar platform) (Fig. 1).

Metamorphic rocks of the pericratonic belt overlie the outboard Cassiar platform along a series of east-verging thrust faults [46]. Deformed and metamorphosed Permian strata in the pericratonic hangingwall of the thrust system limits emplacement to the Upper Permian or younger. Triassic conglomerate containing clasts of eclogite, blueschist and other distinct lithologies derived from the pericratonic belt unconformably overlies the Cassiar platform, indicating thrust emplacement in the Triassic. The inner Rocky Mountain–Mackenzie platform was characterized by a starved passive margin with

local phosphorite deposition into the Lower Jurassic [47], suggesting that the margin faced an open ocean basin. Inundation of the passive margin by westerly-derived flysch began at about 152 Ma [48], terminating phosphorite deposition and recording structural loading of the North American margin.

3. Potential Translation Paths

Utilizing the key constraints provided by the stratigraphic relationships described above, we employ
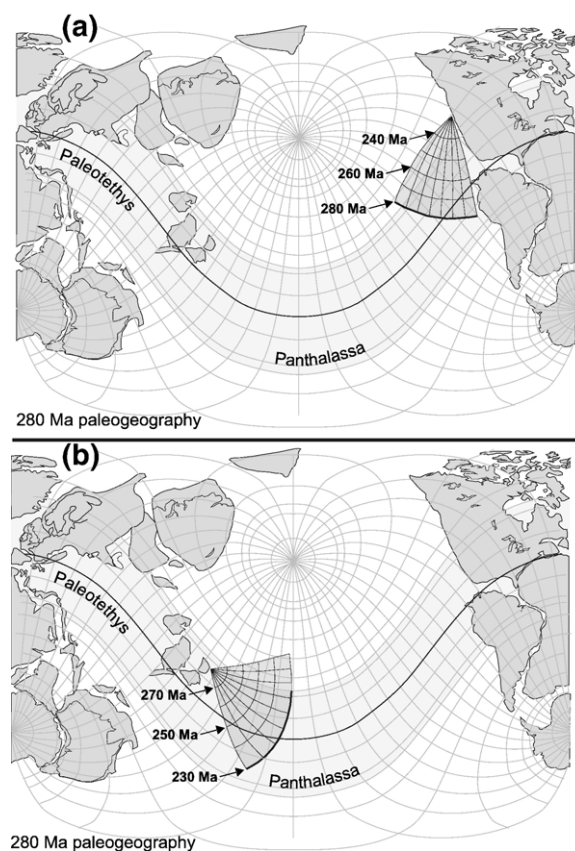

Fig. 5. PTP plots assuming a translation rate of 11 cm/a for the period from 280 Ma (soon after the Upper Carboniferous origin of the Cache Creek seamounts) to 230 Ma (the time at which the seamounts accrete to the Stikinia–Quesnellia arc), drawn on a 280 Ma paleogeographic map. (a) PTP plot drawn assuming that the Cache Creek seamounts accrete to arcs along the American margin. In this case the origin of the PTP velocity net represents the point of accretion at 230 Ma. Time lines are constructed back through time to 280 Ma. The bold 280 Ma time line indicates the range of possible starting points for the Cache Creek seamounts. (b) PTP plot drawn assuming that the Cache Creek seamounts originated within the Tethyan domain. We assume a point of origin for the velocity net at 280 Ma at the eastern edge of the Chinese crustal blocks that lay along the eastern margin of the Paleotethys sea. The bold 230 Ma time line indicates the maximum distance travelled prior to accretion to the Stikinia–Quesnellia arc.
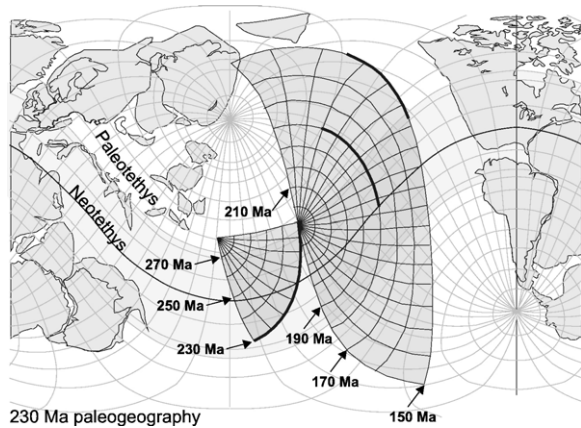
Fig. 6. PTP plot shown on a 230 Ma paleogeographic map assuming a Tethyan origin for the Cache Creek seamounts. The 280 Ma to 230 Ma Cache Creek velocity net is indicated. Note that the Chinese crustal blocks have already migrated to the northeast. We assume accretion of the Cache Creek seamounts to Stikinia–Quesnellia to have occurred within the northernmost tropical belt, and use this as the origin of a 230 to 150 velocity net. Bold portions of the 180 and 150 Ma time lines indicate the range of probable locations of collision of Stikinia– Quesnellia with the pericratonic belt–outboard continental platform, and accretion to the North American plate, respectively.

a series of Potential Translation Path (PTP) plots (Figs. 3–6) in order to place limits on the paleogeographic location of the Cache Creek seamounts throughout their translation, accretion, and final incorporation into the Cordilleran accretionary orogen. On PTP plots the Potential Translation Paths of a terrane are indicated as a series of great circles radiating out from an assumed starting location. Small circles perpendicular to the great circles are time lines showing the maximum distance travelled per increment of time (typically 10 million year increments) assuming a set velocity. Therefore, the small circles show the maximum possible distance covered by a terrane from an assumed starting point, given a constant vector of motion over a given period of time. Together the time lines and the translation paths define a velocity net that shows the maximum limits a terrane (or point on a plate) can travel in any given time period (Fig. 3).

The motion of any point on a plate describes a small circle about a pole of rotation (Euler Pole). Only the motion of points located 90° from the Euler pole describe great circle routes. While the angular speed on any point on a rotating plate is the same (measured in degrees per m.y.), velocity measured in km per m.y. increases to a maximum 90° from the Euler pole. By using great circle routes as PTP, we tacitly assume a location on an Euler equator. Translation rates utilized in PTP plots are therefore the maximum possible rates for

motions of the plates on which the translating points resided.

Our PTP plots are constructed assuming that plate tectonic rates have not changed appreciably throughout the Phanerozoic and that recent plate velocities are not anomalous. Plate motion models, the most commonly utilized being the NUVEL models, make use of sea floor spreading rates calculated over the past 3 million years as a means of constraining current vectors of plate motion [49]. These models indicate that the current maximum full spreading rate across mid-ocean ridges is about 16 cm/a (along a portion of the East Pacific Rise). The global average spreading rate is 4 cm/a. Convergence rates at subduction zones average 7 cm/a, with maximum rates of 11 cm/a (in the southwest Pacific) [50]. Longer term, though less accurate rates of plate motion calculated using the greater sea floor record of spreading extending back into the Jurassic, and by the use of hotspot tracks assuming a relatively fixed hotspot reference frame, yield similar estimates of rates of plate motion [51,52]. Plate motion rates, extending from the present day back to the Jurassic appear, therefore, unchanged, with maximum full spreading rates of about 16 cm/a and maximum convergence rates across subduction zones of about 11 cm/a. In most of our PTP plots we assume average, long term translation rates of 11 cm/a (1° per m.y.). Though above the average observed spreading and convergence rates, 11 cm/a is below the maximum observed spreading rate, and is about the maximum observed rate of convergence. Such a rate, therefore, provides a reasonable means of estimating the possible distance travelled during a given period of time.

Key geological constraints used in constructing PTP plots for the Cache Creek and associated Cordilleran terranes, are that (1) the Cache Creek seamounts originated adjacent to the east margin of the South Chinese crustal blocks that lay along and defined the eastern limit of Tethys; (2) eastward translation of the Cache Creek seamounts away from the Tethyan domain and across Panthalassa began at 280 Ma; (3) seamount accretion to Stikinia–Quesnellia occurred at 230 Ma; (4) Stikinia–Quesnellia remained at tropical latitudes until about 200 Ma; (5) accretion of Stikinia–Quesnellia to the previously combined pericratonic belt–Cassiar platform occurred at 180 Ma; and (6) the accreted collage of seamounts, arcs and pericratonic terranes were obducted onto the west margin of the North American plate at approximately their current latitude with respect to the autochthon at 150 Ma. We consider these assumptions conservative. Given the overwhelmingly Tethyan nature of the Middle and Upper Permian

limestones of the Cache Creek terrane, it may be that the seamounts originated within a more central location in Tethys and did not depart from the seaway until or after 260 Ma. Previous workers [16] have postulated that accretion of the seamounts to the magmatic arcs had begun by the end of the Permian. Pre-Middle Triassic seamount accretion may indicate that the Cache Creek seamounts formed a chain that extended some distance east into western Panthalassa. Stikinia–Quesnellia and pericratonic belt are stitched together by 186 Ma [41], some 6 m.y. in advance of our assumed 180 Ma collision. Cessation of the Late Triassic Stuhini–Lewes River arc may record entry of the pericratonic belt into the subduction zone, indicating that collision may have begun even earlier (∼200 Ma).

3.1. Accretion of Cache Creek seamounts to Stikinia–Quesnellia

If the Stikinia–Quesnellia arc did develop on or immediately adjacent to the western margin of North America, then the Cache Creek seamounts were faced with the immense task of crossing the entire Panthalassan ocean basin prior to accretion (Figs. 2, 4). Given the 50 m.y. window for translation (280 Ma to 230 Ma), crossing the >16 000 km wide Panthalassa using the most direct route possible (great circle route from tropical easternmost Tethys to the North American margin) would require a translation rate of >32 cm/a. Such a direct translation path results, however, in departure of the seamounts from the tropics in the Middle Permian, and ignores the need to maintain the Cache Creek seamounts at tropical latitudes into the Lower Triassic. A more realistic but significantly longer translation path, maintaining the Cache Creek seamounts at low latitudes throughout the Permian, would require translation velocities of >40 cm/a. In the absence of evidence pointing to a substantially different plate tectonic regime prior to 180 Ma, translation paths requiring long term plate tectonic rates well in excess of 15 cm/a are viewed as untenable.

PTP plots constructed utilizing a translation rate of 11 cm/a obliges us to conclude that the Cache Creek seamounts could not have crossed Panthalassa in 50 m.y. (Fig. 4). Either the Stikinia–Quesnellia arc did not develop along the western margin of North America, or the Cache Creek seamounts did not originate in the Tethyan domain. If we assume that Stikinia–Quesnellia was located along the American continental margin, then the Cache Creek seamounts are restricted to having originated within the tropics less than 3000 km west of the American coast (Fig. 5a). The alternative interpretation is that the Cache Creek seamounts did originate within the Tethyan domain (Fig. 5b), in which case accretion to Stikinia–Quesnellia at 230 Ma must have occurred within western Panthalassa, less than 5000 km east of the eastern margin of Tethys. Because of the substantial faunal evidence for the Cache Creek seamounts having originated in Tethys, our preferred interpretation has the Cache Creek seamounts accreting to Stikinia–Quesnellia in western Panthalassa. Accretion is assumed to have occurred within the northern hemisphere, based on the paleomagnetic data from Permian strata that place Stikinia–Quesnellia north of the equator at that time.

3.2. Post-Cache Creek seamount accretion

We assume that the Cache Creek seamounts accreted to Stikinia–Quesnellia within the northernmost tropics 10 000 to 11 000 km west of the nearest portion of the western margin of North America (Fig. 5b). Accretion of the seamounts near the equator or farther south increases the distance to North America. Eastward migration beginning at 230 Ma at 11 cm/a brings the Stikinia–Quesnellia arc, with its accreted seamounts, to within 1500 to 2000 km of the inferred western margin of North America by 150 Ma (Fig. 6); the more southerly the overall 230 to 150 Ma translation path, the shorter the distance to North America. It is, therefore, possible for the Cache Creek seamounts to have accreted to the North American plate, via transport on the Stikinia–Quesnellia arc, by 150 Ma given reasonable rates of translation. The 230 Ma to 150 Ma translation interval was, however, punctuated by the collision of Stikinia–Quesnellia with the previously combined pericratonic belt–outer Cassiar platform at 190 to 180 Ma. Assuming a constant 11 cm/a rate of eastward translation limits collision to having occurred within central Panthalassa, some 4000 to 6000 km west of the North American margin (Fig. 6).

4. Discussion

It is commonly assumed that the Cache Creek terrane, with its Tethyan fauna, is exotic with respect to autochthonous North America. Most of the other terranes that constitute the Cordilleran orogen are presumed to have originated within or immediately adjacent to the North American continental margin [53]. These two assumptions are, however, mutually exclusive. Interpretation of Stikinia–Quesnellia as a North American marginal arc limits the Cache Creek seamounts to having originated within 3000 km of the North American margin. Such an American-proximal

origin is unlikely, as coeval tropical North American carbonate sequences are characterized by a distinctly different faunal assemblage. Offshore (westerly) drift of trade wind-driven tropical ocean currents should have seeded nearby seamounts with American fauna, and yet no such cross-fertilization is observed. Furthermore, interpreting the Cache Creek seamounts as having originated adjacent to the American continental margin would imply that Tethyan fauna were common within Panthalassa and ignores the DUPAL isotopic signature of the Cache Creek basalts. The record of Tethyan terranes outside of Asia is restricted (small volume isolated allochthons in Japan and easternmost Russia), inconsistent with models that require the widespread distribution of Tethyan fauna within Panthalassa. DUPAL mantle is an isotopically distinct mantle reservoir that is enriched and radiogenic [10] and which underlies the Indian ocean region. The DUPAL anomaly is thought to be long-lived, probably having originated in Precambrian time, and likely characterized the Tethyan domain during the Paleozoic and Mesozoic [10]. Thus the DUPAL isotopic signature of the Cache Creek basalts provides an independent verification of the Tethyan origin of the Cache Creek seamounts.

Placing Stikinia–Quesnellia in western Panthalassa allows for the Tethyan origin and DUPAL isotopic character of the Cache Creek seamounts, and better explains the mixed (McCloud) faunal character of Stikinia–Quesnellia. The presence within Stikinia–Quesnellia of Tethyan faunal elements as old as Upper Devonian may imply that Stikinia–Quesnellia originated within or immediately adjacent to the Tethys in the Devonian, before migrating east into Panthalassa. Alternatively, if the Cache Creek seamounts did form a chain that extended out into western Panthalassa, the seamounts may have facilitated some limited faunal exchange between the Tethyan domain and the Stikinia–Quesnellia arc.

4.1. Accretionary orogens

Accretionary orogens are commonly interpreted to develop through the incremental addition of terranes above a convergent plate boundary developed along the margin of a continent [1]. If, however, we accept the faunal evidence of a Tethyan origin for the Cache Creek seamounts, then the concept of the Canadian Cordillera as an accretionary orogen that progressively developed during Devonian to Jurassic subduction beneath North America, as recorded by the Stikinia–Quesnellia arc, is untenable. In our view, the constraints provided by the Cache Creek seamounts indicate that the Canadian

Cordilleran orogen developed in a distinctly different fashion, with accretion events spanning 80 m.y. and having taken place within the western to central portions of the >16 000 km wide Panthalassa ocean. The Canadian Cordillera did not grow or deform, therefore, through the stepwise addition of terranes to the North American margin, but rather by the arrival at 150 Ma of a major composite superterrane or ribbon continent, previously referred to as Saybia [54,55] incorporating various terranes and lithotectonic assemblages that had been amalgamated elsewhere. Cordilleran evolution was, therefore, a two stage process: (1) accretionary development of a composite ribbon continent within Panthalassa, followed by (2) collision of the composite ribbon continent with the North American plate beginning in the Lower Jurassic.

Shale, argillite and chert of the Selwyn and correlative basin domains separate the outboard Cassiar platform, the eastern most portion of the ribbon continent, from the inboard Mackenzie–Rocky Mountain platform. Interpretation of the Cassiar platform as exotic requires the presence of a cryptic suture within or along the margins of the Selwyn basin. Locally the inboard margin of the Selwyn basin is characterized by a major foreland-verging thrust fault, such as the Dawson Fault in Yukon (Fig. 1). In most places, however, the inboard and outboard margins of Selwyn basin have been interpreted as facies changes [56]. How such a significant tectonic boundary could be cryptic remains unclear [54,55], but the answer may lie in resolving the significant post-150 Ma translations that have occurred within the orogen. Paleomagnetic data implies that large portions of the orogen underwent significant mid-Cretaceous southerly displacements [57], coeval with fold and thrust belt formation within the foreland, widespread dextral strike-slip faulting and voluminous granitic magmatism as far inboard as the eastern limit of Selwyn basin [58]. Paleomagnetic data from Late Cretaceous strata require significant northward translations, relative to the autochthon [59,60] coeval with fold and thrust belt formation in the foreland and oroclinal buckling of the ribbon continent in Alaska [55].

4.2. Panthalassa

In crossing Panthalassa, the Cache Creek seamounts first collided with and accreted to the Stikinia–Quesnellia arc. The arc then subsequently collided with the previously combined pericratonic belt–Outer Carbonate Platform. In both instances, collision was preceded by arc magmatism on Stikinia–Quesnellia, indicating that it was subduction beneath this arc, first of

the slab on which the Cache Creek seamounts lay, and subsequently of the slab that connected to the pericratonic belt, that led inexorably to the collisions. The implication is that subduction occurred within Panthalassa, far removed from the margins of the bordering Pangea supercontinent (Fig. 7). Panthalassan tectonics, with its internal arcs and subduction zones, was, therefore, significantly different from the tectonic setting of our Pacific Ocean basin, with its geometry of circum-oceanic (Ring of Fire) outward dipping subduction zones fed by a central spreading centre.
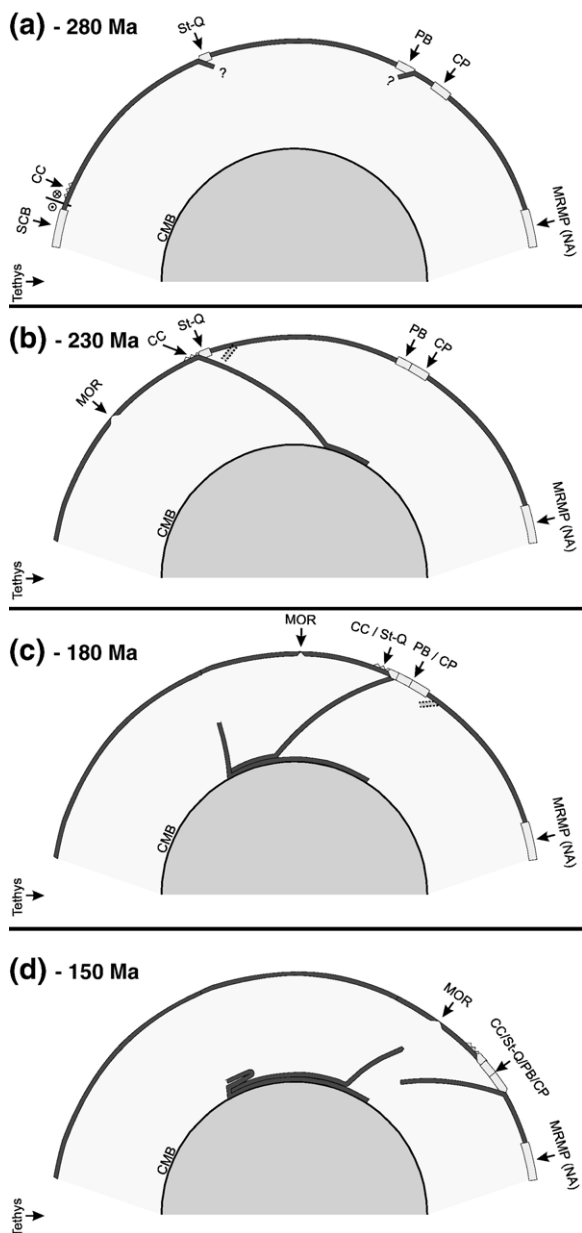
The Pacific Ocean is the post-Pangean remnant of Panthalassa. The basin is host to a number of significant hotspots, most notably the Hawaiian. Most of these hotspots appear to tap into a deep seated mantle source consisting, in some models, of deeply subducted oceanic slabs [61,62]. In addition the region is host to a "superswell" of anomalously hot, seismically slow mantle, and a related geoid high of over 600 m [63]. A mid-Cretaceous superplume event centred in the Pacific basin [64,65] gave rise to voluminous plume related oceanic plateau and seamounts (e.g. Ontong–Java). The magmatic flux at mid-ocean ridges was 15 to 30% higher at that time [66] due to increased mantle

Fig. 7. Scaled cross-sections of earth depicting, via sequential diagrams at 280 (a), 230 (b), 180 (c) and 150 Ma (d), the translation of the Cache Creek seamounts (CC) across Panthalassa in a fixed North America reference frame. 100 km thick oceanic lithosphere in dark grey; continental lithosphere, magmatic arcs and seamounts shown in light grey (slightly exaggerated thickness). A simplified mantle is employed (no upper or lower mantle) that ends down against the Core Mantle Boundary (CMB). Oceanic lithosphere is assumed to subduct directly to the CMB with preservation of line length (no internal strain). Subducted lithosphere is balanced by the growth of new oceanic lithosphere at Mid-Ocean Ridges (MOR). (a) 280 Ma — The CC seamounts are assumed to originate immediately east of the South China crustal blocks (SCB) which form the east limit of the Tethys. A transform fault is shown separating the SCB from oceanic crust underpinning the seamounts in order to facilitate the translation of old oceanic crust past the SCB. Devonian to Permian arc rocks indicate that subduction was ongoing beneath the Stikinia–Quesnellia arc (ST-Q) and the pericratonic belt (PB), although the polarity of subduction is, in both cases, poorly constrained. West-dipping subduction facilitates accretion of the PB and CP, but earlier east-dipping subduction is probably required to explain the history of PB arc magmatism and terrane migration. We assume ongoing east-dipping subduction beneath the west side of St-Q facilitating eastward translation of the Cache Creek seamounts. The locations of the PB and Outer Cassiar continental platform (CP) are conjectural — it may be that the PB was much more closely aligned with St-Q (discussed in text). St-Q may have originated farther east than shown, as 280 to 230 Ma subduction beneath St-Q may have resulted in westward migration of the arc due to roll back of the subducting plate. (b) 230 Ma — Accretion of CC seamounts to St-Q. A change in subduction polarity at this point in time to east-dipping subduction beneath the east margin of St-Q (dashed grey slab shows incipient subduction) facilitates subsequent eastward migration of St-Q. The flipping of subduction polarity is not thought to have been a result of seamount accretion. Oroclinal buckling of the St-Q arc, perhaps in response to seamount accretion [16] may explain the polarity flip. (c) 180 Ma — Termination of eastward translation of CC/St-Q by accretion to the previously amalgamated PB/CP. Initiation of subduction beneath the eastern margin of the resulting composite ribbon continent (dashed grey slab shows incipient subduction), consisting of CC/St-Q/PB/CP, explains its subsequent eastward migration. (d) 150 Ma — Subduction beneath the eastern margin of the composite ribbon continent brings it into proximity with continental lithosphere of the lower plate North American margin (MRMP).

temperature [67]. The mid-Cretaceous sea level high and greenhouse climate may have been related environmental effects of the superplume. The superplume event was coeval with the Cretaceous Normal Superchron, pointing to a deep seated (core–mantle boundary) origin for the superplume [64,65].

The origin of the long-lived positive thermal anomaly in the Pacific may lie in the vast volume of Panthalassan oceanic lithosphere subducted during the transit of the Cache Creek seamounts from Tethys to North America (Fig. 7). Thermal modeling of subducted slabs [68] suggests that they can penetrate intact to the core–mantle boundary where they would give rise to "normal" hotspots along the edges of the slabs. Blanketing of the core–mantle boundary by subducted slabs is interpreted to result in an increased temperature gradient at the core–mantle boundary, resulting in increased heat transfer from the core to the mantle. The heat transferred to the lowermost mantle is then trapped beneath the cold slabs which, because of their high viscosity must be conductively heated. The consequence is a long term build-up of heat beneath the slabs that eventually gives rise to a superplume event [68]. If all the oceanic lithosphere subducted during the transit of the Cache Creek seamounts sank to the Core Mantle Boundary, the result would have been the development, between 280 Ma and 150 Ma, of a substantial slab blanket on the sub-Pacific portion of the core (Fig. 7). We suggest that it was this blanket of subducted Panthalassan oceanic lithosphere which gave rise to the Pacific hotspots (from along the margins of the subducted slabs), and spawned the mid-Cretaceous superplume event (and the Cretaceous Normal Superchron), the remnant of which is the Pacific Superswell. Our model, which places the Cordilleran Triassic–Jurassic subduction system far removed from the west margin of Pangea, within Panthalassa, is at variance with models [69,70] which seek to explain the Pacific and African superswells as products of landward-dipping, circum-super continental subduction beneath Pangea.

4.3. Pangea break-up

Did the Cordilleran accretionary orogen play a role in the break-up of Pangea [71, 72]? The oldest recognized magnetic anomaly (M25–155 Ma) in the western Central Atlantic Ocean is separated from the continental margin by ~500 km of older oceanic crust. Magnetic anomalies in oceanic lithosphere offshore of Morocco in the eastern Central Atlantic are of Toarcian age (175–183 Ma) [73], consistent with a Lower Jurassic transition from rift stage evaporites to drift stage open marine carbonates along the North American continental margin following about 20 m.y. of rifting [74].

Thermal modeling suggests that supercontinents can insulate the mantle, giving rise to a gradual increase in the temperature of the underlying asthenosphere [75]. Upwelling of abnormally warm mantle may, therefore, have had a role in the break-up of Pangea. The rift to drift transition during Pangea break-up was not, however, accompanied by massive, plume related magmatism along the length of the margin, suggesting that the role of the sub-Pangea mantle in initiating supercontinent break-up was spatially restricted. In addition, intra-Tethyan subduction cooled eastern Pangea, and 100 m.y. (the maximum lifespan of Pangea) is not a long time for significant insulation.

Explanation of Pangea break-up may, therefore, lie in the far field stress that was acting upon the supercontinent. Collision of Stikinia–Quesnellia with its previously accreted Cache Creek seamounts, and the Pericratonic Belt / Cassiar platform occurred between 190 and 180 Ma, and was followed by the initiation of west-dipping subduction beneath the east margin of the composite ribbon continent. Closure of the basin intervening between the composite ribbon continent and the west margin of North America was accommodated by westward subduction, as indicated by arc magmatism on the ribbon continent versus a passive margin setting for continued sedimentation along the ancient western coast of North America. The oceanic lithosphere subducting beneath the ribbon continent was, therefore, continuous with and part of the same plate that contained Pangea (Fig. 7). Initiation of west-dipping subduction was coincident with the rift to drift transition in the Central Atlantic. Slab pull exerted by this subducting slab may, therefore, have been responsible for a tensile stress field that ultimately caused failure and break-up of Pangea. Supporting this contention is that closure of the basin lying west of North America, and docking of the ribbon continent with the North American plate at 150 Ma was coeval with a dramatic slowing of the rate of spreading within the Atlantic domain, from between 2 to 2.5 cm/a half spreading rate, to 0.5 to 1.0 cm/a [76,77].

5. Conclusions

Middle to Upper Triassic accretion of the Tethyan Cache Creek seamounts to Stikinia–Quesnellia, and Lower Jurassic collision of Stikinia–Quesnellia with the combined pericratonic belt–Cassiar platform, occurred >10 000 km and >4000 km west of autochthonous North America, respectively. Most of the Cordilleran orogen is, therefore exotic with respect to North America. The

development of the Cordilleran accretionary orogen was not, therefore, the result of sequential terrane accretion along the continent margin, but was instead a two stage process and resulted in significant growth of the North American continent. Stage one involved the 230 Ma to 150 Ma accretionary amalgamation of a ribbon continent within central to western Panthalassa. Stage two, from 150 Ma to 55 Ma, consisted of collision, margin parallel translation and final coalescence of the composite ribbon continent with North America. Evolution and development of the Canadian Cordillera implies that accretionary orogens may, therefore, involve an off shore amalgamation stage that may take place far removed from the autochthonous continent.

The Panthalassa ocean basin was significantly different from our current Pacific Ocean basin, being characterized by a number of internal subduction zones in which large volumes of oceanic lithosphere were consumed. Sinking of these slabs to the Core Mantle Boundary may have insulated the core beneath the Pacific giving rise to the mid-Cretaceous Pacific Superplume and the related Cretaceous Normal Superchron, and explaining the origin and geochemistry of the Pacific hotspots.

Westward subduction of oceanic lithosphere, starting at 180 Ma, that was part of the same plate as Pangea, closed the ocean basin separating the supercontinent from the terranes amalgamated within Panthalassa. Far field tensile stress attributable to the pull of the subducting slab pulled Pangea apart, initiating the dispersal phase of the supercontinent cycle. Closure of the basin at 150 Ma terminated the slab pull induced stress and resulted in a drastic reduction in the rate of spreading within the growing Atlantic Ocean.

PTP plots provide a simple and efficient means of testing suggested paleogeographic reconstructions. Faunal constraints, like those provided by the Cache Creek terrane, can aid in the recognition of longitudinal and latitudinal displacements. Such faunal constraints are, however, unavailable for much of earth history, limiting our ability to test most proposed paleogeographic reconstructions. The use of PTP plots, together with assumptions regarding acceptable plate tectonic speed limits, can, however, help to distinguish between plausible and implausible models of continental assembly and dispersal.

Acknowledgements

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