EPSL
Earth and Planetary Science Letters 193 (2001) 259–272
www.elsevier.com/locate/epsl

The Great Alaskan Terrane Wreck: reconciliation of paleomagnetic and geological data in the northern Cordillera

Stephen T. Johnston *

School of Earth and Ocean Sciences, University of Victoria, P.O. Box 3055 STN CSC, Victoria, BC, Canada V8W 3P6

Received 26 June 2001; received in revised form 19 August 2001; accepted 11 September 2001

Abstract

Paleomagnetic studies place much of the Cordilleran orogen ≥3000 km south, relative to autochthonous North America at 85 Ma. This conflicts with geological studies which have been interpreted to indicate minor displacement. The inability to reconcile these interpretations has precluded understanding the tectonic development of the Cordillera, and has cast doubt on global paleogeographic reconstructions which rely upon paleomagnetic studies. I demonstrate that Alaska and Yukon are divisible into a series of geological belts, including the northerly east–west-trending Arctic Alaska, the central southwest-trending Ruby, the southerly east-trending Dillinger and the southeast-trending Yukon–Tanana belts. Each belt is characterized by four regularly arranged rock sequences; (1) a Paleozoic continental margin strata, (2) a Devonian–Mississippian arc assemblage, (3) an ophiolite, and (4) an Early to mid-Cretaceous arc. These correlations greatly simplify the terrane nomenclature of the northern Cordillera and provide a basis for a new palinspastic reconstruction of the Cordillera. Continuity of the belts can be demonstrated through connecting oroclines, and facing a structural vergence directions vary in a consistent and predictable fashion indicating that the belts previously formed part of a linear ribbon continent. This ribbon continent, referred to here as SAYBIA, originally extended south from eastern Siberia and was ~8000 km long. Northward translation in response to coupling with the Kula plate was accommodated by buckling (oroclinal orogeny) of SAYBIA, much like a derailing train, with scissored 'cars' forming much of Alaska. Oroclinal orogeny makes consistent interpretations of available geological and paleomagnetic data in the Cordillera, provides a means for the rapid construction of continent, and may have been an important process involved in the construction of ancient continental nuclei. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: tectonics; orogen; oroclines; paleomagnetism; terranes; super-continents; North America; Cordillera

1. Introduction

Paleogeographic reconstructions, showing the location of terranes and plate boundaries through time, are essential for understanding (1) orogenic processes, (2) the growth of continents, and (3) the forces that initiate, maintain, and terminate plate motions. The Cordillera of western North America is a relatively young, well studied orogen and should therefore provide us with an excellent opportunity to develop and test models of orogenesis and continental growth. However, there is little agreement concerning the Late Cretaceous

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* Fax: +1-250-721-6200.
E-mail address: stj@uvic.ca (S.T. Johnston).

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PII: S0012-821X(01)00516-7

to early Tertiary paleogeographic evolution of the Cordillera [1–4]. This enduring discrepancy is rooted in conflicting interpretations of geological and paleomagnetic data sets.

Paleomagnetic data for Cretaceous intrusions and layered volcanic and bedded sedimentary sequences of the Intermontane and Insular domains of the Cordillera (Fig. 1) imply that the crust containing these units lay far (2000–3000 km) to the south during cooling and deposition, and require significant Late Cretaceous dextral translation to bring these terranes to their current position [5]. This model, which is sometimes referred to as the Baja BC hypothesis, is consistent with well constrained plate motion models; the Cretaceous and early Tertiary motions of oceanic plates adjacent to the Cordilleran margin included prolonged periods of strongly oblique convergence [6,7], an ideal setting for the entrainment and orogen-parallel translation of crustal blocks. Regional and detailed mapping has, however, yet to reveal the strike-slip faults along which such displacements are inferred to have occurred. Correlation of stratigraphy and structures across those strike-slip faults that have been mapped suggests that they have insufficient offset to account for the paleomagnetic data [8–12]. Either the paleomagnetic data are being interpreted incorrectly, or structures accommodating thousands of kilometers of margin-parallel displacement are being systematically overlooked [13]. If paleomagnetic and geological data cannot be reconciled within this youthful, well studied orogen, it calls into question all Paleozoic and Precambrian paleogeographic reconstructions, which rely heavily on paleomagnetic data [14].

Previously suggested correlations of rock sequences in Siberia, Alaska and Yukon may hold the key to resolution of this enigma. Box [15] suggested that an east–west-trending, north-verging structural stack of rock sequences underlying the Arctic Alaska region of northern Alaska is continuous over a strike distance >4000 km west into Siberia and southeast into Yukon. These sequences include, in descending structural order, a Jurassic to Early Cretaceous oceanic arc, an ophiolitic assemblage, a metamorphic assemblage, and a Paleozoic continental margin sequence. Correlation of these sequences into Siberia and Yukon requires continuity around a number of significant ‘bends’, including a 90° southward bend west through the Seward Peninsula and a complementary 90° westward bend through St. Lawrence Island into the Chukotsk Peninsula of northeastern Siberia. To the east, along the Alaska–Yukon border, the sequences bend >110° south around a broad structural bend. A complementary bend in central–south Alaska of equal magnitude explains the rock sequences wrapping back and continuing southeast through Yukon. Box [15] interpreted most of these bends as being primary features of the Paleozoic continental margin of western North America and suggested that younger terranes draped over this sinuous margin during accretion. Dover [16] similarly recognized these correlations and observed that they described a Z pattern, with an east–west-trending tectonic stack extending across Arctic Alaska that turns down to the southwest and trends southwest across central Alaska before turning back east again into Yukon. Dover [16] interpreted these bends as being a combination of inherited bends of the continental margin and mid-Cretaceous tectonic features. Here I further develop these suggested correlations of rock sequences in Siberia, Alaska and Yukon and describe and reinterpret the bends affecting these sequences (terrane descriptions are taken from Gabrielse and Yorath [17], Plafker and Berg [18] and Monger [12]) (Fig. 1). Based on this analysis I present a testable palinspastic restoration of the northern Cordillera that is consistent with the available paleomagnetic and geological data.

1.1. Correlation of geological belts

Central and northern Alaska is divisible into the northerly east–west-trending Arctic Alaska, the central southwest-trending Ruby, and the southerly east–west-trending Dillinger belts (the three main components of the ‘Z’ pattern described by Dover [16]). A fourth belt, the northwest-trending Yukon–Tanana belt, occurs in east–central Alaska and extends southeast into Yukon (Fig. 1). Each of these belts is characterized by a

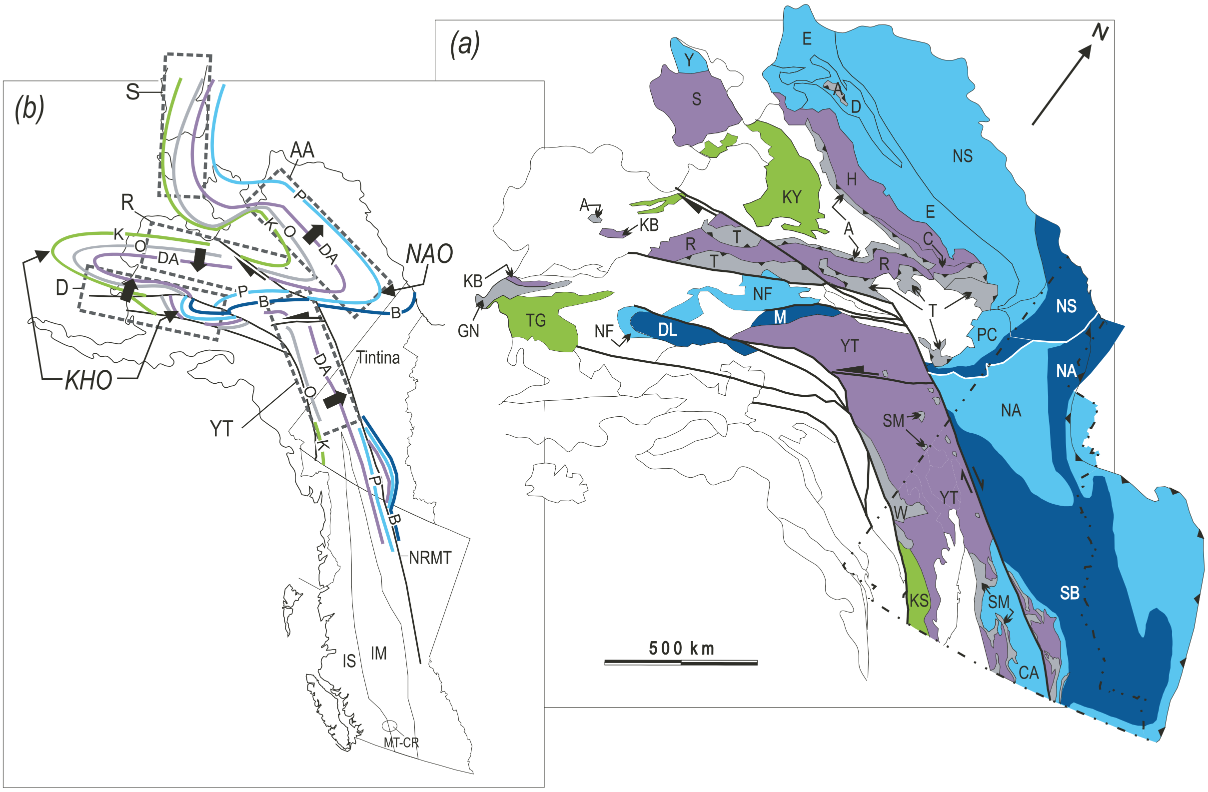

Fig. 1. (a) Lithotectonic map of Alaska and Yukon. Paleozoic platform terranes (light blue) include North America (NA), York (Y), North Slope (NS), Endicott (E) and Delong (D), Porcupine (PC), Nixon Fork (NF), and Cassiar (CA). Paleozoic Basin terranes (dark blue) include parts of NA, NS and PC, Minchumina (M), Dillinger (DL), and Selwyn basin (SB). Devonian–Mississippian arc terranes (purple) include Seward (S), Hammond (H), Coldfoot (C), Ruby (R), Kilbuk (KB), and Yukon–Tanana (YT). Ophiolite terranes (grey) are Angayuchum (A), Tozitna (T), Goodnews (GN), Seventy-mile and Slide Mountain (SM), and Windy McKinley (W). Mid-Cretaceous oceanic arc terranes (green) are Koyukuk (KY), Togiak (TG) and Kluane schist (KS). Terranes of the Insular domain (largely south of the Denali fault) are uncolored, as are areas in Alaska covered by Late Cretaceous and younger sedimentary and volcanic rocks. (b) Inset map showing the correlation of terranes into continuous basin (B), platform (P), Devonian–Mississippian arc (DA), ophiolite (O) and mid-Cretaceous oceanic arc (K) sequences – color-coded as in (a). The sequences together define a series of 'cars' (boxes defined by dashed gray lines), including the Arctic Alaska (AA), Ruby (R), Dillinger (D), and Yukon–Tanana (YT). The AA and R belts are connected through the North Alaskan orocline (NAO), while the R and D belts are connected through the Kulukbuk Hills orocline (KHO). Thick black arrows within each 'car' point in the direction of structural vergence and platform to basin-facing direction. Part of the YT 'car' is cut by and offset along the Tintina – NRMT fault. IM – Intermontane domain; IS – Insular domain; MT-CR – Methow–Tyaughton – Churn Creek region.

regularly arranged sequence of little metamorphosed Paleozoic continental margin strata, an adjacent meta-igneous Devonian–Mississippian arc assemblage, an ophiolitic sequence with both allochthonous and rooted components, and an Early to mid-Cretaceous volcanic-sedimentary succession. The belts are connected through oroclines, and facing and structural vergence directions vary in a consistent and predictable fashion from belt to belt, indicating that they previously formed a coherent linear ribbon continent.

1.1.1. *Arctic Alaska*

The Arctic Alaska belt consists of a northerly, west-trending, Paleozoic continental shelf sequence that was deposited on a Precambrian crystalline basement (Endicott Mountain, Delong Mountain and North Slope terranes). The shelf and basin deposits are little metamorphosed (greenschist and sub-greenschist grade), and are imbricated along north-verging folds and thrusts (Brooks Range). They are in contact to the south with a structurally complex and polymetamorphosed assemblage of middle Paleozoic and Precambrian pericratonic and granitic rocks and Devonian and Mississippian plutonic rocks (Hammond and Coldfoot terranes), which have been interpreted as an Andean-type arc complex [19]. Mid-Cretaceous granites are rare. An ophiolitic assemblage has been thrust over these rocks from the south. The ophiolite is preserved as an allochthonous klippe in a broad synclinorium in the southern Brooks Range (Brooks Range ophiolite in the west and Tozitna terrane in the east), and as a south-dipping root zone (Angayuchum terrane) along the southern margin of the Hammond terrane. Cooling ages on associated metamorphic rocks as old as 192 Ma limit ophiolite emplacement to the Early Jurassic or earlier [20]. Early to mid-Cretaceous immature clastic rocks and andesitic volcanic rocks (Koyukuk terrane), which are part of an oceanic magmatic arc, crop out south of and structurally overlie the Angayuchum terrane.

These sequences trend east–west across northern Alaska. They are traceable to the west through a ~90° bend to the south (looking west), through the Seward Peninsula of westernmost Alaska, and further, through a bend of similar magnitude to the west (looking south), through St. Lawrence Island and into the Chukotsk Peninsula of eastern Siberia. From there, they can be followed > 1500 km further west along the north coast of Siberia [15,21]. To the east along the Alaska–Yukon border, the continental shelf sequence shales out to the north and east. In addition, structural and facies trends are traceable through a ~110° deflection to the south (looking east), referred to as the Northeast Alaskan orocline [22], into the Porcupine terrane. The south–southwest-trending shelf to basin sequence of the Porcupine terrane is truncated to the south against the Tintina fault, an Eocene strike-slip fault across which 420 km of dextral displacement has occurred [23]. The Angayuchum ophiolite and underlying Devonian–Mississippian arc sequences in the 'core' of the orocline exhibit a similar, albeit more abrupt change in trend. The Arctic Alaska belt, including the Porcupine terrane, is in fault contact to the east with Jurassic to Cretaceous clastic strata. These Mesozoic molasse deposits, which separate the Arctic Alaska belt to the west from autochthonous Paleozoic continental margin sequences of ancestral North America to the east, are involved in and affected by the North Alaskan orocline. They therefore limit orocline formation to the Late Cretaceous to Tertiary [24].

Paleomagnetic data from Lower Cretaceous strata (130 Ma) in the northern Arctic Alaska belt imply that the belt lay 12°+5°/−4° (1320+550/−440 km) to the south during deposition, and has since rotated 105° (+49°/−43°) counter-clockwise (cratonic North American reference frame here and in all references to paleomagnetic data) [25]. This paleomagnetic evidence for counter-clockwise rotation of Arctic Alaska belt has previously been cited as evidence in support of models of Arctic Alaska having rotated away from the Canadian Arctic margin, giving rise to the Canada basin [26,27]. Rotation was inferred to have occurred after 130 Ma, the age of the strata studied by Halgedahl and Jarrard [25], but prior to 100 Ma, the inferred age of a secondary remanence in Paleozoic rocks of the Brooks Range which yield a cratonic mid-Cretaceous remanence [25,28,29]. However, this model is inconsistent with the far-sided pole reported by Halgedahl and Jarrard [25] which places the Arctic Alaska terrane far to the south; with the age of oceanic crust underlying the Canada basin (chrons M15 to M19) which limits rifting to the latest Jurassic (Tithonian) to earliest Cretaceous (Barresian) (i.e. ~147–141 Ma); with paleomagnetic studies of the mid-Cretaceous Nanushuk Formation of the North Slope of Alaska that indicate ~10° of northward translation since deposition [30]; and with geological evidence which demonstrates that Arctic Alaska did not rift away from the Canadian Arctic margin [31].

Paleozoic carbonates within the Northeast Alaskan orocline yield a secondary remanent magnetization that post-dates early Late Cretaceous folds and faults and is assumed to be Late

Cretaceous or younger [32]. The paleomagnetic pole defined by these data requires 90° of Late Cretaceous to Tertiary clockwise rotation consistent with the observed involvement of Late Cretaceous sedimentary rocks in the North Alaska orocline.

1.1.2. Ruby belt

The Ruby belt, though structurally complicated by strike-slip faults (Kaltag, Susulatna, Iditarod–Nixon Fork, Tintina), is characterized by the same architecture as the Brooks belt, albeit reversed. The belt trends southwesterly across central Alaska. A southerly Ordovician chert and argillite sequence (Minchumina and Dillinger terranes) passes north into a coeval package of reefal and platformal carbonate rocks (Nixon Fork terrane). Together, these assemblages define a south-facing platform to basin continental margin [33]. A structurally complex crystalline terrane (Ruby terrane) characterized by Devonian–Mississippian intrusions occurs north of the platformal sequence, and has been interpreted as a magmatic arc [18]. Mid-Cretaceous intrusions are also abundant. The crystalline arc sequence and platformal rocks were overthrust from the north by ophiolitic assemblages prior to 145 Ma, the oldest cooling ages in related metamorphic rocks [20]. The latter sequences include allochthonous south-verging klippen preserved in synclinoria (Tozitna and Innoko terranes) and a more northerly, south-verging, north-dipping root zone (Angayuchum terrane) that dips beneath and is structurally overlain by Early to mid-Cretaceous immature clastic and andesitic volcanic rocks (Koyukuk terrane).

The northerly portions of the Ruby belt, including the Early to mid-Cretaceous Koyukuk arc, the Devonian–Mississippian Ruby terrane, and the obducted Angayuchum–Tozitna ophiolite, can be traced northwest through the North Alaska orocline, into correlative sequences in the Arctic Alaska belt. The more southerly platformal and basinal sequences (Nixon Fork and Minchumina terranes) terminate to the northeast in a structurally complex region, and cannot be traced directly into the coeval platform and basin sequences of the Arctic Alaska belt (the Porcupine terrane). To the southwest, the belt is largely covered by younger rocks, or is not exposed. Exposures include an isolated exposure of highly metamorphosed, Precambrian basement (Kilbuk–Idono terrane), which may be the basement to the Devonian–Mississippian Ruby terrane [18]. An isolated exposure of ophiolite characterized by a northwest dip occurs east of and appears to lie structurally above the Kilbuk–Idono terrane, consistent with relationships observed to the east. Paleomagnetic data for the Ruby belt are limited. Paleocene volcanic rocks (Nowitna Volcanics) are characterized by a primary remnant magnetization that is consistent with little or no post-55 Ma latitudinal displacement or rotation relative to North America [34].

1.1.3. Dillinger

The Dillinger belt is deformed by younger strike-slip faulting, most significantly the Denali fault system, and is, to a great extent, covered by extensive younger sedimentary and volcanic rocks. However, restoration of the known movement along the strike-slip faults suggests the following geometry. As in the Ruby belt, a little metamorphosed platform to basin continental margin is recognized (Nixon Fork and Dillinger terranes). However, in contrast to the south-facing platform in the Ruby belt, this platform faces to the north. The south-facing Ruby belt platform to basin transition is traceable directly into the north-facing Dillinger platform to basin transition through a $>120°$ bend to the southeast (looking southwest) of structural trends and lithological boundaries located in the northern Taylor Mountains–southern Sleetmute areas [35] (Fig. 1). This orocline, here referred to as the Kulukbuk Hills orocline, is overlapped by undeformed latest Cretaceous and Tertiary strata and deformation is assumed to have occurred in the Late Cretaceous [35].

The crystalline and ophiolitic components of the Dillinger belt occur along the southwest Alaskan coastline where upper amphibolite to granulite facies, pericratonic Precambrian rocks (Kilbuk terrane) are overthrust from the south along north-verging thrust faults by the Goodnews ophiolite. Volcanic and sedimentary rocks (Togiak terrane), part of an Early to mid-Cretaceous oceanic arc, occur south of, and have in turn been thrust north over the Goodnews ophiolite. Unlike the platformal portion of the Dillinger belt, which can be traced around the Kulukbuk Hills orocline directly into correlative strata in the Ruby belt, the crystalline, ophiolite and mid-Cretaceous arc components continue west into the Bristol Bay and cannot be traced around into the Ruby belt. I assume that, like the continental margin sequences, these sequences are continuous around the offshore portion of the orocline and are continuous with correlative sequences in the Ruby belt. Younger volcanic and sedimentary rocks obscure the eastward continuation of the crystalline, ophiolite and mid-Cretaceous arc components, preventing identification of these sequences south of the continental margin sequences. In addition, the region south of the Kulukbuk Hills orocline is complicated by numerous younger dextral strike-slip faults which may have tectonically removed outboard portions of the Dillinger belt (Fig. 1).

Reliable paleomagnetic data are limited to the results of a study of latest Cretaceous volcanic rocks exposed in North Bristol Bay. These rocks imply that the belt lay 9 ± 7° (1000 ± 700 km) south and has since rotated 43 ± 23° counterclockwise [34].

1.1.4. Yukon–Tanana

The components of the east–northeast-trending Dillinger belt end to the east against the northwest-trending Yukon–Tanana belt. In Alaska, the Yukon–Tanana belt consists primarily of quartzofeldspathic schist and gneiss (Yukon–Tanana terrane). Meta-igneous rocks yield Devonian and Mississippian crystallization ages, consistent with Devonian paleontological ages for interlayered carbonate layers. These rocks are intruded by Late Triassic and Early Jurassic quartz-diorite plutons and mid-Cretaceous quartz monzonite batholiths, and are overthrust from the southwest by ophiolitic assemblages (Seventy-mile terrane) [36]. The Yukon–Tanana belt is continuous to the southeast into Yukon where the Yukon–Tanana terrane lies southwest of imbricated but little metamorphosed platformal rocks of the Cassiar platform, an early Paleozoic continental shelf. The Yukon–Tanana and Cassiar terranes are overthrust by ophiolite (Slide Mountain terrane) emplaced along northeast-verging thrust faults [37–39]. Ophiolite along the southwest margin of the belt (Windy McKinley terrane) may mark the root zone of the Seventy-mile−Slide Mountain allochthons. An offset slice of the belt occurs northeast of the Tintina fault, where Yukon–Tanana and Cassiar terranes are in contact to the northeast with basinal rocks of the early Paleozoic Selwyn basin. Metamorphosed immature clastic sediments (Kluane schist) crop out along the westernmost margin of the Yukon–Tanana belt and provide a record of mid-Cretaceous oceanic arc development southwest of the Yukon–Tanana terrane [40].

The Yukon–Tanana belt terminates to the northwest near the northwesternmost part of the Tintina fault. Rocks in this region include Paleozoic continental margin sequences (Wickersham, White mountains, and Livengood terranes) and overlying Jurassic–Cretaceous molasse (Manley terrane) that can be correlated with autochthonous North American stratigraphy east of the Tintina fault in Yukon [16]. Therefore, Tintina fault appears to have cut across the boundary separating the Yukon–Tanana belt from autochthonous North America, stranding a slice of the belt in Yukon, and carrying along a slice of the autochthon into Alaska. Tintina fault terminates in a complex zone near the confluence with the west-trending Kaltag (130 km dextral strike-slip displacement), west-southwest-trending Susulatna (100 km dextral strike-slip displacement - poorly constrained) and the southwest-trending Nixon Fork (100 km dextral strike-slip displacement) faults [18]. These three sub-parallel dextral faults are inferred to be coeval with, and originate near the termination point of the Tintina fault [18].

The Yukon–Tanana belt intervenes between the Porcupine terrane of the Arctic Alaska belt, and the correlative Nixon Fork and Minchumina terranes of the Ruby belt. In addition, the Yukon–Tanana belt truncates the Dillinger belt. The northwesternmost portion of the Yukon–Tanana belt is characterized by abundant southwest-trending sinistral strike-slip faults, including the Cretaceous to Tertiary Shaw Creek fault which is interpreted to have accommodated 120 km of sinistral displacement and which ends to the northeast against the Tintina fault [36].

Late Cretaceous (70 Ma) flood basalt of the Carmacks Group was erupted onto and unconformably overlies metamorphic and plutonic rocks of the Yukon–Tanana terrane, as well as the northernmost portions of the Intermontane domain, in Yukon. Paleomagnetic studies of this mantle plume-related magmatic sequence [7,41,42] place the Yukon–Tanana belt 1900 ± 700 km south at 70 Ma, near the paleolocation of the Yellowstone hotspot during deposition. The spatial coincidence, similarity of tectonic setting, and lithological and geochemical similarity of the Carmacks Group and Yellowstone volcanic successions suggests that the Carmacks Group is the 70 Ma effusion of the Yellowstone hotspot [7], thus providing a geological pinning point consistent with the paleomagnetic data. Reconstructions of North America in a Pacific plume reference frame at 70 Ma [7] place the Yellowstone hotspot 1000 km west of the current western coast of North America [7], suggesting that the Yukon–Tanana belt was significantly west of North America at the time of Carmacks magmatism.

The Carmacks Group unconformably overlies and ties the Yukon–Tanana belt to the northern Intermontane domain, which is continuous (Fig. 1b) to the south through the length of British Columbia. Paleomagnetic studies of Late Cretaceous volcanic rocks in the Mount Tatlow and Churn Creek areas that overlie strata along the west margin of the Intermontane domain in southern British Columbia place these rocks 3000 ± 500 km south at 85 Ma [43,44]. Paleomagnetic studies of the Slide Mountain terrane in northern British Columbia, where it is thrust over the Cassiar terrane, suggest that it lay 2000 to 2500 km to the south in Permian time [45]. A southerly origin has also been suggested for the Cassiar terrane. Pope and Sears [46] have argued, based on paleontological grounds, that the Cassiar terrane originated >1500 km to the south near the latitude of Idaho in the Lower Cambrian.

To summarize, Alaska and Yukon are divisible into four belts, each of which is characterized by (1) a Paleozoic continental margin sequence, (2) a Devonian–Mississippian arc complex, (3) allochthonous overthrust and rooted ophiolite, and (4) a mid-Cretaceous arc (Fig. 1). These sequences are arranged in a regular fashion; folds and thrust faults verge from the Jurassic–Early Cretaceous arc toward the continental margin rocks. Continental shelf to basin facies transitions face in the same direction (away from the Cretaceous arc). A welcome consequence of this analysis is that the myriad of terranes and sub-terranes identified in Alaska and adjacent parts of Siberia and Yukon are shown to all have originated as parts of only four major rock sequences, thus resulting in a significant simplification of the terrane nomenclature of the northern Cordillera.

The belts are, with the exception of the Yukon–Tanana–Dillinger belts, linked through connecting oroclines (Fig. 1). The Arctic Alaska belt is linked to the west to the Chukotsk Peninsula through two oroclinal bends - one connecting Seward Peninsula and Arctic Alaska, and a second bend through St. Lawrence Island. The Arctic Alaska and Ruby belts, and the Ruby and Dillinger belts are linked through the Late Cretaceous-Tertiary North Alaskan and Kulukbuk oroclines, respectively (Fig. 1).

The structural relationships at the north end of the Yukon–Tanana belt are consistent with a model of lateral, west-directed escape of a crustal wedge (the Dillinger belt) in advance of an indenting block (the Yukon–Tanana belt) [47]. The array of west to west–southwest-trending dextral strike-slip faults (Kaltag, Susulutna, and Nixon Fork–Iditarod) and the more southerly system of southwest-trending sinistral strike-slip faults within the Yukon–Tanana belt (e.g. Shaw Creek), originate near the termination of the Tintina fault. They define a crustal wedge (the Dillinger and leading edge of the Yukon–Tanana belts) that migrated to the west out of the way of the indenting Yukon–Tanana belt. These relationships imply that the Dillinger belt was, prior to displacement along the Tintina fault, continuous with the north end of the Yukon–Tanana belt. Escape of the Dillinger belt to the west accommodated displacement of the Yukon–Tanana belt along the Tintina fault and allowed penetration of the Yukon–Tanana indentor into but not through the Ruby belt. Collision of the Yukon–Tanana belt resulted in the separation of the originally continuous continental margin sequences of the Arctic Alaska (Porcupine terrane) and Ruby (Nixon Fork and Minchumina terranes) belts.

Paleomagnetic data, though complicated by the lack of primary remnant magnetism in both mid- and Late Cretaceous rocks from all the belts, imply that increasingly far-sided paleo-poles characterize the more southerly belts. Thus, displacement of the Arctic Alaska belt (1320+550 km/ −440 km) is less than that of the Yukon–Tanana belt and attached strata to the south (3000 ± 500 km south at 85 Ma, and 1900 ± 700 km south at 70 Ma). Rotations required by the paleomagnetic data include counter-clockwise rotation of Arctic Alaska, clockwise rotation of strata within the North Alaskan orocline, significant counter-clockwise rotation of the Dillinger belt, and little rotation of the Yukon–Tanana belt.

1.2. Oroclinal orogeny

The shared architecture and geological evolution, the continuity of the belts, structural relationships (oroclines and escape structures), together with paleomagnetic data, indicate that the belts originated as an elongate linear 'ribbon continent' hereafter referred to as SAYBIA (Siberia–Alaska–Yukon–British ColumbIA) that extended south from the Chukotsk Peninsula into the paleo-Pacific ocean basin, and which was separated from autochthonous North America by a narrow basin. The current geometry of SAYBIA is the result of oroclinal orogeny – the buckling of the ribbon continent about vertical axes of rotation.

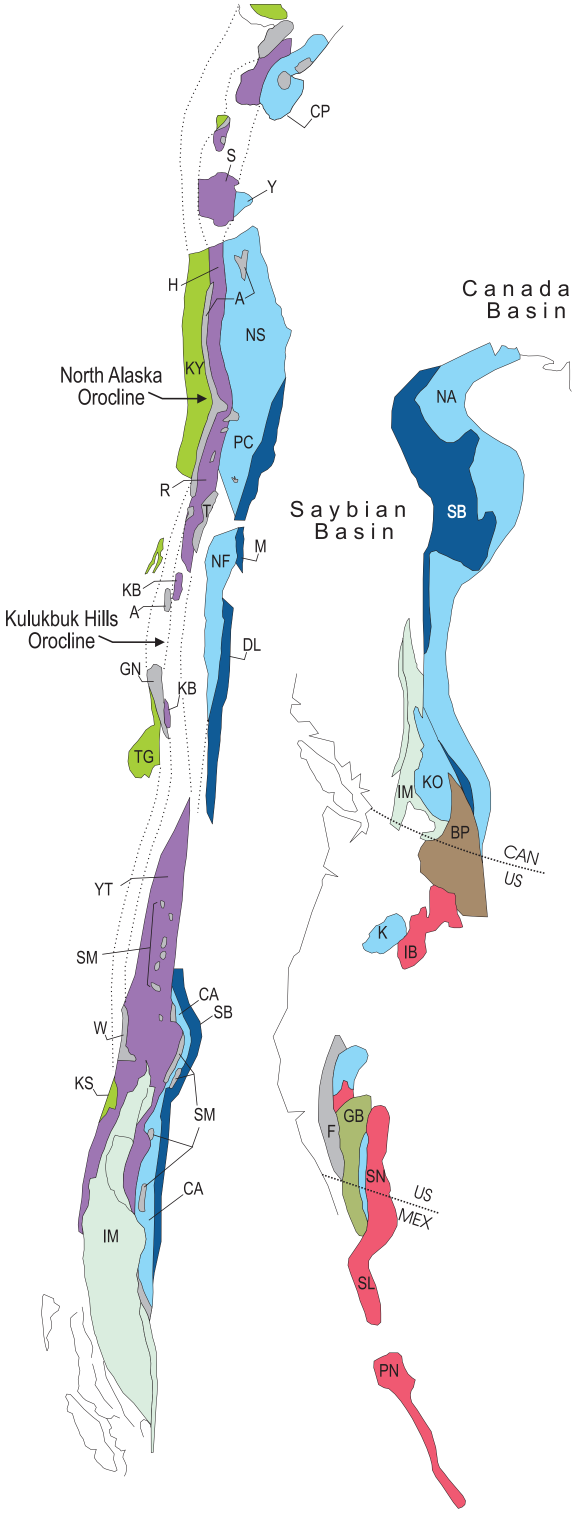

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Fig. 2. Palinspastic restoration of SAYBIA to its geometry at 85 Ma, the age at which northward translation was initiated. Color coding and letters indicating terrane and lithotectonic package names are as in Fig. 1. Additional designations include the Chukotsk Peninsula (CP), Kootenay (KO), Belt–Purcell (BP), and Klamath (K) terranes. The paleomagnetically determined positions of the Idaho (I), Sierra Nevada (SN), Salinian (SL), and Peninsular (PN) batholiths and the Great Basin (GB) (taken from Cowan et al. [4]) are also indicated.

Buckling and related northward translation postdates the mid-Cretaceous accretion of the oceanic Koyukuk arc, and had largely ended by the deposition of Paleocene sedimentary rocks on the Ruby and Dillinger belts that yield concordant paleomagnetic poles. Early Eocene displacement along the Tintina fault appears to have been the final stage of northward displacement.

Restoration of the SAYBIA to its original linear geometry (Fig. 2) restores southern British Columbia 3000 km south to the latitude of central Mexico (assuming that the Chukotsk Peninsula portion of SAYBIA remains fixed), and shows that the core of the ribbon continent is a Paleozoic carbonate platform (Arctic Alaska–Nixon Fork–Cassiar terranes) that faced east toward a shale basin (Porcupine–Minchumina–Dillinger terranes). The east (North American) side of this basin consists of autochthonous strata of Selwyn basin and Kechika trough. These features indicate that SAYBIA originated as an elongate continental ribbon or strip that rifted from the North American craton probably in the Cambrian, the age of initial rifting in, and formation of, the Selwyn basin [48].

The SAYBIA ribbon continent, including the Siberian continuation of the belts established here, was over 8000 km long and was probably no where wider than about 500 km. No comparable modern ribbon continent currently exists. Japan, which is characterized by a thin but continuous strip of continental basement that was rifted from the Asian margin, is about one quarter the length of SAYBIA, and provides the closest thing to a modern analogue. A ribbon continent of comparable dimensions to SAYBIA (> 9000 km long and no where wider than 500 km), referred to as the Cimmerian strip continent [49], rifted from the northern margin of Gondwanaland in the latest Mississippian, swept north across the Tethyan basin, and subsequently accreted to the southern (Eurasian) margin of Laurasia during the latest Permian/earliest Triassic [49]. The tectonic impetus for the rifting of such elongate, narrow continental ribbons remains unclear.

The Devonian through mid-Cretaceous evolution of SAYBIA was dominated by interaction with oceanic plates of the paleo-Pacific basin lying west of the archipelago. An Andean arc (Coldfoot–Ruby–Kilbuk–Yukon–Tanana terranes) was emplaced upon the west side of the SAYBIA archipelago in the Devonian–Mississippian. Subsequent ophiolite (Angayuchum–Tozitna–Goodnews–Seventy-mile–Slide Mountain–Windy McKinley terranes) obduction onto the archipelago from the west occurred in the Triassic–Jurassic. Collision in the Early to mid-Cretaceous emplaced a mid-Cretaceous oceanic arc (Koyukuk–Togiak terranes) onto the western margin of SAYBIA.

Northward translation of SAYBIA was initiated at about 85 Ma when the oceanic Farallon plate, which floored most of the northern Pacific basin, rifted into a northerly Kula plate and a southerly Farallon plate [6]. Displacement of SAYBIA was facilitated by coupling with the Kula plate, which was characterized by rapid (> 10 cm/a) northward motion relative to autochthonous North America [6,7]. Alternatively, SAYBIA may have initially been entirely embedded within the Kula plate. The rapid northerly motion of the Kula plate suggests that it was continuous with old oceanic crust being subducted to the north. The geometry and location of this subduction zone is broadly constrained to having lain along the northeastern margin of Asia, as indicated by the presence of Late Cretaceous to Tertiary volcanic arcs within this region (for instance the Campanian and younger portions of the East Sikhote–Alin, Okhotsk–Chukotka and Kamchatka–Koryak magmatic arcs). However, the relationship of this subduction zone relative to SAYBIA remains to be resolved. Buckling of SAYBIA appears to have begun almost immediately after the initiation of northward displacement. Thus the leading (Siberian) northern edge of SAYBIA was either already firmly pinned to or was only a short distance removed from the Eurasian plate at 85 Ma. This fixed or pinned northern edge of SAYBIA acted as a buttress behind which the northward-translating, southerly continuation of SAYBIA buckled (Fig. 3).

The ribbon continent deformed in a fashion similar to that of a derailing train. The Arctic Alaska, Ruby, Dillinger and Yukon–Tanana belts

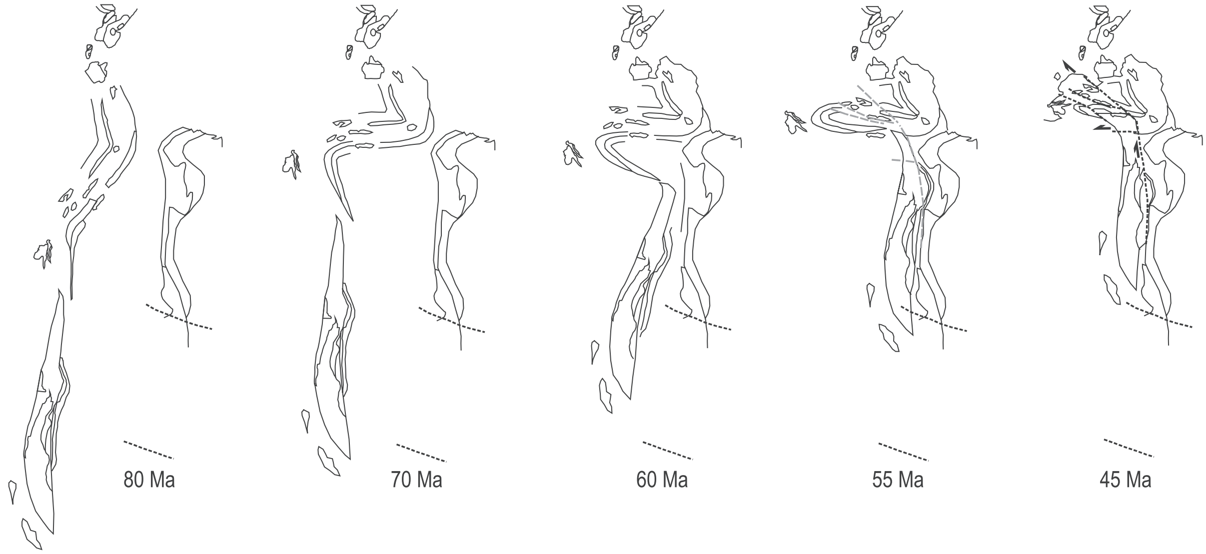

Fig. 3. Schematic paleogeographic maps showing, from left to right, northward migration and buckling of SAYBIA. See Fig. 2 for identification of all terranes. Age, shown at the bottom of each panel, is approximate. The first frame (80 Ma) is from 5 Myr after the commencement of northward motion, with buckling already initiated. For reference, the Mexico–US and US–Canada borders (dark dashed lines) are indicated in each frame. Gray dashed lines in the second last frame (55 Ma) are incipient faults (dextral Tintina, Kaltag, Nixon Fork–Iditarod, and Susulatna, and the sinistral Shaw Creek). Dashed solid lines with associated arrows in the last frames show locations of these faults after movement.

comprise the 'cars' involved in the derailment. The leading Chukotsk Peninsula–northern Siberia 'car' remained fixed and undeformed during the terrane wreck, while the southward continuation of the Cordillera through British Columbia formed the trailing cars. Derailment resulted in 'scissoring' or jack-knifing with the Arctic Alaska and Dillinger 'cars' rotating counter-clockwise, while the intervening Ruby car rotated clockwise. The trailing Yukon–Tanana car, which crossed over the Yellowstone hotspot during northward translation giving rise to the Carmacks Group flood basalts, continued north into the collision zone, causing detachment and westward escape of the Dillinger car. This allowed the Yukon–Tanana car to penetrate into, but not through the Ruby car. The cessation of northward movement of the Yukon–Tanana car marked the end of the Great Alaskan Terrane Wreck (Fig. 3).

Much of the debate concerning the conflict between paleomagnetic and geological data has focussed on the lack of an identifiable strike-slip fault or fault system with thousands of kilometers of dextral displacement [50]. Three aspects of the model presented here explain the absence of such a fault system: (1) margin-parallel shortening in the northern portion of the Cordillera was accommodated by buckling of the Saybian ribbon continent (oroclinal orogeny), not by displacement of a rigid crustal block along a discrete strike-slip fault – hence the lack of an identifiable strike-slip fault in Yukon and Alaska is because one never existed; (2) the buckling of SAYBIA resulted in the tectonic juxtaposition of shale facies rocks from the west margin of the basin that separated SAYBIA from the autochthon, against shale facies rocks of the autochthon, effectively masking the faults separating SAYBIA from the autochthon; and (3) northward translation was coeval with shortening in the foreland, including the formation of the Rocky Mountain and Mackenzie foreland fold and thrust belts. Therefore, strike-slip faults accommodating the northward translation of the southern portion of SAYBIA would have been progressively carried inboard, away from their root zones resulting in the eventual cessation of strike-slip movement along these faults [51]. Drag along the basal detachment would have resulted in tilting of the abandoned strike-slip faults toward the foreland, orienting them favorably for reactivation as thrust faults. This begs the question – did many of the thrust faults within the hinterland portion of the Mackenzie and Rocky Mountains originate as strike-slip faults?

This model does not predict the location of the boundary between SAYBIA and the autochthon in the southern Cordillera. In Fig. 2 the eastern margin of SAYBIA is depicted as running down or east of the Northern Rocky Mountain Trench (NRMT) to the south end of the NRMT, where it is offset to the west into the southern Cache Creek terrane. There the margin is continued south to the San Juan islands where it intersects the current continental margin (Fig. 2). However, it seems just as likely that, as in Alaska and Yukon, the eastern margin of SAYBIA continues south within the Paleozoic shale facies rocks along the entire length of the Cordillera.

An implication of this model is that Alaska did not exist prior to 85 Ma, and that construction of much of the state, which covers an area >1.4 million km^2, occurred during a brief 30 Myr interval extending from 85 to 55 Ma (Fig. 3). Thus, oroclinal orogeny provides a means for the rapid construction of large, equidimensional microcontinents from linear crustal belts. Geochemical studies indicate that continental lithosphere could have been the product of arc magmatism [52]. However, it has remained unclear how linear magmatic arcs could give rise to equidimensional cratons, or how coherent cratons appeared relatively suddenly in the Archean. Oroclinal orogeny in response to the collision of magmatic arcs provides a means for the rapid construction of cratons from arcs, and explains the granite–greenstone geometry of Archean cratons as the buckled remains of formerly linear arcs, as opposed to numerous sequentially accreted distinct arc terranes. The current collision of the northward migrating Izu Bonin arc with the Honshu arc in the western Pacific may be a modern analogue for this process – buckling of these arcs in response to collision could provide us with Earth's next craton.

2. Conclusions

Previously recognized correlations of rock sequences in Siberia, Alaska and Yukon [15,16] were largely attributed to wrapping of younger accreted terranes around a pre-existing sinuous continental margin. However, a model of Late Cretaceous to early Tertiary oroclinal orogeny in the northern Cordillera best explains these correlations, structural relationships and paleomagnetic data. This model, which has significant implications for the formation of cratons, is testable through further paleomagnetic studies of the 'cars' involved in the Great Alaskan Terrane Wreck; faunal, geochronological and geochemical checks of correlations within SAYBIA; structural studies of the oroclinal hinge zones; and focused studies aimed at locating the faults along which SAYBIA and the autochthon are juxtaposed. Additional research is needed to understand the pre-85 Ma history and kinematics of SAYBIA. For instance paleomagnetic data indicate that SAYBIA occupied much the same latitude as North America from Permian to Jurassic time and again during the mid-Cretaceous [5,53]. This implies that SAYBIA may have 'shunted' back and forth along the margin for a considerable period of time prior to its involvement in the Great Alaskan Terrane Wreck. Application of oroclinal orogeny in analysis of orogenic belts characterized by conflicting interpretations of paleomagnetic and geological data, for instance the Carpathian–Aegean region; of orogenic belts characterized by significant bends in otherwise continuous rock sequences, for instance the Kolyma Mesozoids of northeastern Siberia; and of Precambrian granite–greenstone terranes, will comprise a broader test of this model.

Acknowledgements

This manuscript is based in part on research funded by NSERC, Lithoprobe (SNORCLE transect), and Yukon Geology Program research grants to the author. Logistical support was provided by the GSC through the Ancient Pacific

Margin NATMAP, and by the Yukon Geology Program. Drafting assistance was provided by Kyle Larson. I have benefited from discussions with, and advice provided by Grant Abbott, Judith Baker, Chris Barnes, Dante Canil, Maurice Colpron, Randy Enkin, Philippe Erdmer, Craig Hart, Ted Irving, Larry Lane, Brian Mahoney, Mitch Mihalynuk, Jim Monger, Don Murphy, Derek Thorkelson, Clint Tippett and Jane Wynne. Constructive reviews of earlier versions of this manuscript were provided by Chris Barnes, Dante Canil, Randy Enkin, Ted Irving, Mitch Mihalynuk and Derek Thorkelson. Comments by journal reviewers Andrew Hynes and Darrel Cowan greatly improved the final product. Editorial guidance was provided by Rob Van der Voo. This is Lithoprobe contribution 1243.*[RV]*

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