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Cache Creek terrane entrapment: Oroclinal paradox within the Canadian Cordillera

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Abstract. Exotic and far-traveled oceanic crustal rocks of the Cache Creek terrane (CC) are bordered by less exotic Quesnel (QN) and Stikine (ST) arc terranes to the east, north, and west. All of these terranes are enveloped by an arcuate belt of displaced continental margin rocks; the Kootenay (KO), Nisling (NS), and parts of the Yukon-Tanana (YTT) terranes, that have indirect ties to ancestral North America (NA). Initial ^{87}Sr/^{86}Sr isopleths conform to this arcuate pattern. Such a pattern of concentric belts presents a geological conundrum: How did the QN, ST, and CC come to be virtually enveloped by terranes with ties to NA? Past and current models that explain assembly of the Canadian Cordillera are deficient in their treatment of this problem. We propose that Early Mesozoic QN and ST were joined through their northern ends as two adjacent arc festoons that faced south toward the Cache Creek ocean (Panthalassa?). Oceanic plateau remnants within the CC today were transported from the Tethyan realm and collided with these arcs during subduction of the Cache Creek ocean. Counterclockwise oroclinal rotation of ST and NS terranes in the Late Triassic to Early Jurassic caused enclosure of the CC. Rotation continued until these terranes collided with QN in the Middle Jurassic. Paleomagnetic declination data provide support for this model in the form of large average anticlockwise rotations for Permian to Early Jurassic sites in ST but moderate clockwise rotations for sites in QN. Specific modern analogues for the Cordilleran orocline include the Yap trench, where the Caroline rise is colliding end-on with the Mariana Arc and the Banda Arc, located on the southeastern "tail" of the Asian plate, which is being deformed into a tight loop by interactions with the Australian and Pacific plates.

Introduction: The Cache Creek Terrane Problem

The Cache Creek terrane (CC) is a composite oceanic terrane distinct from its neighbors (see Table 1). Salient features that bear on its evolution and tectonics include the following: (1) it is host to a distinctive Tethyan fauna featuring Verbeekinid fusilinids, as opposed to exclusively Swagerinid fusilinids in adjacent terranes of this age [*Monger and Ross*, 1971]; (2) it hosts blueschists [*Paterson and Harakal*, 1974; *Gabrielse*, 1991]; (3) it was produced in an oceanic environment from Early Mississippian to Middle Jurassic times, the last vestige of perhaps 6000 km of consumed oceanic crust [*Cordey et al.*, 1991]; (4) CC sedimentation was not strongly influenced by continental sources until the Late Triassic when the first coarse, quartz-rich clastics were deposited on it; and (5) CC magmatic components show no indication of evolved crustal influence until at least Cretaceous time [*Mihalynuk et al.*, 1992].

Although of oceanic and probably far-traveled origin, the CC lies within the Intermontane Superterrane [*Monger et al.*, 1982], enclosed between arc terranes with North American-influenced faunas (Quesnel (QN) and Stikine (ST)) and displaced continental margin terranes (Kootenay (KO), Nisling (NS), and parts of Yukon-Tanana (YTT); Table 1 and Figure 1). Increasing evidence has emphasized linkages between ancestral North America (NA), displaced continental margin terranes, and middle to late Paleozoic basement of both ST and QN.

Some lines of evidence for the loose linkage among NA and displaced continental margin terranes, particularly NS terrane, date to pre-Devonian times. From oldest to youngest these include (1) detrital zircons within pre-Devonian strata that are most reasonably derived from cratonic North America [*Mortensen*, 1989, 1992; *Gehrels et al.*, 1990, 1991]; (2) Devono-Mississippian magmatism that affects pericratonic terranes and the margin of NA, alike [e.g., *Rubin et al.*, 1991]; (3) evolved isotopic compositions indicate an old crustal component within NS (^{87}Sr/^{86}Sr$_i$) [*Armstrong*, 1988] (Figure 1) and εNd [*Samson et al.*, 1991]); and (4) presence of an arcuate belt of Late Triassic to Early Jurassic plutons that intrude the YTT and correlative terranes to the east and pericratonic or displaced continental margin terranes to the north and west of CC [*Wheeler and McFeely*, 1991].

Linkages between continental margin terranes and ST/QN include from oldest to youngest (1) apparent stratigraphic continuity between the Paleozoic Stikine Assemblage and underlying siliciclastic strata of the NS [*McClelland*, 1992]; (2) Mississippian zircons with inherited older lead that have been obtained from ST magmatic units [*Sherlock et al.*, 1994]; (3) Permian McCloud fauna strata that occur in both ST and terranes along the western margin of NA [e.g., *Miller*, 1987; *Stevens and Rycerski*, 1989]; (4) Upper Triassic metamorphic detritus, probably of Nisling terrane derivation [*Werner*, 1977; *Bultman*, 1979; *Mihalynuk and Mountjoy*, 1990], displaying an evolved εNd signature [*Jackson et al.*, 1991] and deposited on the ST; (5) Upper Triassic ST strata in northwestern British Columbia and southwestern Yukon locally containing abundant metamorphic clasts presumably derived from the Nisling terrane [*Bultman*, 1979; *Mihalynuk and Rouse*, 1988; *Hart and Radloff*, 1990; *Jackson et al.*, 1991]; and (6) Early Jurassic magmatic units at several localities within ST providing indications of Proterozoic to Archean crustal contamination [*Bevier and Anderson*, 1991; J. Mortensen, personal communication, 1992].

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Table 1. Abbreviations Used in Text

Abbreviation	Definition
Continental or Displaced Continental Margin	
NA	Ancestral North America
CA	Cassiar terrane
NS	Nisling terrane
Pericratonic Terranes	
KO	Kootenay terrane
Accreted Terranes	
AX	Alexander terrane
CC	Cache Creek terrane
QN	Quesnel terrane
SM	Slide Mountain terrane
ST	Stikine terrane
WR	Wrangellia terrane
Terranes of Mixed Affinity	
YTT	Yukon-Tanana terrane
DY	Dorsey terrane

Terranes modified after *Wheeler and McFeely* [1991] and *Mortensen* [1992].

Although unequivocal proof is lacking, these data collectively suggest that the early Mesozoic and probably the Paleozoic arcs of ST and QN were built flanking continental margin terranes. If so, then the YTT and ST were a single, linked paleogeographic entity at least in Late Triassic time and possibly much earlier. That this entity lay outboard of the CC is the crux of the Cache Creek problem. Earlier models of terrane accretion address some aspects of this problem, but none provides a full solution. In this paper we review earlier attempts at solving the Cache Creek problem in light of recent geologic, isotopic, and revised paleomagnetic data and further develop the oroclinal enclosure model briefly outlined by *Nelson and Mihalynuk* [1993].

Previous Solutions

In the two decades since *Monger et al.* [1972] recognized that most rocks within and west of the Intermontane Belt are allochthonous with respect to NA, many models have been developed to explain their distribution. We outline milestones within this tectonic model evolution as they pertain to development of the oroclinal enclosure model.

Anvil Ocean: Collapse of Rifted Continental Margin

One of the earliest attempts to explain the distribution of terranes in the northern Canadian Cordillera is the collapsed continental rift model of *Tempelman-Kluit* [1979]. This model proposes that a sliver of the continental margin (YTT) was rifted away from ancestral North America forming the Anvil ocean. Subsequent reduction of the Anvil ocean by subduction beneath YTT formed parts of the Stikine arc. Final closure of the Anvil ocean resulted in obduction of part of the oceanic crust and mantle (Slide Mountain terrane (SM) and CC) and reunion of the continental margin sliver with North America. However, CC and SM are now recognized as distinct entities in several respects. (1) They occupy unique structural positions with respect to other terranes. (2) They host Permian Tethyan versus non-Tethyan faunas, respectively. (3) Each displays its own characteristic internal structural style [*Monger and Ross*, 1971; *Monger*, 1977a; *Monger and Price*, 1979; *Monger et al.*, 1991]. The Anvil ocean model omits these important distinctions; in particular it does not provide a means for the introduction of strata with Tethyan faunas, which are sandwiched between less far traveled terranes.

Northward Translation of Terranes: Application of Paleomagnetism

Coney et al. [1980] and *Monger and Irving* [1980] proposed that the Cordillera is built up of terranes that were swept up against and accreted to the convergent western margin of NA (Figures 1 and 2a). Synaccretionary and postaccretionary, transcurrent slippage between terranes explained thinning and anomalous thickening of terranes as they shuffled along the Cordilleran margin.

This model was supported by early paleomagnetic studies in the Cordillera [*Packer and Stone*, 1974] that revealed aberrant paleopoles explained by hundreds to thousands of kilometers of northward translation. Displacements of tectonic elements in the Cordillera appeared to increase from the inner to the outer terranes, and all displayed variable amounts of rotation. Clockwise rotations were most commonly recorded, giving rise to the "ball bearing" hypothesis that invoked rotations combined with small northerly translations [e.g., *Beck*, 1976], resulting from dextral shear between NA and oceanic plates. However, *Monger and Irving* [1980] demonstrated that ST paleopoles were consistent with anticlockwise rotations and northward translation of about 1300 km from Late Triassic to Cretaceous time, inconsistent with the dextral ball bearing hypothesis.

A revision of the timescale [*Harland et al.*, 1990] and the Early Jurassic reference poles for North America [*Hodych and Hayatsu*, 1988] called for a reinterpretation of the Early Jurassic paleomagnetic database [*May and Butler*, 1986]. A reevaluation of Lower Jurassic ST volcanic strata in light of the new constraints showed ST and NA to be latitudinally concordant [*Vandall and Palmer,* 1990]. Reinterpretation of data from a variety of other sources consistently indicated that from the Permian to Early Jurassic time, ST and QN were at much the same latitude with respect to NA as they are today. Large anticlockwise rotations were found typical of terranes outboard of CC, while clockwise rotations are more characteristic of those inboard.

Latitudinal translations of thousands of kilometers which might account for the juxtaposition of contrasting North American and exotic Tethyan faunal realms within the Cordilleran collage are now incompatible with paleomagnetic data. Furthermore, it is difficult to reconcile such large latitudinal displacements with an apparently continuous belt of pericontinental rocks that wraps around northern ST and CC (Figures 1 and 2b).

Megathrusting

The existence of evolved continental margin rocks in the Coast Mountains (NS), contrasting with the more primitive isotopic character of inboard ST and the CC, recently has led several authors to suggest that ST and CC comprise an enormous thrust sheet (now a klippe, Figure 2c) emplaced 175 to 400 km

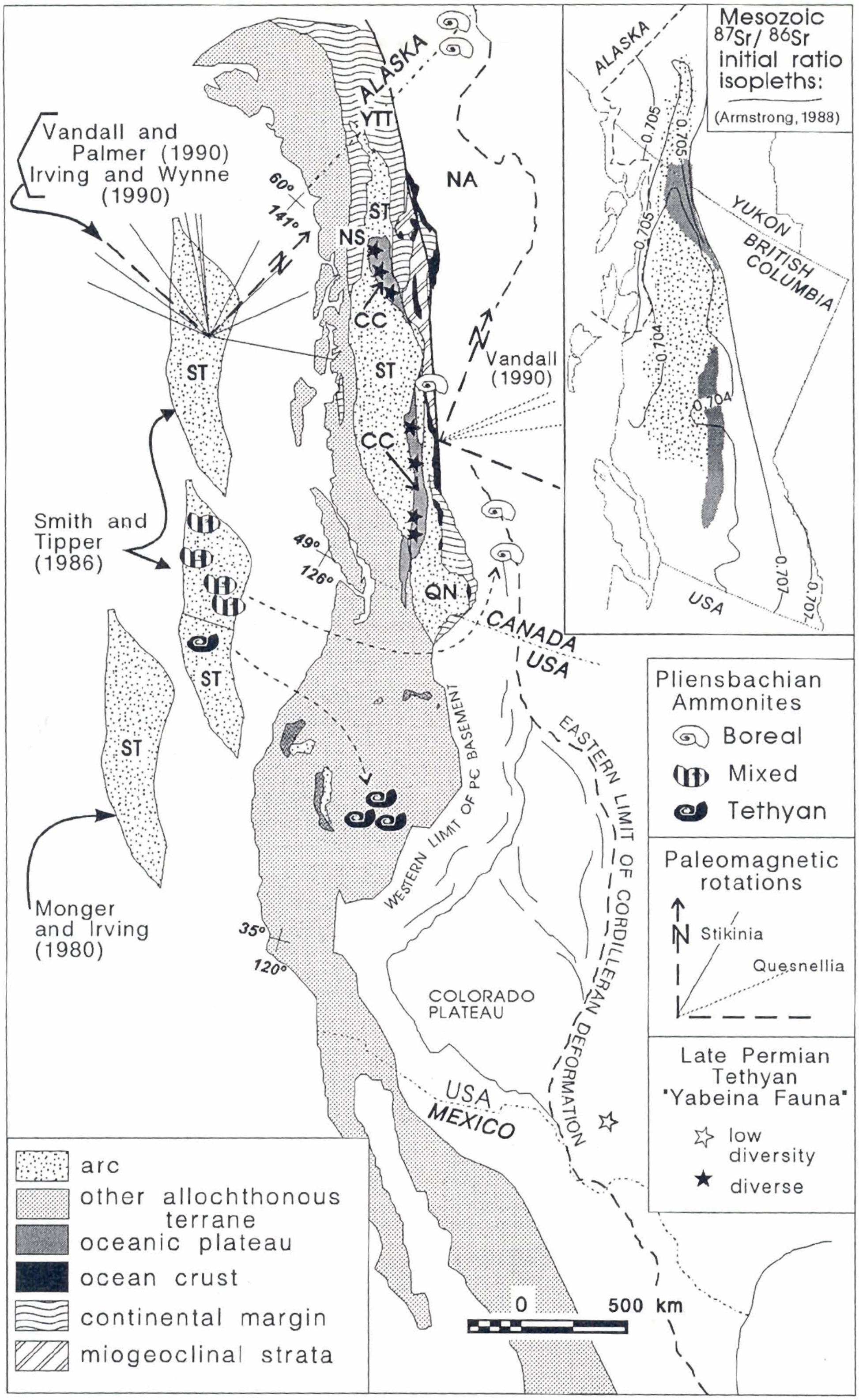

Figure 1. Generalized terrane map of the Cordillera showing Cache Creek faunas, initial $^{87}Sr/^{86}Sr$ isopleths [*Armstrong*, 1988], offset of biogeographic zonations, and paleomagnetic rotations for Stikinia and Quesnellia.

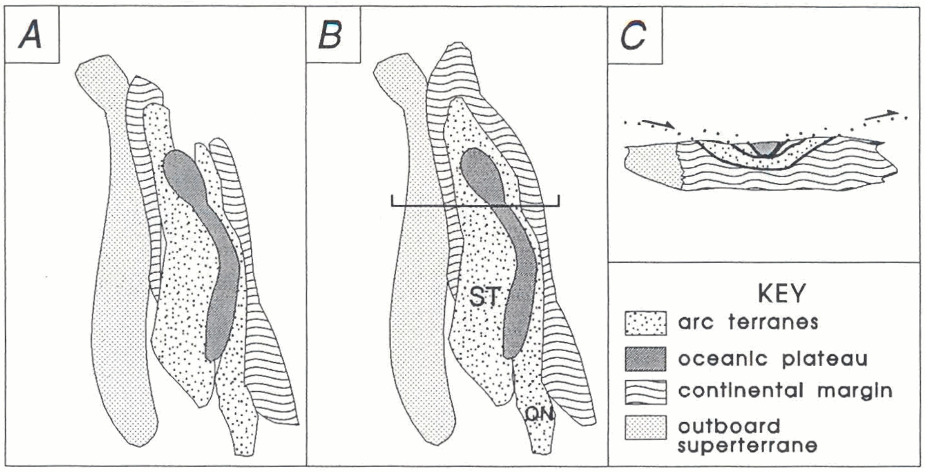

Figure 2. (a) Diagrammatic terrane associations based on the classical stacked cards on edge model of the northern Canadian Cordillera. (b) A more representative depiction of terrane configurations showing continental margin terranes as they wrap around the northern end of Stikine and Quesnel arc terranes, which in turn envelope the Cache Creek terrane. (c) A schematic cross section displaying the fundamental tenet of the overthrust model with emplacement of Cache Creek and Stikine-Quesnel terranes atop displaced continental margin. Crustal cross-section location is shown in 2b.

eastward over the ancestral continental margin [*Coney*, 1989; *Samson et al.*, 1991; *Gehrels et al.*, 1991]. The timing constraints implied by this model are awkward. Presumably the megathrust occurred following Early to Middle Jurassic time, the age of the youngest oceanic sediments in the CC and widespread isotopically primitive [*Samson et al.*, 1989] volcanism in ST; yet ST and NS were apparently loosely linked by the Late Triassic and perhaps earlier as described above. Modeling of CC as a klippe resting on continental margin is not supported by isotopic data from postkinematic Middle Jurassic plutons that intrude the western margin of northern CC and which show no evidence of inheritance from an old, isotopically evolved source [*Mihalynuk et al.*, 1992]. Finally, the model does not explain similarities between ST and QN but necessitates that they be isolated during their genesis.

Rotational Closure of ST Against QN and Oroclinal Development

Linkages between northern QN and ST and the YTT suggest that successive late Paleozoic, Triassic, and Early Jurassic arcs lapped over the edges of the YTT. In latest Paleozoic to Triassic time, ST and QN were two adjacent arcs, facing southward toward the Cache Creek ocean (Figure 3a). Yet these arcs must have remained sufficiently widely separated from early Late Permian to Late Triassic time to permit emplacement of the Cache Creek oceanic plateaus with associated exotic faunas. In our reconstructions we show a 120° angle between the two limbs during this interval (Figure 3b). This is approximately the present average angle between major arc segments in the western Pacific. Impingement of the CC oceanic plateaus at the QN-ST arc cusp in Late Permian to Late Triassic time established it as a hinge zone and caused deformation in the YTT (Figure 4a).

A continuation of seafloor spreading behind the ST arc, which began in the Devonian with the creation of the Slide Mountain basin, caused ST to rotate counterclockwise. This progressively reduced the angle between ST and QN arc segments and eventually isolated Cache from Panthalassa in Early Jurassic time (Figure 5a). For an outer limb 1600 km long (combined length of ST and YTT), rotation through 120° in 70 million years (250-180 Ma) implies a geologically reasonable maximum rate of travel of 5 cm/year.

Final collision of ST with QN in the Middle Jurassic entrapped CC remnants, including the exotic, far-traveled oceanic plateaus and produced a two-sided, doubly verging orogen (Figure 6a). Also related are synchronous cessation of arc volcanism in both ST and QN; thrust emplacement of QN eastward over the North American continental margin; and development of westerly verging structures in both eastern ST and in the YTT, west of the Middle Jurassic hinge line.

In the paragraphs that follow we describe geological constraints and suggest modern analogues for each stage of a four-stage hypothetical history for the Mesozoic orocline. Three regions are highlighted; the inner limb (QN), the outer limb (ST), and the hinge (YTT plus northernmost QN and ST). CC events are described where they define interactions with QN, YTT, or ST, such as during the formation of flanking accretionary complexes.

Geological Constraints

Spatial extents of structural, stratigraphic, and magmatic units within the northern Cordillera that constrain the model during each one of the preceding time slices are presented in Figures 7 through 10. Distribution of geologic elements is based on their present spatial relationships. No attempt has been made to palinspastically restore the Cordillera. Lithologic and chronostratigraphic comparison of limb and hinge zones are shown in Figure 11, along with Permian to Jurassic stage names, which are referred to below.

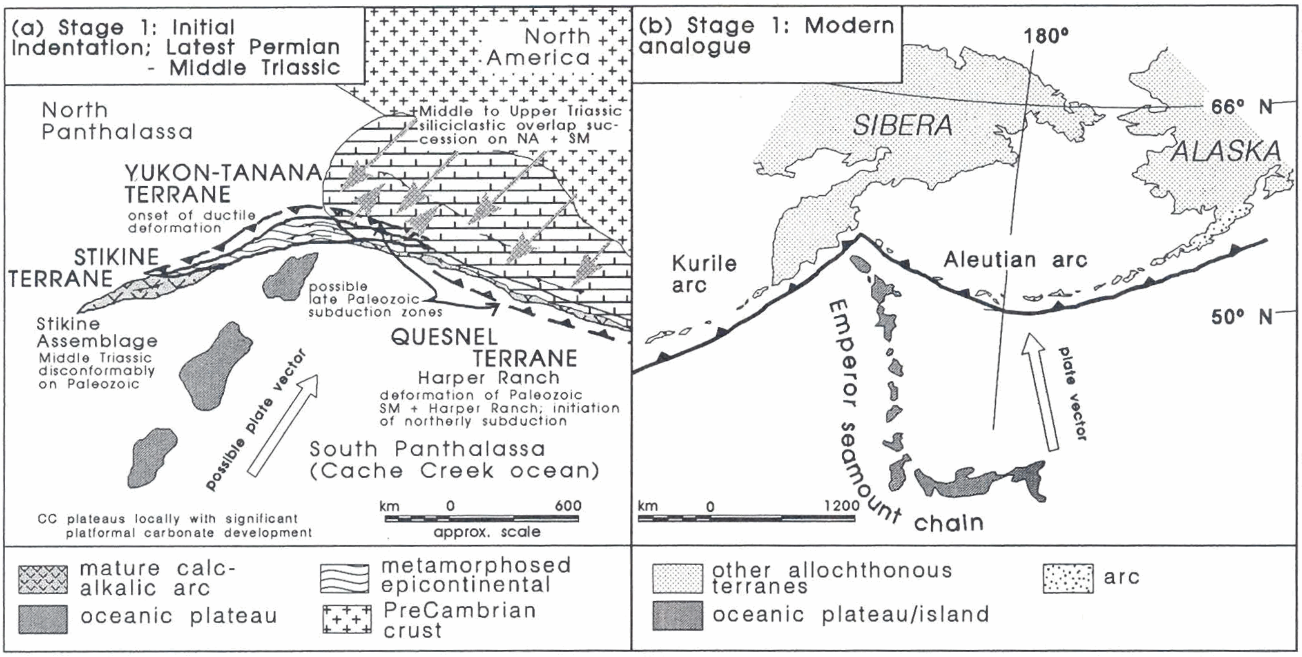

Figure 3. (a) Latest Permian to Middle Triassic arrangement of tectonic elements predicted by the model. (HR indicates the Harper Ranch assemblage.) (b) Modern analogue for this stage of the oroclinal development with the Emperor Seamount chain impinging on the cusp between the Kurile and Aleutian arcs.

Stage 1: Initial Impingement (Latest Permian to Middle Triassic) (Figures 3 and 7)

Inner limb. Terrane amalgamation and increasing proximity to NA mark this phase of the evolution of QN. Youngest rocks within the Lay Range arc and SM are Early to Late Permian [*Ferri et al.*, 1993; *Orchard and Foster*, 1988]. Both of these terranes are overlain by a Middle to Upper Triassic deepwater siliciclastic sequence consisting dominantly of dark grey to black slate, limestone, and quartz-rich siltstone and sandstone (from south to north in Canada: Slocan Group, basal Takla Group, Slate Creek Formation, and Table Mountain sediments within

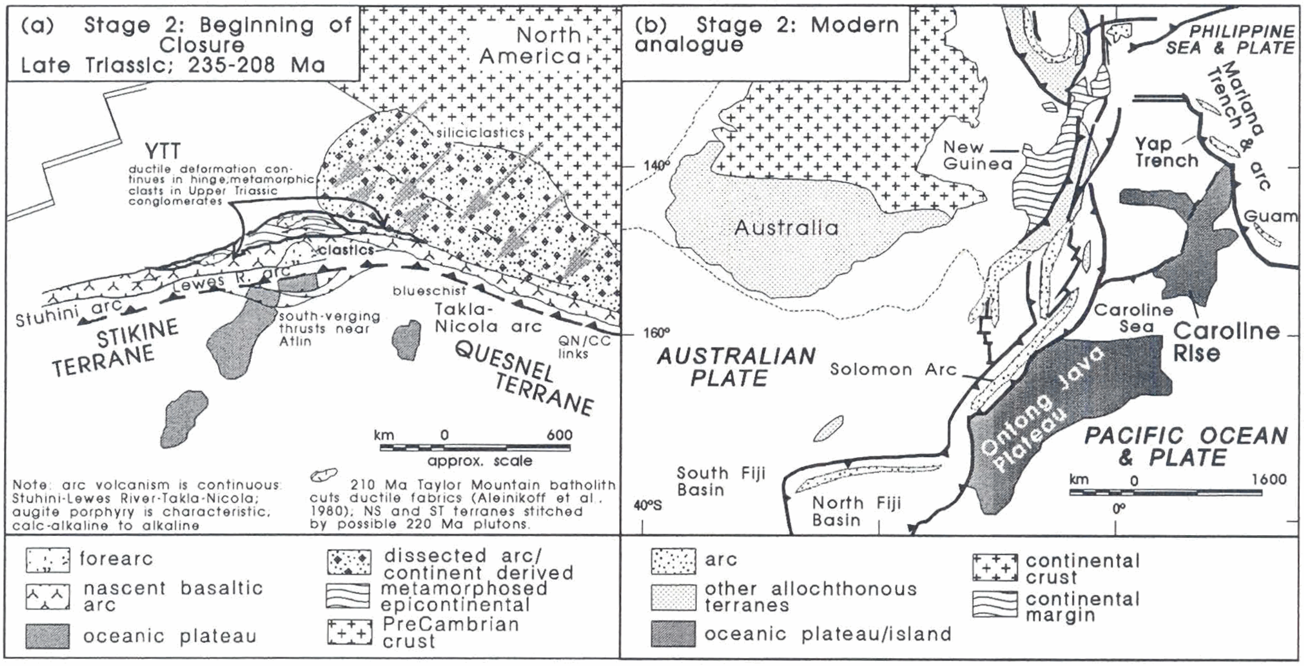

Figure 4. (a) Late Triassic configuration of tectonic elements predicted by the model. (b) Caroline Rise interaction with the Marianas arc/trench as a modern analogue for this stage of the model.

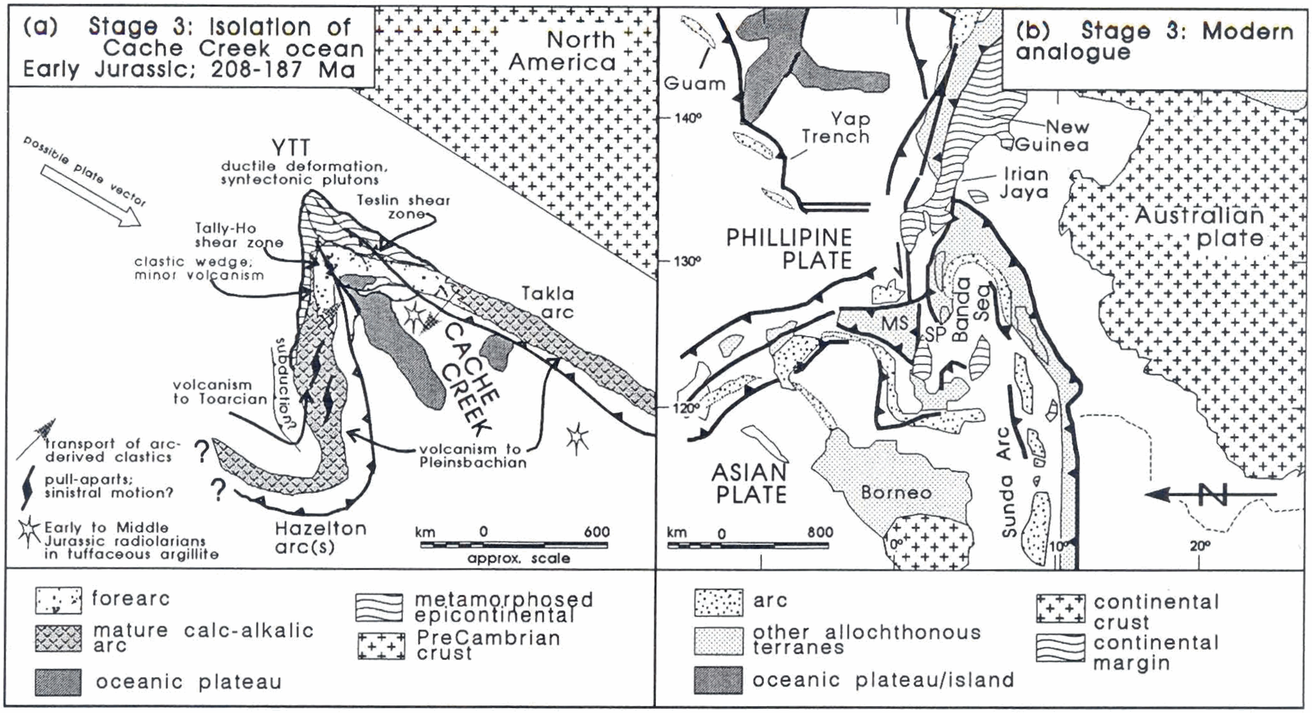

Figure 5. (a) Early Jurassic configuration of tectonic elements predicted by the model. (MS and SP indicate the Molucca Sea and Sula Platform.) (b) Geology of the Banda Sea analogue after *Hamilton* [1979].

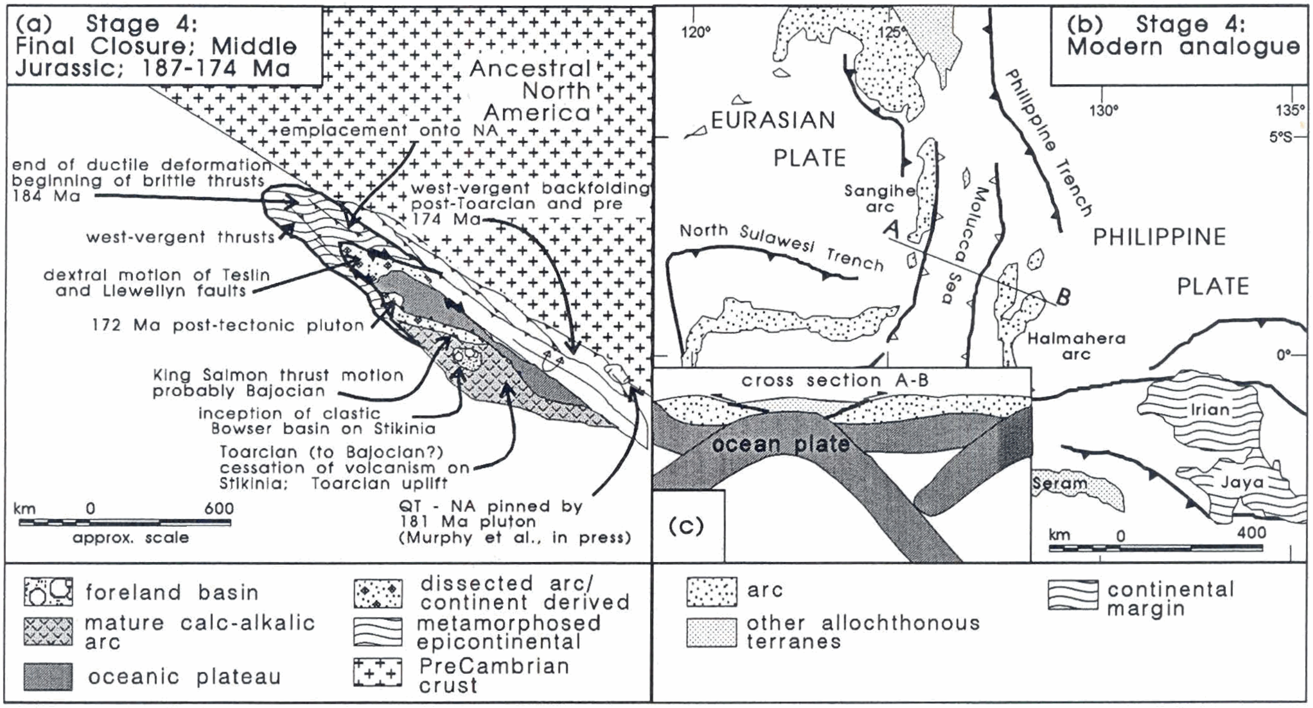

Figure 6. (a) Middle Jurassic configuration. (b) Halmahera collision zone after *Hamilton* [1979]. (MS indicates the Molucca Sea.) (c) A schematic cross section of the Halmahera collision zone across the location shown in 6b.

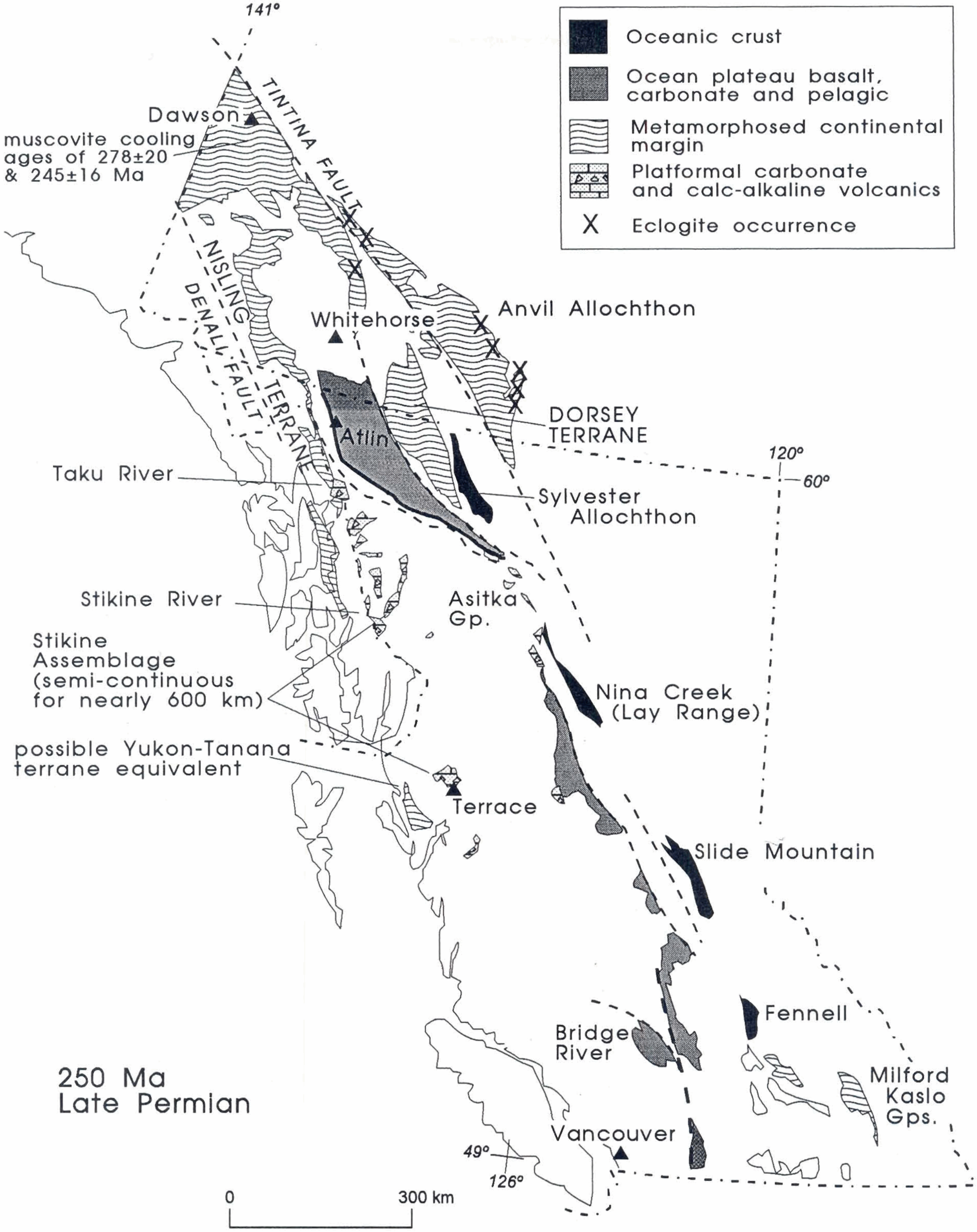

Figure 7. Latest Permian to Middle Triassic geological elements that constrain the model. Present-day features shown for reference only are dashed and labeled in italics.

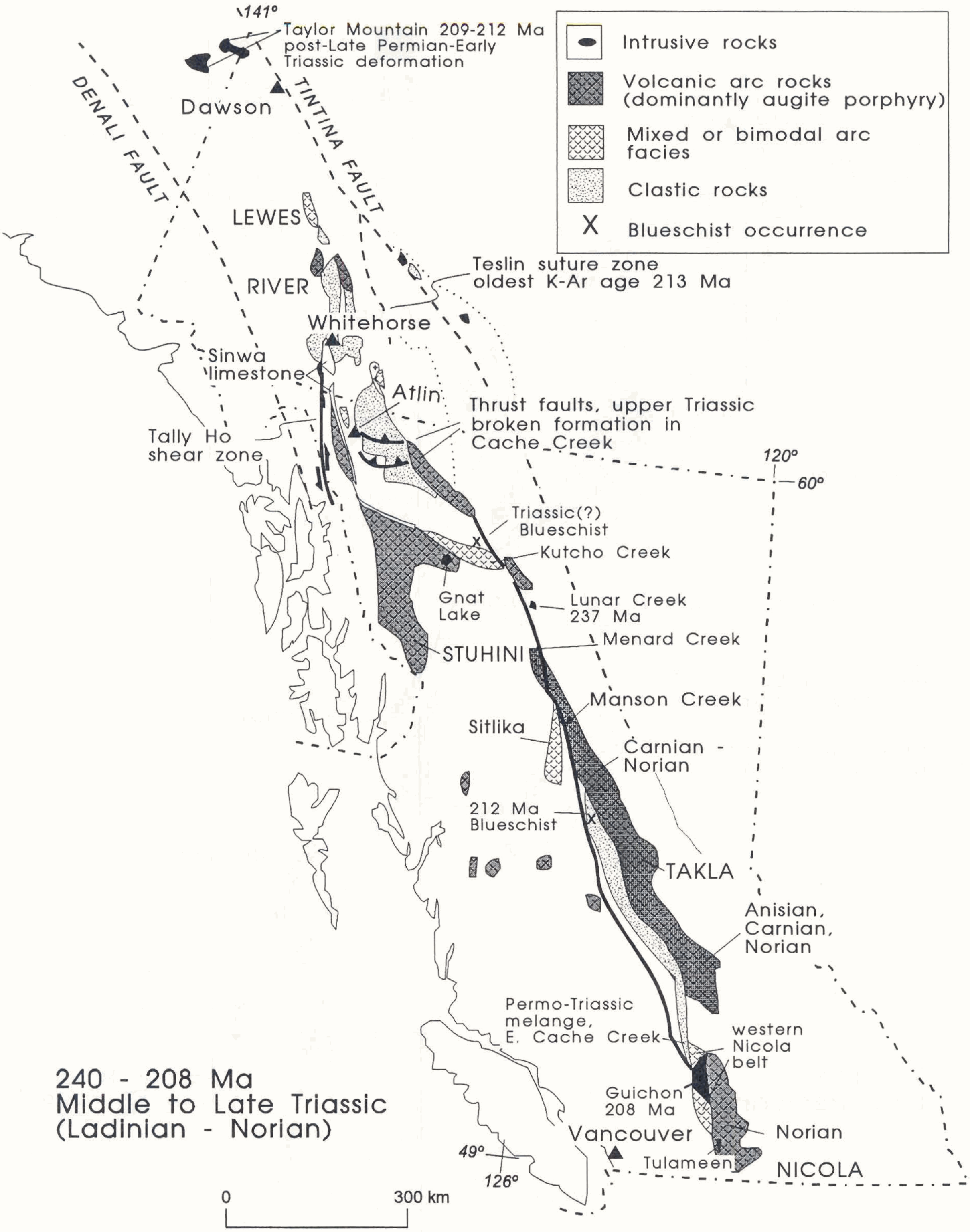

Figure 8. Late Triassic geological elements that constrain the model. Present-day features shown for reference only are dashed and labeled in italics.

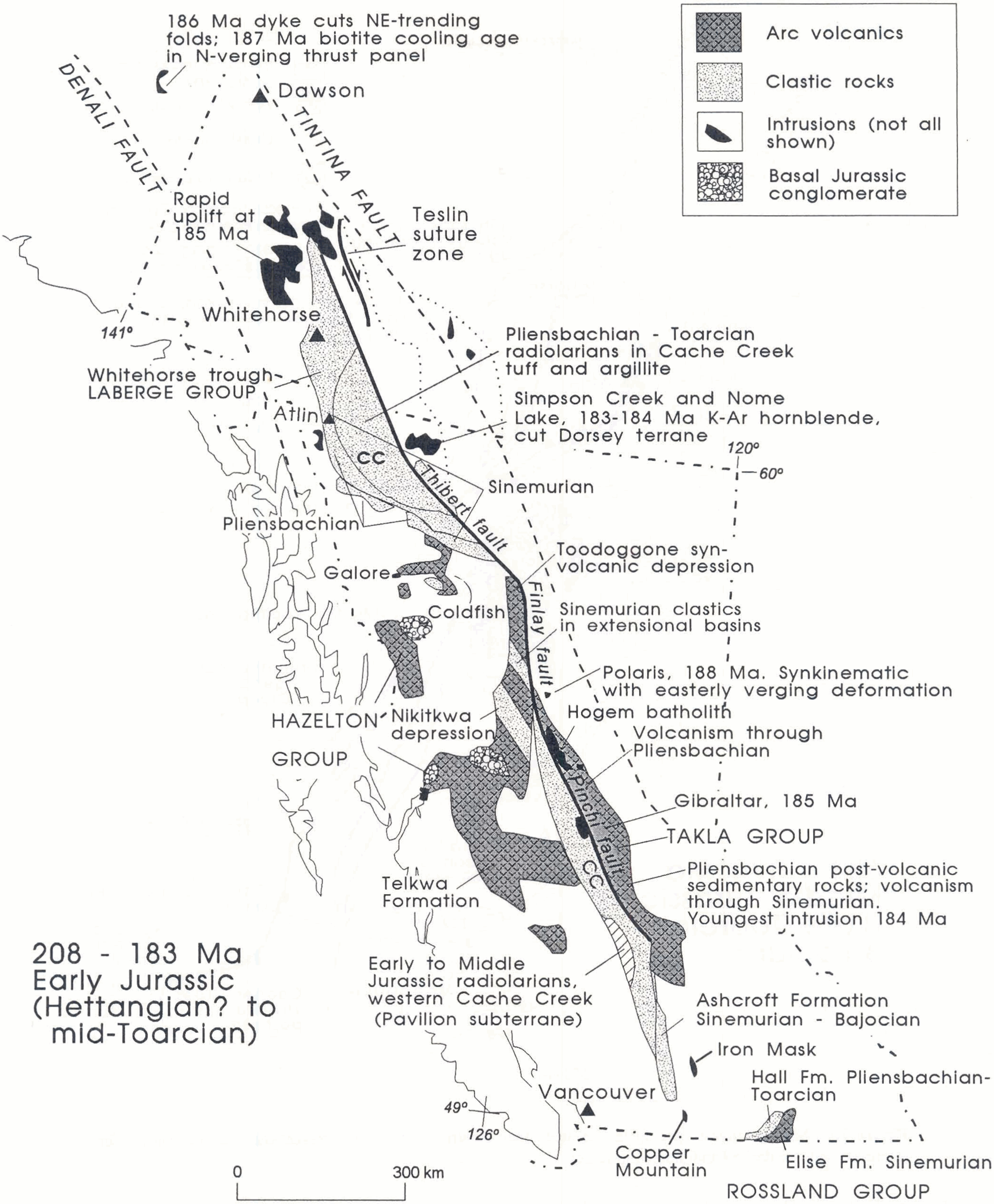

Figure 9. Early Jurassic geological elements that constrain the model. Present-day features shown for reference only are dashed and labeled in italics.

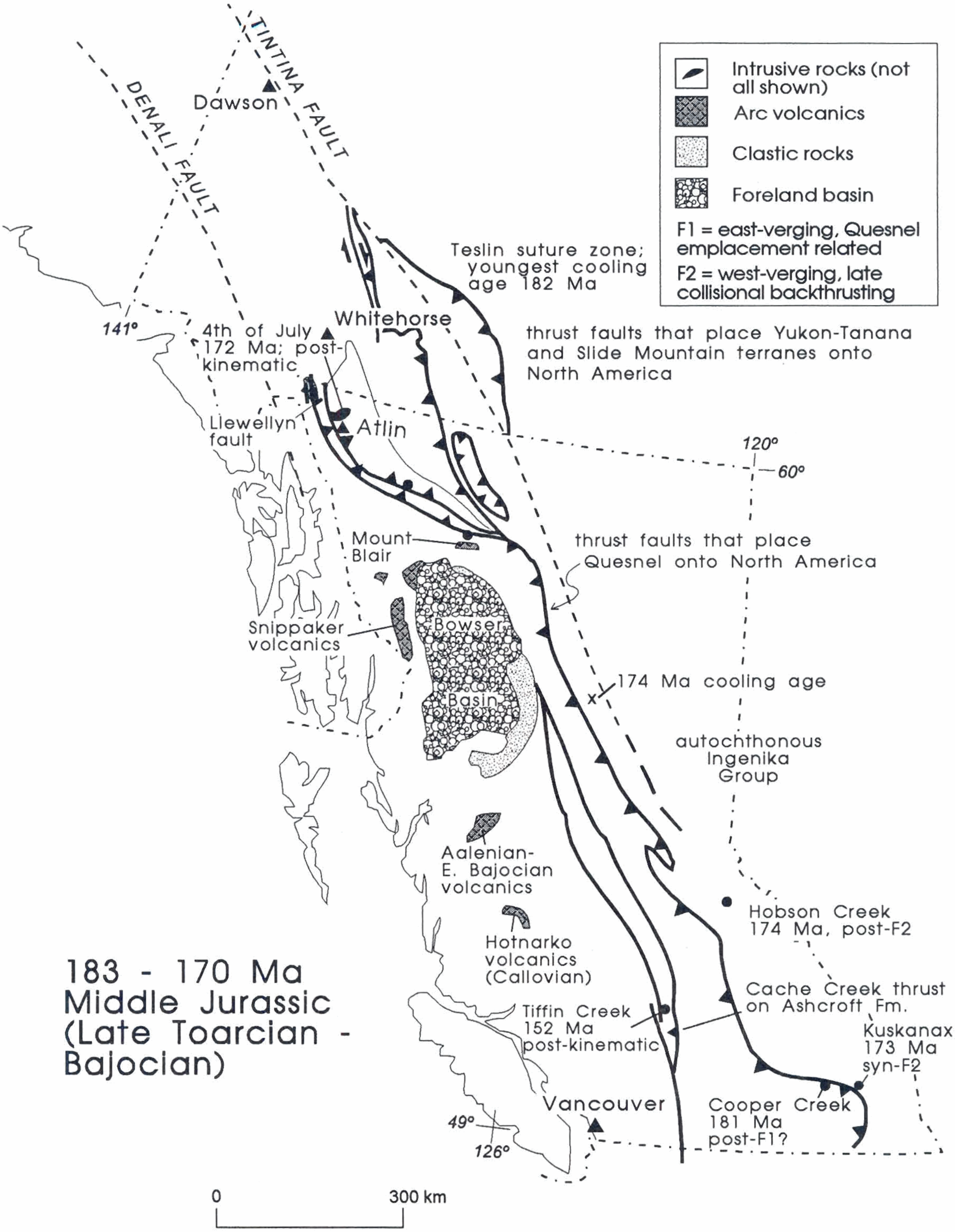

Figure 10. Middle Jurassic geological elements that constrain the model. Present-day features shown for reference only are dashed and labeled in italics.

the Sylvester Allochthon). Depositional ties between Middle to Upper Triassic and the underlying late Paleozoic rocks have only been documented in southern British Columbia [e.g., *Klepacki and Wheeler*, 1985; *Preto*, 1964]; elsewhere, the base of the Triassic sediments is a regional décollement. Similar Triassic sequences occur within NA [*Pelletier*, 1961; *Gordey et al.*, 1981] and the YTT [*Tempelman-Kluit*, 1979] and thus constitute a possible depositional link between QN and the YTT and NA.

Deformation within QN during this period is obscure, but there is ample evidence for a depositional break and at least a

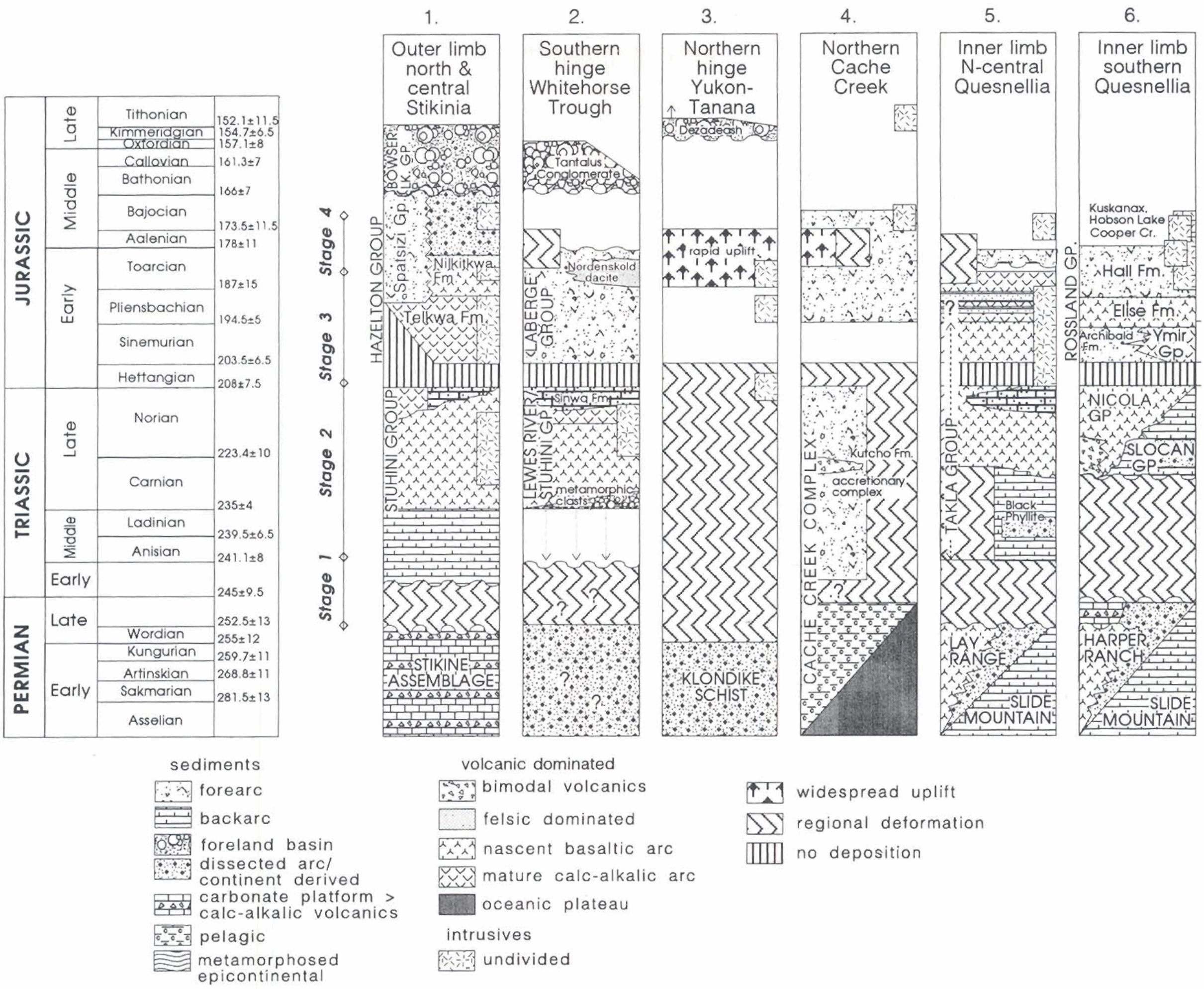

Figure 11. Pseudostratigraphic column showing similarities and differences between hinge and limbs. The many sources of data are referenced in the text.

loose amalgamation between SM, QN (Harper Ranch Assemblage), and the distal edge of NA [*Klepacki and Wheeler*, 1985; *Preto*, 1964]. Intense ductile deformation like that in the YTT is absent.

Hinge. Most of the early deformation producing a strong, subhorizontal fabric within the YTT (first phase of deformation (D1) of *Mortensen* [1992]) probably occurred during the latest Permian to Middle Triassic since Middle Permian igneous rocks are strongly affected, but plutons as old as 212 Ma [*Aleinikoff et al.*, 1980] are relatively undeformed. The cause of D1 is not well known. *Tempelman-Kluit* [1979] suggests an accretionary complex; but the scale of the system, lithologic composition, and lack of a subduction melange tend to favor a continental collisional model such as that proposed by *Mortensen* [1992]. However, YTT was probably not emplaced on the North American margin until Jurassic time [*Tempelman-Kluit*, 1979], so what did it collide with? In the oroclinal model, deformation is due to end-on collision with the Cache Creek oceanic plateaus, followed by the initiation of rotational closure.

Outer limb. Paleozoic strata within ST can be correlated from near Terrace to north of the Taku River, a distance of about 600 km [*Monger*, 1977a; *Brown et al.*, 1991]. Foliated limestone and bimodal volcanic strata of Early to Middle Devonian age are the oldest well-dated rocks [*Logan et al.*, 1992]. They may in part rest unconformably on an older succession of quartzose turbidites [*McClelland*, 1992; *Mihalynuk et al.*, 1994] thought to be correlative with the YTT but mainly are thrust over Lower Devonian and Upper Carboniferous arc strata. Carboniferous through Lower Permian argillaceous carbonate and thin-bedded to massive carbonate are widespread and characteristic of ST. These reach thicknesses of 650 m (and possibly upwards of 2100 m with structural complications) and probably represent an unusually stable carbonate platform or shelf [*Brown et al.*, 1991]. Permian fusilinids and corals from these strata have McCloud faunal affinities, distinct from North American fauna. Thus they are believed to represent a province that was separated from North America, but the degree of separation is a matter of debate [*Miller et al.*, 1992].

Calc-alkalic tuff and basalt are conspicuous within massive, fossiliferous carbonates older than Early Permian but are sparse to nonexistent in younger rocks, perhaps representing a waning arc. Only local preservation of a condensed, argillite, and chert section of latest Permian to Early and perhaps Middle Triassic age (J. Logan and D. Brown, personal communication, 1993) points to a marine transgression beginning in the latter part of the Late Permian.

Sedimentation ended with the onset of a widespread but generally mild deformational and erosional event that appears to have been initiated in the Middle to Late Triassic in the north [*Souther*, 1971] and Late Triassic in the south.

Cache Creek terrane. Within northern CC the oldest strata are mixed volcanic and pelagic rocks of Early Mississippian age that form a sort of stable oceanic platform (Nakina subterrane [*Monger*, 1975]). In Early to Late Permian time, thick, subtidal carbonates were deposited. Late Permian fauna include the Tethyan Yabeina fusilinids [*Monger and Ross*, 1971]. At the end of the Permian and into the Triassic there was a return to argillite and chert deposition. In the Dease Lake area, two phases of deformation are recognized. The older post-Late Permian, pre-Late Triassic phase produced a penetrative, bedding-parallel foliation, isoclinal folds, and local blueschist facies metamorphism [*Monger*, 1975; *Gabrielse*, 1991]. In central CC some of these blueschists give Late Triassic K-Ar dates [*Paterson and Harakal*, 1974], suggesting a subduction zone on the western side of QN of Triassic or older age.

In the central belt of the southern CC the Marble Range subterrane records continuous limestone deposition from Late Permian through Early Triassic time [*Cordey et al.*, 1987]. In the eastern belt, melanges with Permian to Triassic matrix contain a mixture of lithologic blocks of oceanic and island arc affinity [*Orchard*, 1984; *Cordey et al.*, 1987]; perhaps representing an accretionary prism on the western edge of QN.

Summary and implications for the model. Histories of the inner and outer limbs at this time were very similar, involving cessation of Permian arc volcanism, mild deformation and uplift, and reinitiation of subduction zones. Convergent boundary development between QN and the Cache Creek ocean is indicated by a blueschist-bearing melange of appropriate age within the CC. Permo-Triassic deformation intensity within YTT at the hinge is remarkable. In the model it is due to collision of oceanic plateaus, remnants of which are preserved in the Nakina and Marble Range subterranes of the CC.

Modern analogue. Modern arcs of the western Pacific form a set of convex outward festoons that join across blocks of older basement [*Hamilton*, 1979, 1988]. For example, the modern Aleutian and Kurile arcs form two festoons that join on the southern tip of Kamchatka (Figure 3b). This example shows how the Late Paleozoic arcs of ST and QN might have been joined across the pericratonic fragment of the YTT, and in turn how the early Mesozoic Stuhini-Lewes River and Takla-Nicola arcs might have been joined across combined older arc and pericratonic basement. Analogous to Emperor Seamount chain impingement at the cusp between the Aleutian and Kurile arcs is impingement of the CC plateaus against the YTT, separating the ST and QN arcs.

Stage 2: Indentation and Beginning of Closure (Late Triassic) (Figures 4 and 8)

Inner limb. Volcanism resumed in some parts of QN in early to middle Anisian [*Struik*, 1988] to Carnian time and was widespread by the Norian [*Monger and McMillan*, 1984; *Ferri and Melville*, in press]. In the north and south QN, respectively, the rocks deposited comprise the Nicola and Takla groups. They are dominated by augite-phyric basalt ranging from calc-alkaline in the south [*Minehan*, 1989; *Ferri and Melville*, 1994] to very high-K and shoshonitic affinity for over 1000 km in the north [*Mortimer*, 1987; *Nelson et al.*, 1992]. Rhyolite occurs in the western Nicola belt [*Mortimer*, 1987] and in a small fault-bounded sliver along the Thibert fault [*Gabrielse*, 1991]. A west facing arc is indicated by position of the Takla-Nicola belt east of the CC subduction melange, eastward K-enrichment in the Nicola volcanics [*Mortimer*, 1987], and potential back arc sediments of Late Triassic through Early Jurassic age [*Struik*, 1988] suitably situated in a region east of the Takla-Nicola arc. Late Triassic ages from blueschists along the Pinchi fault, which separates QN and CC, support this reconstruction [*Paterson and Harakal*, 1974].

Alkalic intrusions, monzonites of shoshonitic affinity, and ultramafites of Alaskan type typify Upper Triassic to Lower Jurassic rocks of QN. Monzonites, which tend to host Cu-Au porphyry deposits, include Copper Mountain, Iron Mask, and several small porphyry stocks near Germansen Landing including the Mount Milligan intrusion and the Hogem batholith [e.g., *Nelson et al.*, 1992].

Hinge. Following 25 m.y. of quiescence, a significant Late Triassic pulse of magmatism occurred in the YTT and the flanking Stuhini-Lewes arc. Proximity of the arc terranes with metamorphic YTT is suggested by the presence of metamorphic clasts in Upper Triassic conglomerates both north [*Bultman*, 1979; *Mihalynuk and Mountjoy*, 1990] and south [*Souther*, 1971] of the Taku River and east of the Yukon Tanana terrane from the Yukon border to Faro (J. Mortensen, personal communication, 1992).

YTT magmatism is exemplified by quartz diorite or granodiorite to quartz monzonite of the circa 212 Ma Taylor Mountain batholith [*Aleinikoff et al.*, 1980] and associated intrusions in eastern Alaska [*Foster et al.*, 1985] and Yukon (C. Hart, personal communication, 1993). Isotopic data indicate a minor inherited zircon component and moderate initial Sr and Pb ratios [*Mortensen*, 1992; *Aleinikoff et al.*, 1986].

In the Carnian, volcanism in the Lewes River arc was widespread, but limey clastic sedimentation dominated. Arc volcanic rocks occur in two belts, a well-developed western arc axis and a lesser developed eastern arc with an intervening belt of clastic strata [*Wheeler*, 1961]. Typical volcanic strata include coarse augite and bladed feldspar porphyritic flows, variegated lapilli tuff, and breccia.

Sediments derived in part from the Lewes River arc blanketed large portions of CC. At about this same time a series of small felsic volcanic centers were developed along the perimeter of northern CC (circa 210 ± 10 Ma Rb-Sr [*Thorstad and Gabrielse*, 1986]).

Outer limb. Lewes River Group volcanic strata in the hinge zone can be traced into Stuhini Group strata of the outer limb and are thus directly correlative. Volcanic rocks of the Stuhini arc locally form thicknesses in excess of 2500 m, however, fine and coarse clastic sedimentary rocks are dominant [*Brown et al.*, 1991; *Logan et al.*, 1992]. In the Stikine and Taku River areas a marked angular unconformity separates Stuhini arc strata from those of the succeeding Lower Jurassic Hazelton Group. Farther south in the Terrace area, coarse augite-bearing Stuhini(?) epiclastics rest with angular unconformity atop Permian carbonate. They pass into augite-phyric tuffs and flows which in turn apparently grade upward into the calc-alkaline Lower Jurassic Hazelton Group [*Mihalynuk*, 1987].

In northmost British Columbia, two voluminous subalkaline magmatic pulses produced lithologically indistinguishable volcanic strata [*Mihalynuk and Mountjoy*, 1990]. They are separated by a circa 220 Ma plutonic event, a period of extremely rapid arc uplift, erosion, and deposition of a widespread blanket of conglomerate (probably correlative with similar conglomerates in the Taku River area [e.g., *Souther*, 1971]). About 3000 m of pillow basalt and siliceous sediments give way to partly subaerial dacitic volcanic rocks and carbonates of the upper Norian Sinwa Formation. The end of Sinwa deposition marks a foundering of the arc and a return to deepwater clastic deposition.

Stuhini Group is dominantly calc-alkalic, but alkaline magmatism is represented by the Galore Creek syenite dyke complex, host to an important gold-copper porphyry system and comagmatic [*Panteleyev*, 1976] basalt flows. Alaskan-type ultramafite intrusions in ST include the Menard Creek and Gnat Lakes bodies (Figure 8).

Cache Creek terrane. The CC records a Late Triassic history that is very different from its Mississippian through Early Triassic record. For the first time it receives coarse, quartz-rich clastic sediments (interbedded with chert), representing prograding forearc clastic wedges from the Takla, Lewes River and possibly Stuhini arcs. Arrival of CC seems to have exerted an influence over the Lewes River arc as well with the introduction of Tethyan faunal elements, resulting in a mixed faunal realm including both endemic North American and Tethyan types [*Reid and Tempelman-Kluit*, 1987].

By the close of the Late Triassic, CC crustal blocks impinged on the Stuhini-Takla arc. Structural evidence of this collision may be manifested by southward directed thrusts and Upper Triassic olistostromes within northern CC [*Monger*, 1975; *Bloodgood and Bellefontaine*, 1990].

Summary and implications for the model. There is a strong lithologic and temporal similarity between the Late Triassic augite-phyric basalts of QN and ST. Volcanism commenced at approximately the same time in both terranes as evidenced by recent conodont age data from QN [*Struik*, 1988]. Additional similarities between the two terranes in Late Triassic-Early Jurassic time include alkalic and ultramafite intrusions and associated copper-gold-bearing subvolcanic monzonite porphyries (Copper Mountain suite of *Woodsworth et al.* [1991]) and calc-alkalic, unusually felsic volcanic centers adjacent to the CC. They share a progression from felsic volcanics through augite porphyries of the main arcs, which are loosely stitched to pericratonic terranes that lie farthest from the CC. On the basis of these and other similarities, we suggest that in a gross sense ST, and QN are correlative and display a two-fold symmetry about the CC.

Modern analogue. Two mechanisms could have contributed to the rotation of ST toward QN. The first would involve pinning of the junction between the two arcs by end-on collision of a linear oceanic plateau, now represented by parts of the CC. A modern analogue for this event is the end-on collision of the northeast trending Caroline Rise with the Mariana arc (Figure 4b), which has apparently produced a deep indentation in the arc (the discontinuity between the Yap trench and the main Mariana trench) with local cessation of subduction, strike-slip faulting, and 50° clockwise rotation of Guam [*McCabe and Uyeda*, 1983]. Continued eastward expansion of the Philippine Sea will produce farther clockwise rotation of the arc with respect to this cusp, but probably not by itself entrapment of Caroline or Pacific ocean floor. The second mechanism, as shown in the Caroline Sea area, is closure due to relative motions between four plates, the Philippine Plate that carries the Mariana arc, the Pacific Plate, the Eurasian Plate, and the Australian Plate. At present, the Indo-Australian Plate is moving north-northeastward with respect to the Eurasian Plate at a rate of 7 cm/year [*McCaffrey and Abers*, 1991 and references therein].

This analogue is not a perfect match; the CC evidently does not contain a small, late-forming ocean like the Caroline Plate, and the Mariana arc is a young, primitive arc founded on oceanic crust [*Hamilton*, 1979] not superimposed on earlier arcs as are ST and QN. The strength of this analogue is that it models how a piece of far-traveled ocean may be enclosed between less exotic elements as a result of two apparently independent events; indentation of an arc, followed by closure of the two segments against another.

Stage 3: Rotation of ST and Isolation of the CC (Early Jurassic) (Figures 5 and 9)

Inner limb. In southern QN the locus of alkalic arc volcanism shifted eastward from the Nicola to the Rossland volcanic belt between late Norian and Sinemurian time and ceased before early Pliensbachian time [*Monger and McMillan*, 1984; *Höy and Andrew*, 1989]. Postvolcanic sedimentary units are early Pliensbachian to Callovian age [*Monger et al.*, 1991] and are deposited on both QN and the eastern CC [*Travers*, 1978], suggesting forearc origins. Elsewhere in QN, postvolcanic sediments range only to Early Bajocian age. In central QN, a volcanic lull represented by Norian limestone and Sinemurian clastic sediments is followed by felsic volcanic activity up to Pliensbachian time [*Bailey*, 1988]. In north-central QN, Upper Triassic augite-phyric basalts are overlain by a more heterogeneous volcanic suite dominated by latite and andesite [*Nelson et al.*, 1993]. An earliest Jurassic hiatus is succeeded by late Pliensbachian sediments overlain by plagioclase-augite-phyric flows and lahars [*Nelson et al.*, 1992], the youngest known volcanic rocks in QN. In far northern QN, no volcanic rocks of Early Jurassic age are evident; Upper Triassic volcanogenic strata are overlain by the Lower Jurassic clastic strata [*Gabrielse*, 1991; *Monger et al.*, 1991].

Most reasonably, the Quesnel arc developed by continuous or nearly continuous easterly subduction of the Cache Creek ocean crust between Mid-Triassic and late Early Jurassic time. This arc-trench system was unusually persistent, as shown by the prevalence of shoshonitic volcanics over 1000 km of strike length and from Late Triassic to Early Jurassic time, a span of about 30 million years. At a minimum of about 187 Ma (end of Pliensbachian), subduction and arc volcanism essentially ceased. Younger plutons are probably products of residual magmas.

Hinge. In contrast to the Late Triassic, evidence of Early Jurassic extrusive magmatism in the Yukon is sparse. Hazelton-like dacitic volcanism occurs in one restricted region in southwestern Yukon. Farther to the south, a regionally persistent water-lain tuff known as the Nordenskold dacite, is probably correlative. By far the most abundant rocks of this age are Pliensbachian arc-derived wacke, conglomerate and argillite of the Laberge Group. Oldest fossils within the Laberge Group are Sinemurian and rest disconformably atop the Lewes River carbonates. They range in age up to Toarcian and perhaps Bajocian (H.W. Tipper, personal communication, 1992). The Laberge Group has been divided into (1) a fine distal facies, the Inklin Formation [*Souther*, 1971], derived from CC, QN [*Wheeler and McFeely*, 1991], and ST [*Wheeler*, 1961; *Hart and Radloff*, 1990; *Mihalynuk et al.*, 1989] and (2) the Takwahoni Formation, a Pliensbachian and younger, coarse, proximal facies derived from ST [*Souther*, 1971; *Wheeler and McFeely*, 1991]. Numerous well-developed intraformational unconformities and conglomerates in the western Laberge Group occurrences are evidence of synsedimentary tectonism, probably related to motion on the Llewellyn-Tally Ho fault system [*Mihalynuk and Mountjoy*, 1990].

Magmatism in the hinge zone is recorded by the circa 185 Ma Klotassin suite of quartz-diorite, hornblende-granodioritic, and quartz monzonitic composition. Ductile deformation of these bodies is common and in comparison to relatively undeformed Upper Triassic plutons is puzzling. It could indicate crustal thickening and synkinematic intrusion along ductile shear zones or intrusion at deeper crustal levels with Late Triassic intrusions exhumed at that time. Ductile, dominantly sinistral or top-to-the-southwest deformation along the Llewellyn-Tally-Ho shear zone is bracketed by U-Pb ages of 185 Ma magmatism [*Currie*, 1991] and Early Jurassic postkinematic (ductile) pegmatite dike emplacement (M.G. Mihalynuk, unpublished data, 1990) within Klotassin suite rocks.

On the east side of the hinge zone, muscovite developed during a low-angle top-to-the-east deformational event yields a 194 Ma ^{40}Ar^{39}Ar plateau date [*Hansen et al.*, 1989]. Widespread plateau ages in the 188-185 Ma range are believed to indicate a period of rapid uplift (~5 mm/yr [*Hansen*, 1990]), nearly synchronous with Klotassin magmatism.

Outer Limb. Early Jurassic arc magmatism is widespread throughout south and central ST, as represented by volcanogenic rocks of the Hazelton Group and cospatial epizonal plutons. Significant regional volcanic and sedimentary depositional patterns of the Hazelton Group were described by *Tipper and Richards* [1976] and refined by more recent studies.

At present, vestiges of the Hazelton magmatic arc crop out intermittently in two ill-defined belts, separated from one another by thick clastic assemblages of the Middle and Upper Jurassic Bowser Basin and superposed Late Cretaceous Sustut Basin. Initiation of the Hazelton arc apparently corresponds with the Triassic-Jurassic boundary [cf. *Harland et al.*, 1990]. It is superimposed on volcano-sedimentary components of the upper Carnian and Norian Stuhini arc and older poorly exposed Paleozoic basement. A distinctive polymictic conglomerate is found at the base of the Hazelton Group in both arc segments; it unconformably overlies and contains clasts derived from Triassic and Permian units [e.g., *Tipper and Richards*, 1976; *Monger*, 1977b]. These immature sediments signify a period of regional uplift, causing rapid facies changes adjacent to growth faults and sculpting of granitoid and pre-Jurassic rock units exposed in high-standing fault blocks.

Although biostratigraphic and geochronologic constraints on timing of initial arc constructional events vary slightly between regions, the data generally suggest that the earliest phase of volcanic activity was established by late Sinemurian and apparently ceased in early Pliensbachian time. Nowhere are strata spanning this time interval more prevalent than in the eastern segment of the Hazelton arc, which is manifest as a series of volcanic fields extending for more than 600 km from north to south. Extrusive rocks along the arc are almost exclusively subaerial and include a range of low-K to high-K calc-alkaline compositions, except in the north where the arc massif comprises marine and subaerially erupted flows and pyroclastic rocks of tholeiitic composition.

Siltstone, conglomerate, and isolated bioherms containing upper Sinemurian fauna represent a transgressive shallow sea that locally inundated parts of the arc during a short-lived volcanic lull. This early sea was entrenched over a slowly subsiding graben in the central arc from late Sinemurian to Bajocian, time in which submarine volcanics at the base erupted synchronously with mainly subaerial volcanism in flanking highlands [*Tipper and Richards*, 1976]. These volcanics are in turn overlain by a thick monotonous shale sequence that is interrupted by middle Toarcian outpouring of alkali olivine basalt. The stratigraphic record in the graben signifies a protracted history of intra-arc extension; a tectonic regime that apparently dominated early development of the eastern arc massif along the inner margin of ST. This is corroborated by Sinemurian conglomerate facies in the northern arc that are restricted to major grabens [*Tipper and Richards*, 1976, p. 39] or elongate synvolcanic depressions [*Diakow*, 1990]. In southernmost Stikinia a thick, fining upward sedimentary succession represents progressively increasing sea level in late Hettangian to middle Bajocian time (Cadwallader terrane [*Umhoefer*, 1990]). Unlike the explosive arc volcanism evident in correlative strata from Stikinia, these strata apparently lack evidence of nearby volcanic activity.

With the exception of tholeiitic bimodal volcanism in the north (Cold Fish formation [*Thorkelson*, 1992]), volcanic activity in the eastern Hazelton arc all but ceased regionally in early Pliensbachian time. Cessation of arc volcanism corresponds temporally with transgressive marine sediments of the Spatsizi Group [*Thomson et al.*, 1986] and fine-grained clastic sedimentation in the central arc graben.

Volcanic and plutonic rocks defining the western Hazelton arc segment are exposed over a broad area along the west-northwest margin of the Bowser Basin. Sinemurian and Pliensbachian volcano-sedimentary sequences and a coeval plutonic suite in the western Hazelton arc segment broadly mimic time-equivalent magmatism in the eastern arc segment, thereby suggesting a possible connection as components of a coherent Early Jurassic arc-trench system.

During Pliensbachian to Toarcian time, mainly nonmarine, felsic volcanic activity prevailed in a belt that presently extends intermittently from north to southwest of the Bowser Basin. This volcanism marks the final major constructional phase of the Hazelton arc; it also appears to correspond with a regional shift westward in the locus of magmatism that resulted in the eastern arc segment becoming largely extinct and occupying a position behind an active arc at the outer edge of Stikinia. Uplift and erosion preceded Toarcian deposition; an unconformable contact with variably deformed pre-Jurassic basement is widely recognized in the western arc [*Brown et al.*, 1992; *Greig*, 1992].

Cache Creek terrane. The western belt of the southern CC includes tuffaceous argillites of Early to Middle Jurassic age [*Cordey et al.*, 1987], indicating continued arc-influenced marine sedimentation through this interval. In contrast, an oceanic assemblage of this age, previously included in the southwestmost CC but now distinguished as the Bridge River terrane, is dominated by pelagic, bedded radiolarian cherts. Continued, normal open ocean sedimentation in the Bridge River accretionary complex may indicate a position at the outboard end of the ST-QN arc system, separated from overwhelming sources of arc-derived clastics.

In the north, deposition of interbedded chert, wacke, and argillite apparently ceased in western CC in the Late Triassic, overwhelmed by Laberge Group deposition. In the east, distal sedimentation continued to at least the Early Jurassic as indicated by radiolarians in cherts with sparse interbeds of greywacke and tuff [*Cordey et al.*, 1991]. Intercalated and widespread chert breccia points to uplift of the CC perhaps in front of south and southwest directed thrusts [e.g., *Monger*, 1977a; *Bloodgood and Bellefontaine*, 1990] that accompanied emplacement. Very rapid differential uplift in Pliensbachian time is clearly recorded where Laberge Group conglomerates contain abundant cobbles of nearly coeval (within the resolution of current timescales), 186 Ma Klotassin suite plutonic and less common metamorphic rocks [e.g., *Wheeler and McFeely*, 1991; G. Johansson, personal communication, 1993].

Summary and implications for the model. Lower Jurassic arc rocks on both ST and QN pass northward into thick clastic sediments which covered northern CC oceanic plateau fragments where they had plugged the subduction zone. Outboard of this point, continued rotation of ST caused crustal thickening in the hinge zone and the once continuous subduction zone between ST and QN was broken into two segments, separated by a zone of complex deformation, plutonism, and local, dacitic volcanism. Such deformation and synkinematic plutons are evident in exhumed parts of the YTT. East and southwest verging deformation in the eastern and western hinge zones, respectively, transported crystalline rocks to shallow crustal levels. Voluminous intermediate arc volcanism on the limbs records a continuation of east and west subduction of the diminishing Cache Creek ocean and elicited a change in sedimentation from predominantly pelagic cherts and argillites to cherts interbedded with wackes, tuffs, and tuffaceous argillites. Synvolcanic extensional basins in ST developed in response to sinistral coupling along the inner edge of the outer limb as it was rotated southward to enclose the Cache Creek ocean remnants.

Modern analogue. Advanced stages of oroclinal enclosure in the Early Jurassic model have an arrangement of tectonic elements similar to those around the Banda Sea (Figure 5b). Relationships between the Banda Sea and the Australian plate are analogous to those between the Cordilleran terranes and NA, including a continent-verging fold and thrust belt flanking northern Australia [*Silver and Smith*, 1983], much like the Mackenzie-Rocky Mountain fold and thrust belt. In Figure 12, accretionary Borneo is analogous to southern ST, and the Java-Timor segment of the Sunda-Banda arc is analogous to QN. Note, however, that subduction polarities are reversed; the Banda Sea is on the overriding plate, and Australia is being subducted, while the Cache Creek ocean was subducted beneath its enclosing arcs.

Impingement of the relative westward moving Pacific plate at the northern fringe of the Australian craton has resulted in the left-lateral displacement of a crustal sliver which now forms the northwest peninsula of Irian Jaya and much of the Sula Platform (Figure 5b). The net result of this motion has been to enclose the Banda basin on three sides with continental margin rocks. Both the configuration and scale of this system are similar to the CC-YTT relationships.

Stage 4: Final Closure (Middle Jurassic) (Figures 6 and 10)

Inner limb. QN was emplaced as a klippe onto the western margin of ancestral North America at the close of the Early Jurassic. Youngest QN sediments involved in emplacement-related deformation belong to the early Toarcian Hall Formation [*Tipper*, 1984]. Duration of the emplacement event is determined from U-Pb dates on synkinematic plutons in QN. The Polaris ultramafic complex records incipient accretion at the leading, inboard edge of QN at 186 Ma [*Nixon et al.*, 1993]. The Kuskanax batholith, 173 ± 5 Ma [*Parrish and Wheeler*, 1983], is synkinematic with west verging folds that overprint easterly verging emplacement-related structures and thus largely postdates emplacement.

Hinge, including Cache Creek. Many of the crystalline rocks of the YTT in southeast Alaska and southern Yukon record Middle Jurassic cooling ages [*Hansen et al.*, 1988], indicating a period dominated by uplift and erosion. In the early Middle Jurassic, western parts of the Laberge basin were eroded and redeposited as massive conglomerate beds within a bimodal sequence of probable Aalenian or Bajocian(?) volcanic strata that overlie the Laberge Group [*Mihalynuk and Rouse*, 1988]. These volcanics may be part of a regional magmatic event during which the late synkinematic to postkinematic 171 Ma Fourth of July batholith in the Atlin Lake area [*Mihalynuk et al.*, 1992] and a series of similar bodies in the Dease Lake area [e.g., *Stevens et al.*, 1982] intruded the CC, plugging the southwest verging King Salmon thrust and related structures [*Thorstad and Gabrielse*, 1986] that emplace the CC over ST. This marks a period of mainly nondeposition superseded by chert clast-rich Upper Jurassic and younger conglomerates of dominantly CC derivation (*Hart and Radloff*, 1990).

In southern CC the youngest fossils are radiolaria of Early to Middle Jurassic age from tuffaceous argillites interbedded with epiclastic sandstones in the western belt [*Cordey et al.*, 1987; *Monger et al.*, 1991], reflecting a Cache Creek ocean that was still marine but possibly somewhat restricted. Complete closure is constrained to be Bajocian or later when the western CC is cut by the undeformed Tiffin Creek stock which reveals a K-Ar cooling date of 152 ± 5 Ma (hornblende [*Cordey et al.*, 1987]).

Outer limb. Volcanism rapidly declined following the early Toarcian event. Marine sedimentary successions, including the earliest Toarcian Salmon River and Smithers formations, record sedimentation supplanting volcanogenic deposits of the Hazelton arc. By Aalenian time, flexural subsidence of northeastern Stikinia, in response to thrust loading of the Cache Creek terrane on Stikinia, lead to partial to complete submersion of Early Jurassic arc elements [*Ricketts et al.*, 1992]. In Aalenian and early Bajocian time the Smithers Formation, dominated by feldspathic volcanic wackes with sparse tuff and lava interbeds and abundant benthic fauna, accumulated mainly near the shores of emergent volcanic islands. Succeeding these are Oxfordian strata of the Ashman Formation which herald the influx of abundant CC-derived conglomerates with clasts as young as Early Jurassic.

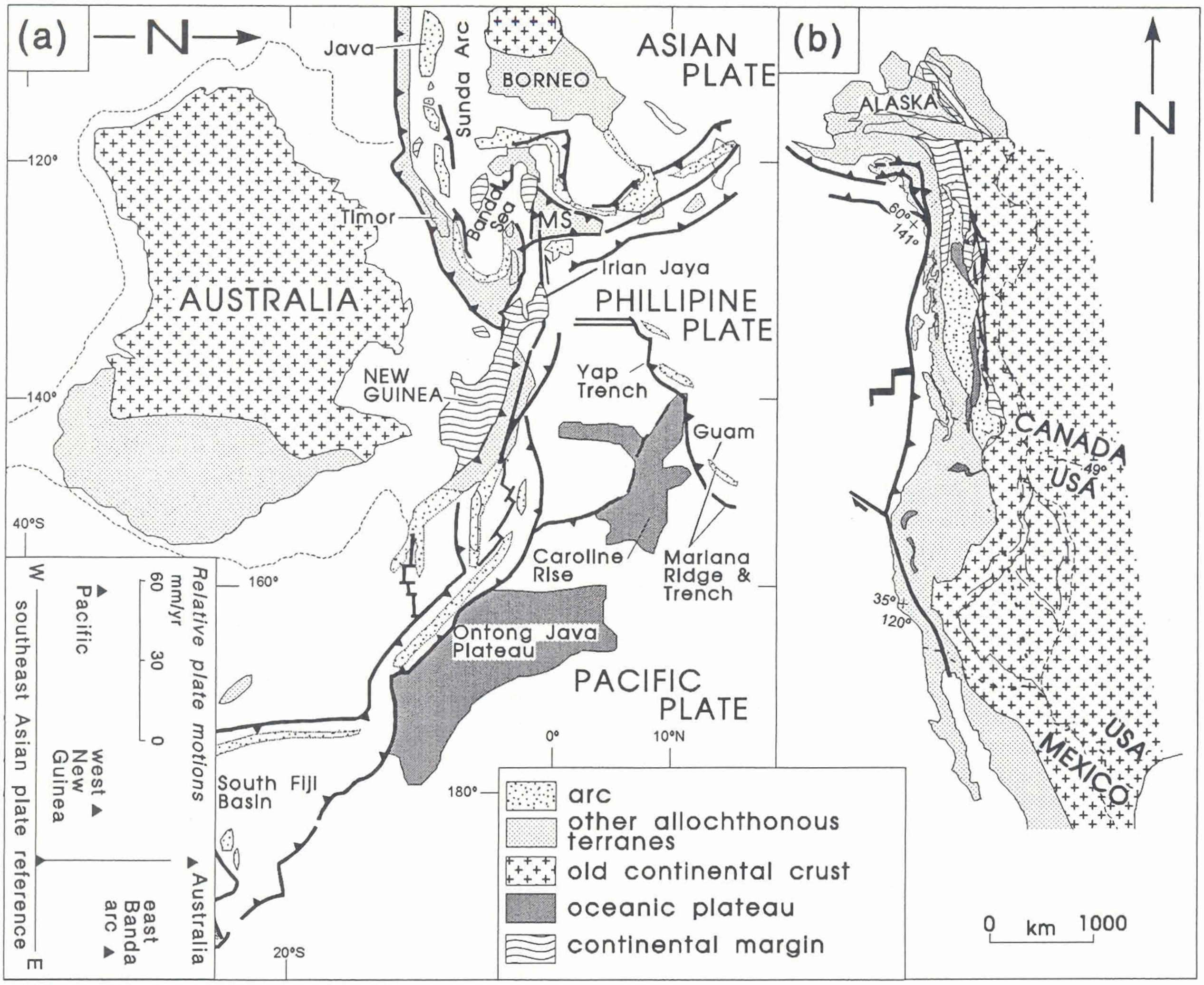

Figure 12. Comparison of the western Canadian Cordillera [after *Coney* 1989] (a) with the southwest Pacific orogen and (b) at the same scale. Gross similarities are striking, particularly the fold and thrust belts flanking the Australian and Canadian cratons and the distribution of pericontinental strata amidst arc terranes [after *Silver and Smith* 1983]. Relative plate motions are from *McCaffrey and Abers* [1991].

Early Middle Jurassic magmatic activity is restricted to a circa 177-172 Ma plutonic suite and Bajocian pillow lava north and west of the Bowser Basin [*Bevier and Anderson*, 1991] and isolated plutons farther south [*Woodsworth et al.*, 1988].

Summary and implications for the model. At this stage the arrangement in cross section of Cache Creek oceanic crust consumed beneath both QN and ST is much like that depicted by *Marsden and Thorkelson* [1992] (e.g., Figure 6c). In Toarcian to Bajocian time this symmetry gives rise to a set of roughly simultaneous events in both limbs of the orocline. Both southwest and east directed thrusting from the core of the collapsing orocline transported crystalline rocks to shallower crustal levels where they rapidly cooled and were eroded. Voluminous arc volcanism ceased, slightly later on ST than on QN, as a result of cessation of both subduction zones, signaling the rupture and westward obduction of cool CC crustal fragments and termination of CC sedimentation. Telescoping and uplift of the western Laberge basin occurred in front of the advancing CC allochthon. Broadly synchronous is a final pulse of magma genesis due to crustal thickening and a foundering subducted slab, now totally detached from the obducted CC. At the same time, QN was transported eastward onto the North American margin, and the formation of the Omineca Belt began. Rapid accumulation of CC-derived strata within the Bowser Basin marks overthrusting and foredeep clastic deposition during final closure of the orocline.

Modern analogue. Final closure of the northern Cache Creek basin in early Middle Jurassic time probably produced an arrangement of tectonic elements similar to the Molucca Sea collision zone [*Morris et al.*, 1983; *Morrice et al.*, 1983], with the thickened axial region rising above sea level as collision continues (Figures 6b and c). Halmahera and Sangihe arcs on both sides of the collision zone are still active, and a doubly verging orogen is forming with the central accretionary complex being thrust over both arcs. In the oroclinal model the arrangement of QN-CC-ST is not as symmetric as the Halmahera-Molucca Sea-Sangihe system. Rather, it appears that the QN subduction zone was plugged by collision of the CC crustal complex, whereas CC consumption beneath ST continued until

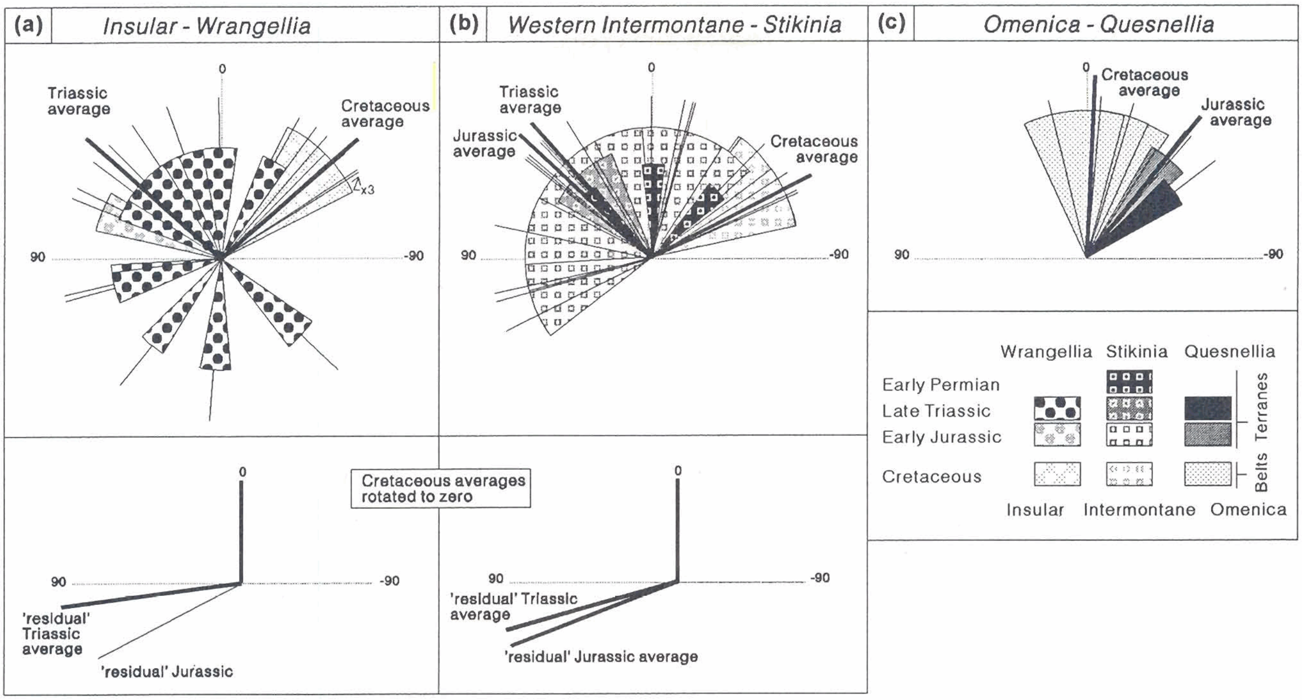

Figure 13. Paleomagnetically indicated rotations and error wedges are shown for (a) the Insular Belt (mainly Wrangellia), (b) Stikinia and the western Intermontane Belt, and (c) Quesnellia and the Omenica Belt. Average rotations within rocks of approximately the same age are denoted by the thick lines. Also shown in 13a and 13b are the effects of removing the pervasive Cretaceous rotations. This crude technique demonstrates the large "residual" rotations recorded by pre-Cretaceous rocks. Rotation data are from *Vandall* [1990] and *Irving and Wynne* [1990].

bending of the down-going CC crust could no longer be accommodated over a diminishing distance. The crust ruptured and was thrust above ST. This latter scenario may be born out in the Banda Sea area if major plate vectors remain relatively constant over the next 10 Ma. Northward migration of the Australian plate will close the Banda Sea [*McCaffrey and Abers*, 1991]. The net result will be volcanic (e.g., QN-ST); accretionary complex and ophiolite belts (e.g., CC) sandwiched between rocks that were originally part of the Australian continent (e.g., NA-NS).

Rotational Tectonics and Paleomagnetic Constraints

A key assumption in the oroclinal model is that rotational tectonics played a major role in the interaction of crustal plates. In fact, rotation of modern tectonic elements has been well documented in many parts of the world; Alaska [e.g., *Lawver and Scotese*, 1990; *Coe et al.*, 1989]; Spain [*Van der Voo*, 1969], the Mediterranean Sea [e.g., *Kissel et al.*, 1987], the Caribbean Sea [e.g., *Wadge and Burke*, 1983], and Southeast Asia [e.g., *Hamilton*, 1979, 1991; *Falvey and Pritchard*, 1982]. Such rotations commonly involve bending of preexisting trends and are thus oroclines according to the definition of *Carey* [1955]. In Alaska, at least two generations of oroclinal features have been proposed. Late Cretaceous to Early Tertiary modification of tectonic trends apparently created a Z-shaped orocline [*Patton and Tailleur*, 1977], and subsequent bending of the Tintina-Kaltag and Denali faults is invoked to explain the Early Tertiary "Alaska orocline" [*Coe et al.*, 1989]. *Scholl and Stevenson* [1991] have likened the Alaska orocline to a "tectonic catcher's mitt" that deforms as it absorbs the strong component of Pacific-North American motion, becoming more concave through time.

Terrane-scale rotations required by the model presented here involve large counterclockwise (ccw) rotation of ST with respect to QN to move the orocline limbs into parallelism. Thus there should be a large disparity in pre-Jurassic paleodeclinations between QN and ST that decrease in Early Jurassic time and vanish in the Middle Jurassic. Paleomagnetic declination data provide a test of this hypothesis. Reliable paleodeclinations from Permian to Early Jurassic sites in ST, QN, and Wrangellia terranes [*Vandall*, 1990; *Irving and Wynne*, 1990] are shown in Figure 13. ST poles show large and variable rotations, from 19° clockwise (cw) to 116° ccw, averaging about 47° ccw; while those in QN are consistently about 40° cw. Cretaceous rocks throughout the Canadian Cordillera have cw rotations that average about 50° in the Insular Belt, 63° in the Intermontane Belt, and 3° in the Omenica Belt (compiled from above sources). In general, ccw rotations prevail in pre-Cretaceous rocks west of the CC, and cw rotations prevail east of the Cache Creek. Given the present inadequate database, quantitative estimates of pre-Cretaceous wholesale rotation of ST with respect to QN are tenuous. However, a first-order approximation involves subtraction of the average Cretaceous rotation from older paleodeclinations. QN rocks would, on average, maintain a paleodeclination of about -37° with respect to those of North America, while ro-

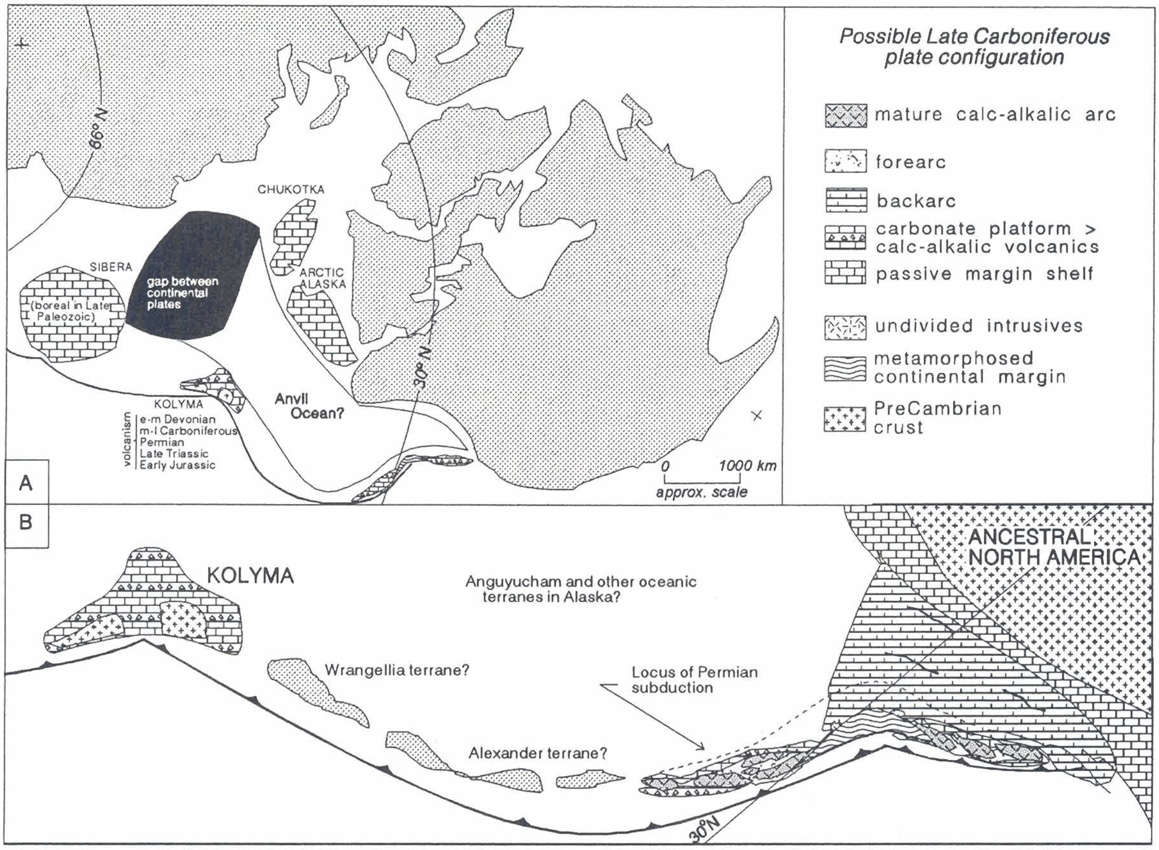

Figure 14. Pre-Triassic constraints on plate geometry predicted by the model shows (a) separation of northern and southern Panthalassa. Late Carboniferous plate configurations modified or extrapolated from *Scotese et al.* [1979], *Scotese* [1987], and *Harbert et al.* [1990]; locations of Cache Creek plateaus from *Stevens* [1983] and *Ross and Ross* [1985]; Siberian plate interactions in part from *Parfenov* [1991]. North America may have been loosely linked with the Kolyma block via an island arc complex (b) in which parts of Alexander and Wrangellia terranes originated.

tations in ST would increase to +44° through +179°. Such a contrast between pre-Cretaceous rotations in ST and QN is consistent with oroclinal enclosure of the CC. Although the paleomagnetic data are consistent with the model, they are not necessarily conclusive since overall terrane rotations cannot be separated from those due to local faulting.

Tests and Paleogeographic Implications of the Oroclinal Model

The model carries a number of testable implications. Several of these appear to be supported by the current, limited geological database, but others warrant further focused investigation.

Both the timing and the character of deformation within the northern Cordillera needs to be more firmly established. Collision-related deformation of the hinge should significantly precede deformation of the limbs. Such deformation should decay rapidly away from the collisional zone into symmetrical escape-block zones where both sinistral and dextral displacements dominate, as in the case of the Himalayas. Tightening of the orocline during final closure would have required a backstop such as NA. In this case, final oroclinal collapse should be broadly synchronous with shortening cratonward of QN. A widespread zone of extension should have persisted outside (north) of the pole of rotation throughout much of the Mesozoic, but the effects of this "extension" are not clearly manifested. However, in modern examples the effects of such extension are not clear either (W.B. Hamilton, personal communication, 1993).

Detailed paleomagnetic studies are needed to more completely document decreasing counterclockwise rotation of ST relative to NA (and QN) from Permian through Middle Jurassic time. Contiguous Triassic-Jurassic stratigraphic sections need to be sampled in both terranes in areas remote from major faults in order to rigorously test the model. Such data must be integrated with careful documentation of structural elements in order to isolate oroclinal terrane rotations from incremental rotations due to transcurrent faulting.

If correct, the oroclinal enclosure model carries some important implications for pre-Triassic global tectonics. A Late Carboniferous reconstruction offered here shows ST projecting as an arm into the Panthalassan ocean (Figure 14). Was this arm the eastern end of a chain of arcs that extended to Eurasia or China; arcs that are now preserved among the terranes of the North American Cordillera, Siberia, and Asia? Did this line of arcs divide Panthalassa into a southern "Tethyan" and a northern Boreal plate? Such a connecting series of arcs between North

America and Asia/China might explain several biogeographic features including (1) similarities between the McCloud faunal belt and the Asian faunal province, possibly due to a shallow water linkage; (2) a distinctive Early Carboniferous faunal realm restricted to miogeoclinal western NA, but also found in Alexander terrane (AX) [Armstrong, 1970], suggesting paleogeographic proximity at this time; and (3) lack of Tethyan faunal elements in long-lived ocean terranes in Alaska (such as the Devonian to Jurassic Angayucham Tozitna and Innoko terranes [*Jones et al.*, 1981; *Coney et al.*, 1980]), perhaps due to isolation behind an arc system composed of ST ± AX ± WR (Wrangellia terrane). Could ocean crust generation behind ST have caused rotation of ST into alignment with QN? Generation of such ocean crust also offers a mechanism for explaining the long standing "ocean gap" conundrum in reconstructions of the Arctic Basin [e.g., *Harbert et al.*, 1990] (Figure 14).

Is it possible that WR and AX terranes linked in the Pennsylvanian [*Gardner et al.*, 1988] were in turn linked to early Mesozoic ST [*van der Heyden*, 1992] in a southwest Pacific-style arc complex? Such linkages are difficult to reconcile with paleolatitudinal data from WR of Alaska. Relative paleolatitudinal displacements of Upper Triassic Nicolai volcanics in WR of Alaska vary between 18° and 33° based on the northern hemisphere option [*Irvine and Wynne*, 1990] to more than 60° based on the southern option. It does not seem plausible that the WR was rotated from a position nearly colatitudinal with the cratonic reference pole in the late Carboniferous (if linked to ST which is apparently colatitudinal in Permian times [*Irving and Monger*, 1987]) to a position several tens of degrees to the south (up to 7500 km) by Late Triassic time. Nevertheless, Upper Triassic Karmutsen volcanic strata in southern Wrangellia display both paleolatitudes concordant with cratonic reference poles and large rotations (nearly 180° for Vancouver Island [*Irving and Wynne*, 1990]) and are thus consistent with the reconstruction.

Conclusions

Enclosure of the CC ocean by Early Mesozoic counterclockwise rotation of ST, pivoting about a hinge zone in the YTT, is a solution to the geometric problem posed by the presence of Tethyan CC faunas between coeval, less exotic faunas of the Stikine Assemblage and Harper Ranch terrane. It circumvents the necessity of large-scale latitudinal terrane displacements, in accordance with recent revisions of paleomagnetic poles. In the hinge zone, latest Permian to Early Jurassic deformation was intense and prolonged, and clastic sedimentation replaced volcanism much earlier than in the main parts of ST and QN. This configuration accounts for the Early Mesozoic tectonic history of northern QN, ST, and the YTT, which otherwise are anomalous with respect to QN and ST farther south.

To help guide working models for Cordilleran evolution, this paper advocates examination of modern arc and collisional systems as analogues, not merely in cross section but in their entirety. Such an approach demonstrates that along-strike variations in an arc, such as the Marianas, gives essential information about its tectonic history that a representative cross section cannot provide. It shows that rotation and large-scale horizontal bending can have important consequences for real geological elements, whether they be modern arcs or Paleozoic/Mesozoic suspect terranes.

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