Evidence for Early to Late Cretaceous sinistral deformation in the Tchaikazan River area, southwestern British Columbia: Implications for the tectonic evolution of the southern Coast belt

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Abstract

*Geological mapping in the Tchaikazan River area has found evidence for Cretaceous sinistral translation within the southern Coast belt. Previously unrecognized large sinistral shear zones are documented within the study area, with latest movement along these zones dated at 89 Ma. The newly recognized Twin Creek assemblage, a sedimentary sequence cut by a Permian-Triassic aplitic dyke (*ca. *251 Ma), is correlated with rocks of the Cadwallader terrane. Based on this correlation, we interpret the adjacent Tchaikazan fault to be the locus of at least 40 to 50 km of sinistral displacement, and as much as 180 km, prior to its reactivation as an Eocene dextral strike-slip fault. Lower Cretaceous rocks of the Tchaikazan River formation are correlated with the East Waddington thrust belt and may have provided source material for the Hauterivian through Albian portion of the Tyaughton-Methow basin. The sinistral displacement we infer along the Tchaikazan fault may be part of a broad zone of Cretaceous sinistral faults that translated the southwest Coast belt, together with slivers of Stikine and Cadwallader terranes, southward to a position outboard of the Bridge River terrane and overlying Tyaughton-Methow basin.*

These relationships are consistent with the model proposed by Monger et al. *(1994) for Cretaceous sinistral displacement of the southwest Coast belt and related terranes. Early Cretaceous emplacement of the southwestern Coast belt, as suggested by Umhoefer* et al. *(2002), cannot be proven but is suspected based on stratigraphic relationships from the Tchaikazan River area.*

Résumé

La cartographie géologique dans la région de la rivière Tchaikazan a révélé des preuves de translation sénestre durant le Crétacé dans le sud du Domaine côtier. De larges zones de cisaillement sénestres, auparavant méconnues, sont documentées dans la région d'étude. Les plus récents mouvements le long de ces zones remontent à 89 Ma. L'assemblage nouvellement reconnu de Twin Creek, une séquence sédimentaire recoupée par un dyke aplitique d'âge permien-triassique (environ 251 Ma), est corrélé avec les roches du terrane de Cadwallader. Cette corrélation nous permet d'interpréter que la faille Tchaikazan attenante aurait accommodé au moins 40 à 50 km, et peut-être jusqu'à 180 km, de déplacement sénestre, avant sa réactivation en décrochement dextre à l'Éocène. Les roches du Crétacé inférieur de la formation de Tchaikazan River sont corrélées avec la zone de charriage d'East Waddington, et pourraient avoir alimenté la portion hauterivienne à albienne du bassin Tyaughton-Methow. Le déplacement sénestre que nous interprétons le long de la faille Tchaikazan pourrait faire partie d'une vaste zone de failles sénestres crétacées le long desquelles la partie sud-ouest du Domaine côtier ainsi que des écailles appartenant aux terranes de Cadwallader et de Stikine, ont subi une translation vers le sud pour se retrouver dans un emplacement au large du terrane de Bridge River et du bassin sus-jacent Tyaughton-Methow.

Ces relations sont compatibles avec le modèle proposé par Monger et al. *(1994) pour le déplacement sénestre crétacé de la partie sud-ouest du Domaine côtier et des terranes affiliés. La mise en place au Crétacé précoce de la partie sud-ouest du Domaine côtier, tel que suggéré par Umhoefer* et al. *(2002), ne peut être prouvée mais est soupçonnée en raison des relations stratigraphiques dans la région de la rivière Tchaikazan.*

INTRODUCTION

The western part of the Canadian Cordillera, comprising the Intermontane, Coast, and Insular belts is constructed from a collage of crustal fragments (terranes) that were accreted to the former western continental margin of North America during Mesozoic through Paleogene time. The Coast belt, characterized by rugged mountains underlain in large part by Late Jurassic to Paleogene granitic rocks of the Coast plutonic complex, forms the boundary between an inner, continentward, group of terranes (Intermontane superterrane) that probably was accreted to the old continental margin by Middle Jurassic time, and a group of outer terranes (Insular superterrane) whose time of accretion is more problematical. Earlier models (*e.g.* Davis *et al.,* 1978; Monger *et al.,* 1982) interpreted the Coast belt as containing a mid-Cretaceous suture between the Intermontane and Insular superterranes, whereas later models (*e.g.* van der Heyden, 1992; McClelland *et al.,* 1992) suggested that the granitic rocks of the Coast belt were intruded across Intermontane and Insular terranes that had all been mutually juxtaposed and accreted to western North America by Middle Jurassic time.

Critical to evaluating these and other models of Coast belt tectonics are relationships in southern British Columbia, where the Coast belt can be divided into western and eastern parts based on differences in plutonic rocks, metamorphism, supracrustal rocks, and structural style (Fig. 1; Monger and Journeay, 1994). The southwestern Coast belt (SWCB) is dominated by Middle Jurassic to mid-Cretaceous plutonic rocks. These plutons intrude Wrangellia (part of the Insular superterrane) along the western margin of the belt, and enclose pendants and septa of variably metamorphosed and deformed Early Cretaceous and older volcanic and sedimentary rocks correlated with Wrangellia terrane exposed on Vancouver Island and that are found across the full width of the southwestern Coast belt.

The southeastern Coast belt (SECB) contains a smaller percentage of granitic rocks than the southwestern Coast belt, and these range in age from mid-Cretaceous through Paleogene. Supracrustal rocks include upper Paleozoic through mid-Mesozoic rocks assigned to the oceanic Bridge River terrane and the Cadwallader-Methow arc terrane, as well as overlapping upper Middle Jurassic to mid-Cretaceous clastic sedimentary rocks of the Tyaughton-Methow basin that are in places metamorphosed to high grade and intensely deformed. These assemblages are mutually juxtaposed and separated from the adjacent southwestern Coast belt by complex systems of contractional, strike-slip, and extensional faults of mainly Late Cretaceous and Cenozoic age.

According to the Cretaceous collisional model, contractional structures and associated high-grade metamorphism and plutonism within and adjacent to the southeastern Coast belt reflect crustal thickening associated with accretion of the Insular superterrane (including the southwestern Coast belt) to the western margin of the Intermontane superterrane during mid-Cretaceous to early Late Cretaceous time (Monger *et al.,* 1982; Fig. 2A). Convergence was accomplished by east-dipping subduction, as interpreted from Early to mid-Cretaceous tectonic elements that include the Okanagan-Spences Bridge arc built across the western Intermontane belt, an associated fore-arc basin (lower part of Tyaughton-Methow basin) within the adjacent southeast Coast belt, and a subduction-accretion complex (part of Bridge River terrane) farther west within the southeastern Coast belt. The coeval Gambier arc of the southwestern Coast belt, together with younger magmatic arc rocks of the Coast belt, are interpreted as products of a separate east-dipping subduction zone along the outboard margin of the Insular superterrane that continues to be active at the present time.

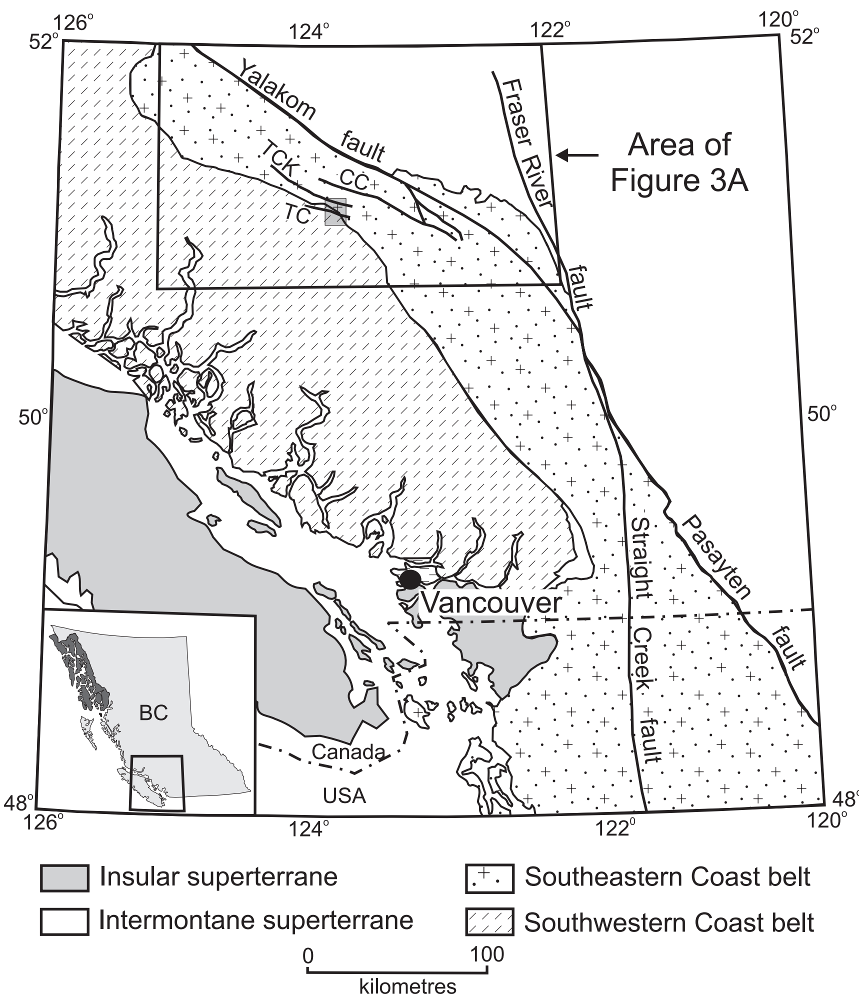

Figure 1. *Location of study area (modified from Schiarizza* et al., *1997). Small box represents the field area. The area highlighted by the large box is shown in Figure 3A.*

The older model of mid-Cretaceous collision has been challenged on the basis of data from central and northern British Columbia and adjacent Alaska, where there is no indication of a mid-Cretaceous oceanic suture between the Insular and Intermontane superterranes, and evidence favours Early to Middle Jurassic ties between them (van der Heyden, 1992; McClelland *et al.,* 1992; Mahoney, 1994; Gehrels, 2001). These relationships spawned models in which the Insular superterrane was amalgamated with the Intermontane superterrane by Middle Jurassic time, and the Coast belt is a long-lived (Middle Jurassic to Cenozoic) Andean-style magmatic arc built across both superterranes (van der Heyden, 1992; McClelland *et al.,* 1992). In this interpretation, the mid-Cretaceous contractional structures within the Coast belt are intraplate structures that in part collapsed a series of intra-arc basins (Fig. 2B).

Monger *et al.* (1994) presented a variation on the single-arc model that attempts to reconcile the conflicting data from the southern versus the central and northern parts of the Coast belt. The salient geological data that must be addressed in any model for the evolution of the southern Coast belt include: (a) the pinching out of remnants of a long-lived oceanic basin north of 50° latitude (the Bridge River terrane); (b) the apparent doubling of an Early to Late Cretaceous volcanic arc (Gambier and Okanagan-Spences Bridge arcs); and (c) paleocurrent data from sedimentary basins (Tyaughton-Methow basin) along the western margin of the orogen that record an abrupt change in direction during the Early Cretaceous and an increase in volcanic detritus (Umhoefer *et al.,* 2002). Monger *et al.* (1994) suggested that the Okanagan-Spences Bridge arc of the southwestern Intermontane belt and the Gambier arc of the southwestern Coast belt are parts of the same arc that was built on the Jurassic-Cretaceous North American plate margin, across previously accreted terranes of the Insular and Intermontane belts. The southwest Coast belt arc was originally along strike and to the north of the Okanagan-Spences Bridge arc, but was displaced ~800 km southward along an orogen-parallel sinistral fault system during the late Early Cretaceous, such that it lay west of the accretionary fore-arc complex of the southeastern Coast belt, to be subsequently imbricated beneath it during the mid-Cretaceous to early Late Cretaceous contractional deformation event (Fig. 2C). Umhoefer *et al.* (2002) presented a similar model except that they push the timing of onset of the sinistral fault system back to the Late Jurassic (Fig. 2D).

Here, we describe the stratigraphy and structural relationships within the Tchaikazan River area, located just north of the northern termination of the Bridge River terrane and straddling the boundary between the southeastern and southwestern Coast belts. We document the presence of sinistral shear zones that were active during early Late Cretaceous time, and we present evidence that the Tchaikazan fault may have been the locus for significant sinistral displacement prior to its reactivation as an Eocene dextral strike-slip fault. Finally, we present a model of tectonic evolution for the southern Coast belt that builds on the models of Monger *et al.* (1994) and Umhoefer *et al.* (2002).

REGIONAL GEOLOGICAL SETTING

The study area is located at the boundary between the southwestern and southeastern Coast belts, ~200 km north of Vancouver (Fig. 1). The Tchaikazan fault, a major structure that separates rocks of sharply contrasting character along most of its length, cuts through the northern portion of the study area (Fig. 3A; Umhoefer *et al.,* 1994). Northeast of the fault, rocks associated with the southeastern Coast belt comprise a nearly complete section of Middle Jurassic to mid-Cretaceous dominantly clastic rocks of the Tyaughton-Methow basin, including the Relay Mountain, Jackass Mountain, and Taylor Creek groups. The Jackass Mountain Group overlies rocks of the Cadwallader terrane to the north and the Relay Mountain and Taylor Creek groups overlie the Bridge River terrane to the south (Fig. 3B; Rusmore and Woodsworth, 1991; Garver, 1992; Umhoefer *et al.,* 1994; Schiarizza *et al.,* 1997). In contrast, rocks southwest of the Tchaikazan fault comprise the East Waddington thrust belt, a structurally and stratigraphically complex belt of rocks consisting of Triassic volcanic rocks of the Mount Moore and Mosely formations and Cretaceous volcanic, volcaniclastic, and sedimentary rocks of the

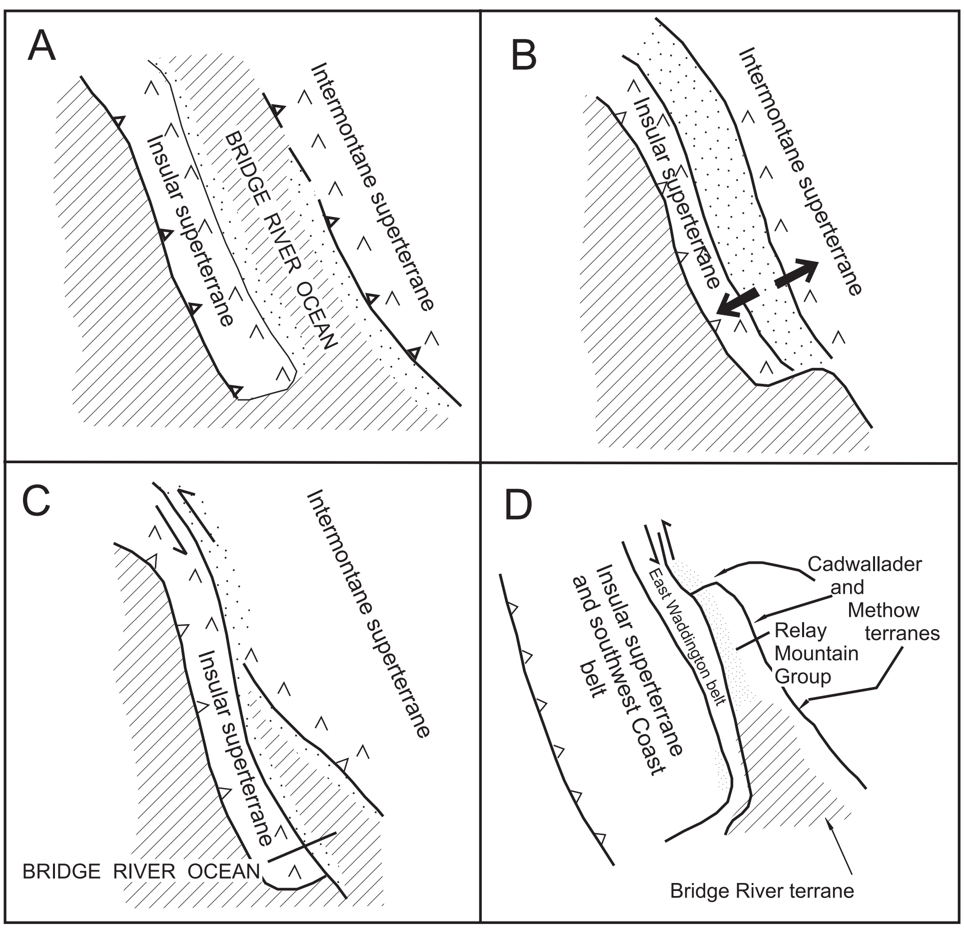

Figure 2. *Tectonic models for the western margin of the Canadian Cordillera. (A) Monger* et al. *(1982); (B) van der Heyden (1992); (C) Monger* et al. *(1994); (D) Umhoefer* et al. *(2002). Modified from Monger and Journeay (1994).*

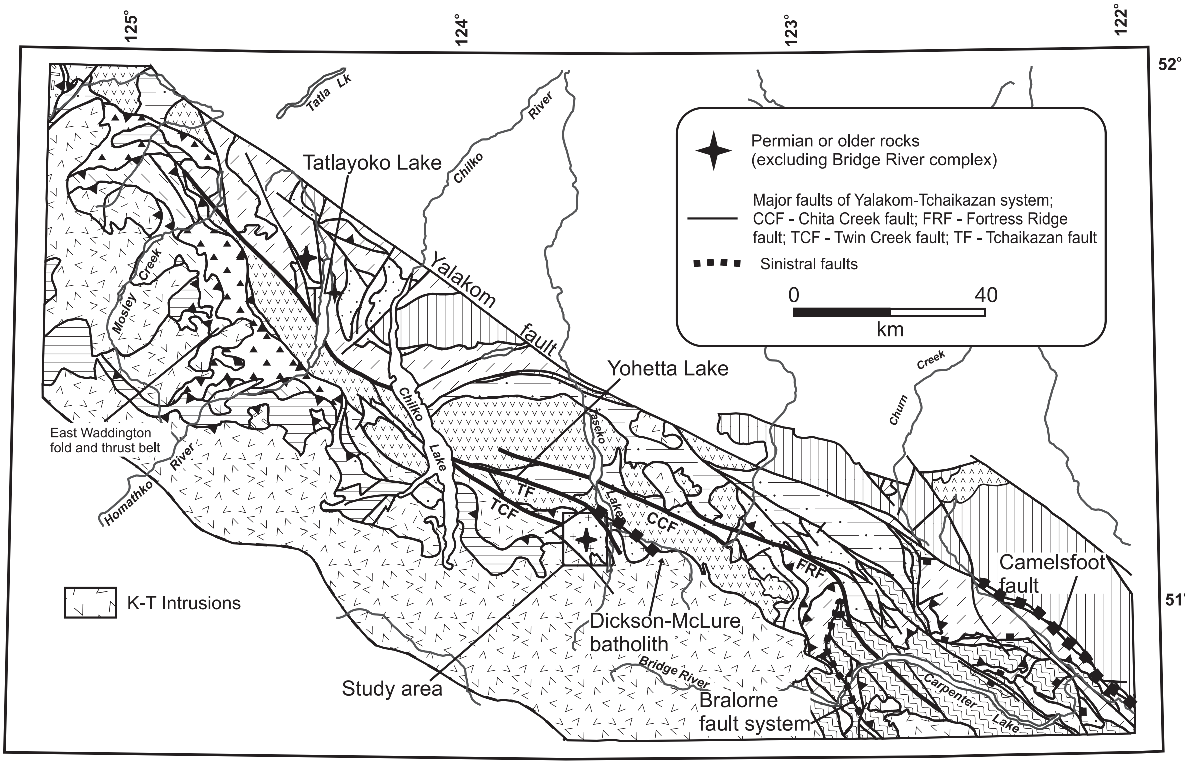

Figure 3A. *Regional geology map showing distribution of terranes and regional fault systems. Map is based on regional mapping by Rusmore and Woodsworth (1991, 1994), Mustard* et al. *(1994), Umhoefer* et al. *(1994), Schiarizza* et al. *(1997), and Israel (2001). Tchaikazan River area is highlighted by the box.*

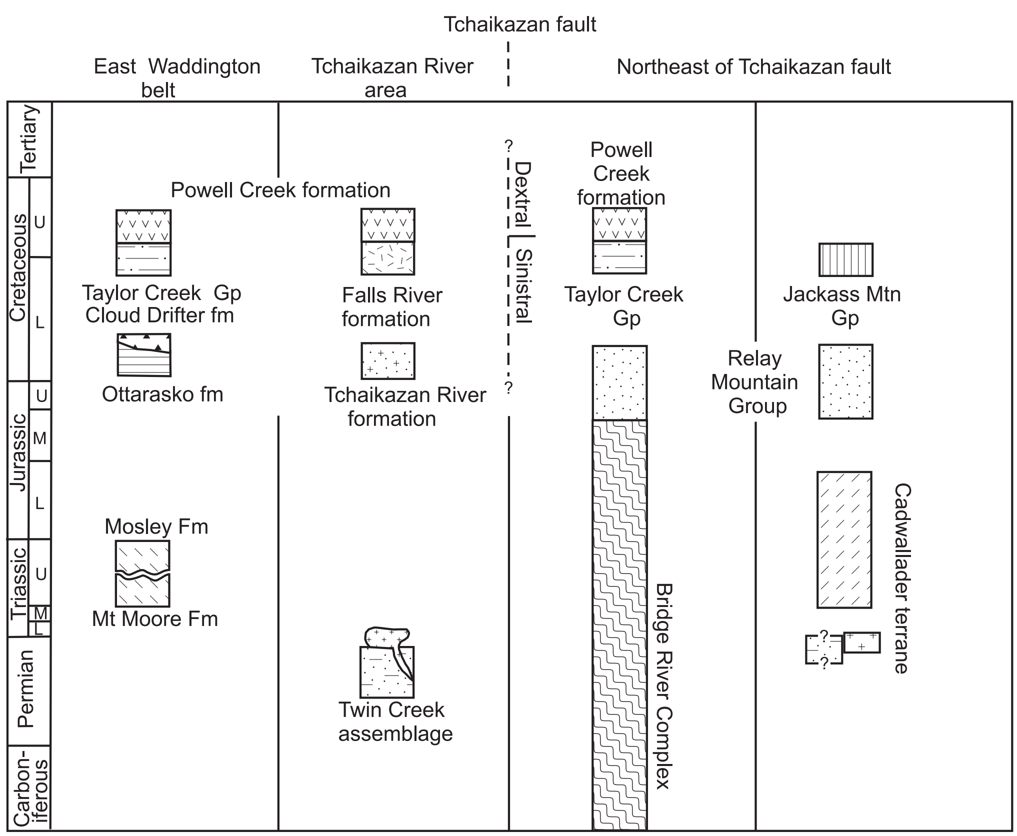

Figure 3B. *Stratigraphic chart for Figure 3A. L = Lower, M = Middle, U = Upper.*

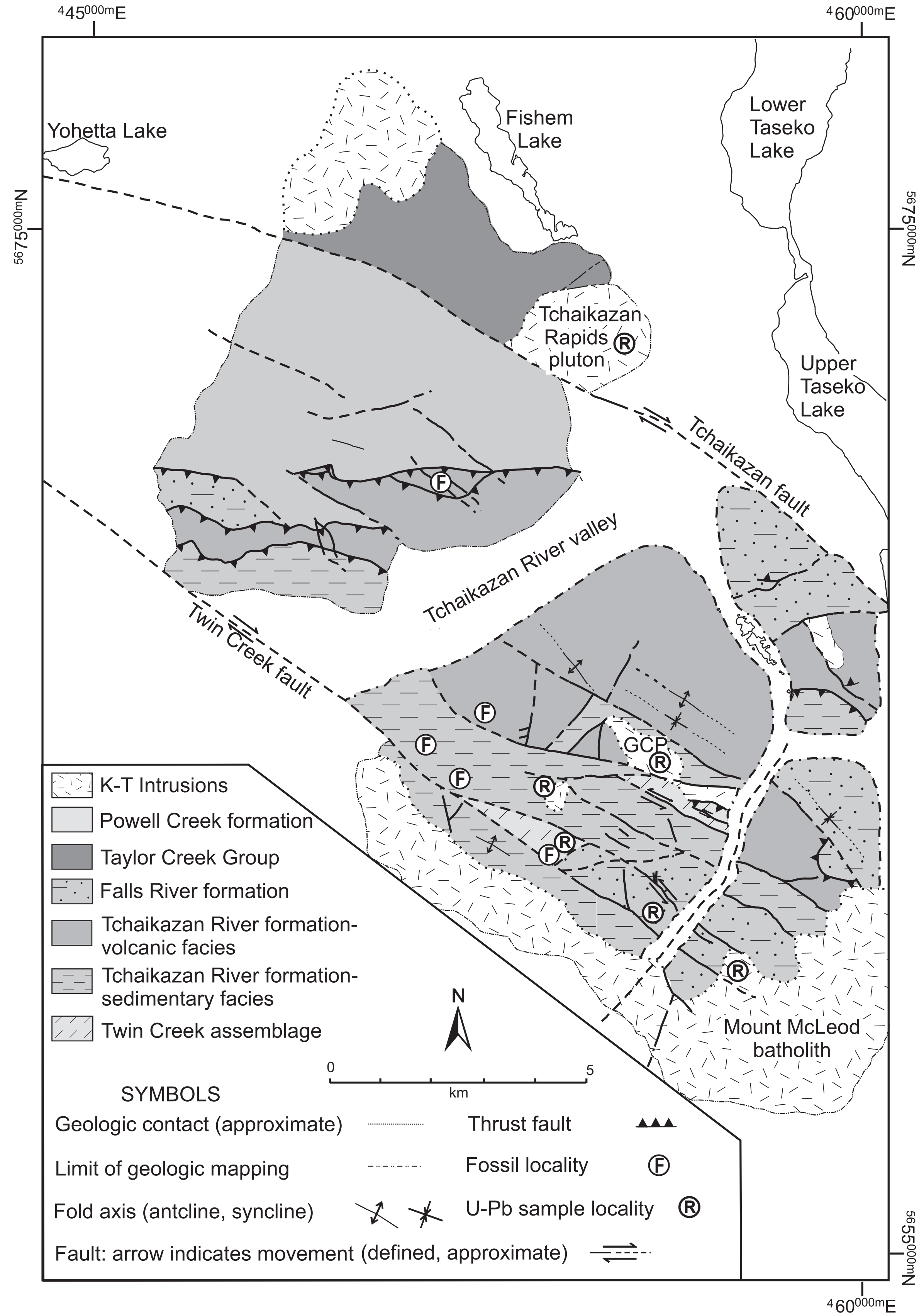

Figure 4. *Generalized geology of the Tchaikazan River area. GCP = Grizzly Creek pluton.*

Cloud Drifter and Ottarasko formations and the Monarch volcanics (Fig. 3B; Rusmore and Woodsworth, 1991; Umhoefer *et al.,* 1994; Mustard and van der Heyden, 1994; van der Heyden *et al.,* 1994; Schiarizza *et al.,* 1997; Rusmore *et al.,* 2000). The Mount Moore and Mosely formations are tentatively correlated with the Stikine terrane (Rusmore and Woodsworth, 1994; Umhoefer *et al.,* 1994), while the Cloud Drifter and Ottarasko formations and Monarch volcanics have been correlated with the Lower Cretaceous Gambier Group of the southwestern Coast belt (Rusmore and Woodsworth, 1991; Rusmore and Woodsworth, 1994; Umhoefer *et al.,* 1994; Rusmore *et al.,* 2000). The Upper Cretaceous Powell Creek formation overlaps rocks to the northeast and southwest of the Tchaikazan fault.

Mid-Cretaceous contraction of the Coast belt was accommodated primarily by the development of southwest-verging thrust faults, located near the eastern edge of the Insular superterrane, that were active between 100 and 91 Ma (Journeay and Friedman, 1993; Umhoefer and Miller, 1996). Younger (*ca.* 95–85 Ma) north- to northeast-verging thrust faults, located near the western edge of the Intermontane superterrane, as exemplified in the East Waddington thrust belt, are interpreted as back thrusts to the major southwest-verging faults (Rusmore and Woodsworth, 1994). South of the Tchaikazan fault in the East Waddington thrust belt, the northeast-verging thrust sheets consist of amphibolite-grade metamorphic rocks, whereas across the Tchaikazan fault, thrust faults are rare and, when found, typically within very low-grade rocks.

A regionally developed system of latest(?) Cretaceous to Eocene dextral strike-slip and locally important faults cuts all other structures (Umhoefer and Schiarizza, 1996; Schiarizza *et al.,* 1997). This system is characterized by large fault arrays and associated minor structures with hundreds of kilometres of accumulated offset. Examples include the Yalakom, Fortress Ridge, Chita Creek, and Tchaikazan fault systems (Fig. 3A).

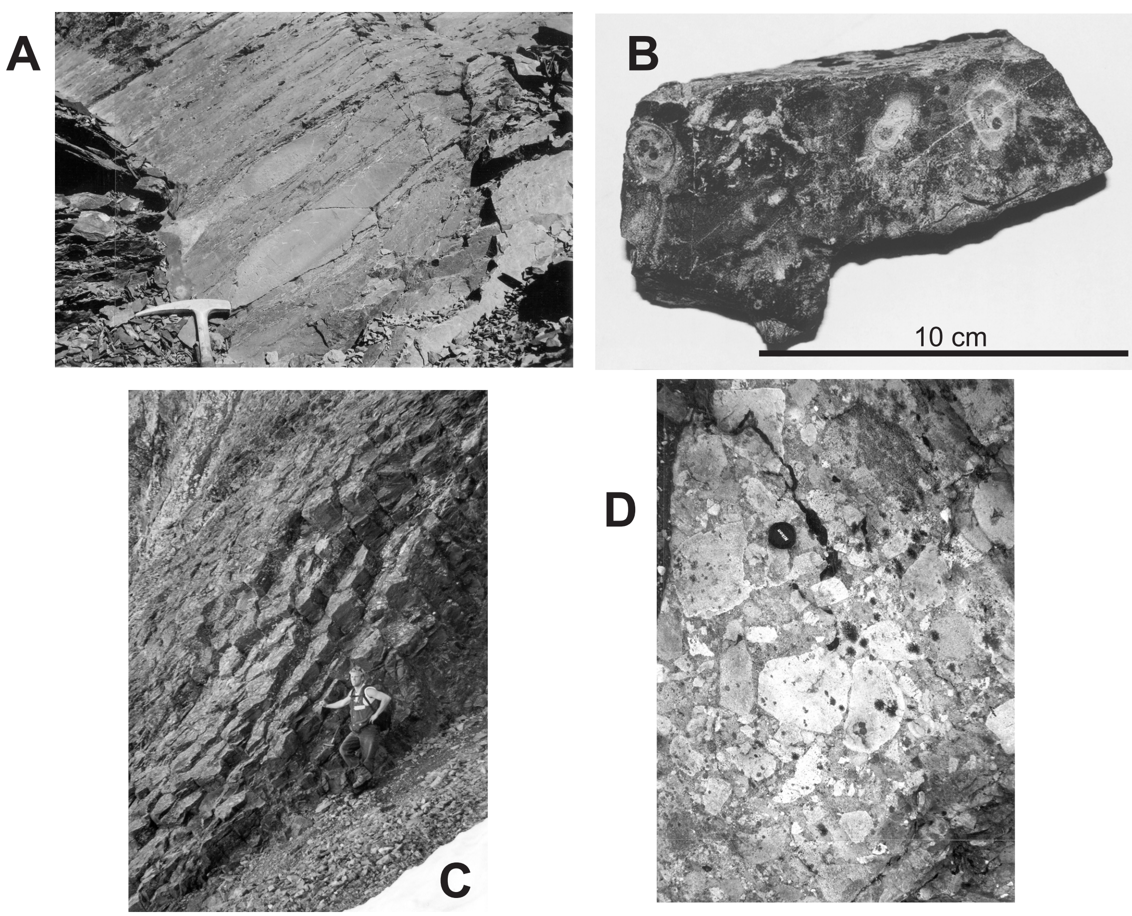

Figure 5. *(A) Limey sandstone channels within black shales of the Twin Creek assemblage. (B) Fossils found within the Twin Creek formation. (C) Columnar jointed andesitic basalts of the Tchaikazan River formation. (D) Felsic to intermediate volcanic clasts within breccia at the base of the Falls River formation.*

STRATIGRAPHY OF THE TCHAIKAZAN RIVER AREA

The Tchaikazan River area is underlain by Permian-Triassic to mid-Cretaceous sedimentary, volcanic, and volcaniclastic rocks associated with several tectonostratigraphic assemblages intruded by mid- to Late Cretaceous granitic rocks of the Coast plutonic complex (Fig. 4; Jeletzky and Tipper, 1968; Tipper, 1978; McLaren, 1990; Israel and Kennedy, 2000). We describe these rock units in detail below to illustrate their stratigraphic characteristics, and we suggest potential correlations to place the study area into a regional tectonic framework.

Twin Creek Assemblage

Two fault-bound packages of marine sedimentary rocks found in the south-central portion of the study area are assigned to the Twin Creek assemblage (Fig. 4). This unit is not well dated but must be older than an aplitic/dacitic dyke that yields a U-Pb zircon age of 251 ± 16 Ma (Appendix Table A1; Appendix Fig. A1A). The thickness of the formation is not known as both upper and lower contacts with other units are everywhere faulted. The Twin Creek assemblage consists mainly of turbiditic sediments likely deposited in a nearshore marine environment.

The assemblage is characterized by dark grey to black, silty turbidites, dark brown to black shale and minor beds of grey weathering limestone and medium-grained sandstone. In most areas, the silty turbidites dominate, yet periods of relative quiescence are indicated by shale beds up to several metres thick. The shale beds locally include limey sandstone channels (Fig. 5A). Rare limestone beds up to several centimetres thick and always overlain by medium-grained, gritty sandstone are found in the most northerly exposure of the Twin Creek assemblage. Structures of probable organic origin characterize the contact between the limestone and sandstone beds locally (Fig. 5B). Breccia of unknown thickness, exposed at the structural top of the section, consists of cobble-sized pyroxene porphyry clasts and minor, angular fragments of siltstone and shale, probably derived from the lower beds, within a dark shaley matrix.

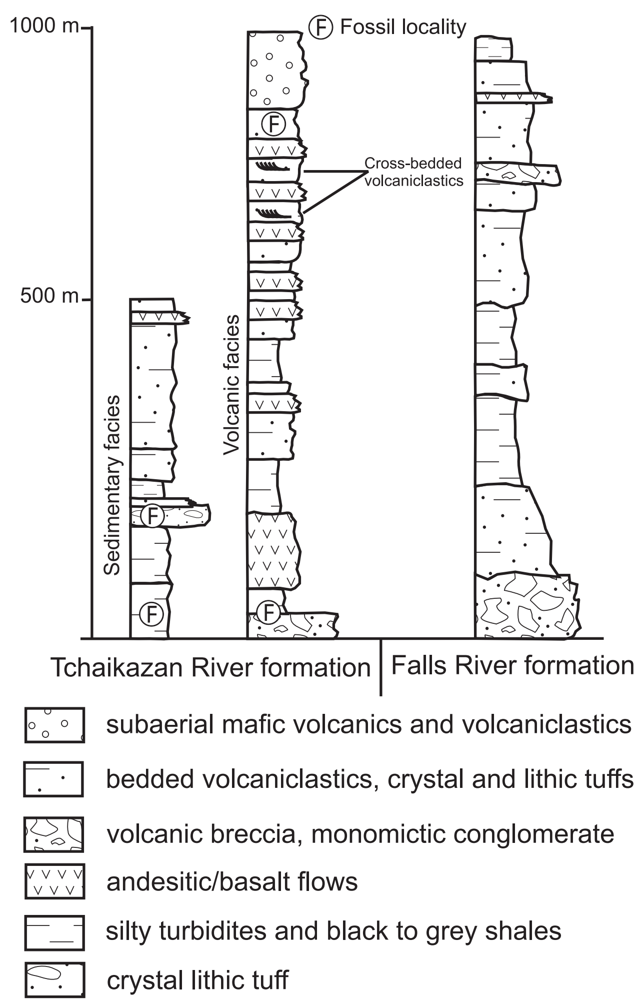

Figure 6. *Schematic stratigraphic columns for the Tchaikazan River and the Falls River formations.*

Tchaikazan River Formation

The informal Tchaikazan River formation is the most areally extensive unit within the field area and is characterized by packages of rock that can be subdivided into a sedimentary-dominated facies and a volcanic-dominated facies (Fig. 4). The formation is found in fault contact with the Twin Creek assemblage and the Falls River formation, and, in the northwest corner of the study area, is thrust over top of the lower Upper Cretaceous Powell Creek formation. Deposition of the sedimentary facies of the Tchaikazan River formation is thought to have taken place in a turbiditic fan that shallowed upwards and eventually became overrun by shallow-marine to subaerial volcanic and volcaniclastic material. The age of the Tchaikazan River formation is Early Cretaceous (Hauterivian or older), based on fossils found within the sedimentary facies (McLaren, 1990).

Sedimentary Facies

The sedimentary facies of the Tchaikazan River formation is characterized by a sequence of fine-grained marine clastic rocks, pebble conglomerates, volcaniclastic material, and minor volcanic flows (Fig. 6). The lowest exposed rocks are finely laminated siltstone turbidites with individual beds up to 10 cm thick, interbedded with shales and argillites that contain rare belemnites, gastropods, and bivalves. Approximately one-third of the way up the section a well-sorted pebble conglomerate forms a laterally continuous bed up to one metre thick composed of rounded to subangular clasts of siltstone, sandstone, and minor chert less than 7 cm in diameter, within a fine-grained silty matrix. Crystal lithic tuff beds, commonly less than 2 m thick, but locally up to several tens of metres thick, are characterized by pebble-sized fragments of intermediate volcanic rocks, siltstone, and shale that lie within a crystal-rich volcanic matrix. The tuff grades into turbidites similar to, but slightly coarser than, those lower in the section. The turbidites pass sharply upsection into coarser grained, massive to well-bedded volcaniclastic rocks that resemble the matrix of the crystal lithic tuff beds. Alternating red and green volcaniclastic strata become dominant near the top of the exposed section which culminates in rare vesicular andesitic to basaltic flows.

Volcanic Facies

The volcanic facies of the Tchaikazan River formation is characterized by subaqueous to subaerial volcanic rock, intercalated with shallow-marine sedimentary rocks that define an overall shallowing-upward sequence (Fig. 6). The base of the exposed section is defined by a monomict breccia composed of angular fragments of intermediate volcanic rock, closely packed in a dark silty matrix. The breccia is overlain by massive basaltic to andesitic flows over 100 m thick. The flows commonly exhibit columnar joints defining columns that range in diameter from 20 cm to over one metre across (Fig. 5C). Pillowed flows cap most of the massive flows, which in turn are overlain by well-bedded volcaniclastic turbidites consisting of pumice-rich pebble conglomerate that exhibits normal grading, and also coarse-grained, commonly cross-stratified volcanic sandstone. Minor metre-scale flows are intercalated with the sandstone and turbidites. Similar sequences of flows, coarse sandstone, and turbidites are repeated several times through the section. The top quarter of the section is dominated by fine- to medium-grained sandstone that has abundant terrestrial plant fossils throughout. Oxidized, subaerial volcanic material is widespread at the top of the exposed section.

Falls River Formation

The informal Falls River formation includes volcanic breccia, volcaniclastic sandstone, marine sedimentary strata, and rare volcanic flow rock that outcrop in fault-bound lenses throughout the field area. It is distinguished from the Tchaikazan River formation by the more intermediate to felsic composition of the volcanic rocks and the abundance of fine-grained marine strata. The age of the Falls River formation is not well defined but is probably late Early Cretaceous. The Mt. McLeod batholith cuts the Falls River formation in the southeast corner of the study area (Fig. 4) and provides a minimum age of deposition of 103.8 ± 0.5 Ma (Appendix Table A1; Appendix Fig. A1B). A felsic tuff horizon within the Falls River formation yields an imprecise U/Pb zircon age of 102–105 Ma.

The lowest exposure of the section is defined by almost 100 m of massive volcanic breccia, characterized by intermediate to felsic volcanic clasts up to 50 cm in diameter within a crystal-rich, medium-grained matrix (Fig. 5D). A thick package of massive to well-bedded volcaniclastic sandstone, displaying normal grading, overlies the breccias gradationally. Thin ash layers and lapilli-sized pumice fragments are found throughout the sandstone. The volcaniclastic rock grades into siltstone turbidites that eventually give way to black, finely laminated siltstone and massive shale. Above the sedimentary rocks the unit again becomes dominantly volcanic, and is characterized by felsic to intermediate volcaniclastic strata and minor flows. The flows are andesitic, no more than one metre thick, commonly a deep maroon to purple colour and contain abundant feldspar phenocrysts and variable amounts of vesicles. The flows are associated with thin breccia beds that contain abundant red jasper fragments, a characteristic that makes them very distinct from flows in the Tchaikazan River formation.

Powell Creek Formation

In the northwestern part of the study area, a large expanse of subaerial volcanic and volcaniclastic rocks, previously mapped as an undifferentiated volcanic and volcaniclastic unit by McLaren (his unit LKpv, 1990), forms the footwall to several large thrust faults, with rocks of the Tchaikazan River formation in their hanging walls (Fig. 4). This unit is similar to rocks mapped to the northeast of the Tchaikazan River area by Schiarizza *et al.* (1997) and is here assigned to the informal Powell Creek formation on the basis of lithological similarities and relationships with other units.

The Powell Creek formation is composed of massive- to well-bedded pyroclastic and volcaniclastic rocks of a deep maroon to red colour that are heavily weathered, which results in poor exposures that are characterized by hundreds of metres of rubble. The volcaniclastic rocks vary from fine-grained tuffaceous horizons to pebble breccias with intermediate volcanic, siltstone, and sandstone clasts. Bedded intervals are commonly up to 2 m thick, whereas massive portions are several tens of metres thick. Lahar deposits up to 20 m thick are found near the top of the section, with clasts of intermediate volcanic rocks several metres in diameter within a fine- to medium-grained muddy matrix.

The Powell Creek formation has been well studied in areas to the northeast and east of the Tchaikazan River area. There, it overlies Albian-Cenomanian rocks and is intruded by the 92 Ma Dickson-McClure batholith, relationships that suggest the base must be Turonian in age (Schiarizza *et al.,* 1997). Maxson (1996) reported ages of 94.6 ± 6.6 Ma and 95.9 ± 3.7 Ma from near the bottom of the formation along the south limb of the Tatlow syncline (north of Yohetta Lake) that probably represent the best date for the base of the formation.

Regional Correlations

Twin Creek Assemblage

The Twin Creek assemblage is significant as it represents the only known rocks in the area that are Permian-Triassic or older; however, correlation with other units is made difficult by the fact that rocks of this age range are rare in this part of the Cordillera. We correlate the Twin Creek assemblage with rocks believed to be the basement of the Cadwallader terrane based on the following lines of evidence.

Rocks most similar to the Twin Creek assemblage both in age and lithological characteristics are found near Tatlayoko Lake, northwest of the study area (Fig. 3). On the east shore of Tatlayoko Lake rocks of the Cadwallader terrane overlie a tonalite dated at *ca.* 254 Ma (Schiarizza *et al.,* 2002; Schiarizza *et al.,* 1995). Found to the west of Tatlayoko Lake is a large pendant comprised of a Paleozoic to Triassic meta-siltstone-sandstone sequence within a 220 Ma tonalite (Schiarizza *et al.,* 2002). The relationships observed at Tatlayoko Lake suggest that the 254 Ma tonalite and the pendant of meta-sediments form part of the basement upon which the Cadwallader arc-terrane was built. The 254 Ma tonalite is the closest intrusive rock of similar age to the dyke that intrudes the Twin Creek assemblage, and the meta-sedimentary rocks that form the pendant also have characteristics that are similar to the Twin Creek assemblage. Based upon these similarities, we believe that a viable correlation can be made between the rocks found in the Tatlayoko Lake area and the Twin Creek assemblage.

Tchaikazan River Formation

Previous maps of the Tchaikazan River area placed many of the rocks that are now mapped as Tchaikazan River formation within the Taylor Creek Group (Jeletzky and Tipper, 1968; Tipper, 1978; McLaren, 1990). This is unlikely as the Taylor Creek Group is a dominantly sedimentary unit of Albian age (Garver, 1992) whereas rocks within the Tchaikazan River formation are dominantly volcanic and are Hauterivian or older. Rocks of similar age and composition include the Ottarasko and Cloud Drifter formations and the Monarch volcanics of the East Waddington thrust belt (van der Heyden, 1991; Mustard and van der Heyden, 1994; Umhoefer *et al.,* 1994; Schiarizza *et al.,* 1997; Rusmore *et al.,* 2000). The Monarch volcanics are characterized by volcanic breccias, crystal lithic tuff, and andesitic to basaltic flows (van der Heyden, 1991; Rusmore *et al.,* 2000), and the Ottarasko formation consists of basaltic to andesitic breccia, purple to green tuff horizons, and rare massive rhyolite (Umhoefer *et al.,* 1994). The Cloud Drifter formation, described by Umhoefer *et al.* (1994), overlies rocks of the Ottarasko formation in some areas, is a coeval facies in others, and is similar to some of the sedimentary rocks within the Tchaikazan River formation.

The similarities in age and composition of rocks within the East Waddington thrust belt with the Tchaikazan River formation suggests a strong correlation, consistent with their along-strike position from one another. The new correlations reinforce the differences in rock types and tectonic settings, described by Umhoefer *et al.* (1994), that are found across the Tchaikazan fault.

Falls River Formation

Felsic, fragmental volcanic rocks are described both to the northwest (Mustard and van der Heyden, 1997) and to the east (Schiarizza *et al.,* 1997) of the study area. In both cases, the rocks are assigned to the Taylor Creek Group. Mustard and van der Heyden (1997) described thrust slices of 106.8 +7/-0.4 Ma felsic volcanic rocks within the East Waddington thrust belt and assign them to the Taylor Creek Group based upon their age. To the east, Schiarizza *et al.* (1997) documented a similar package of volcanic rocks within the Taylor Creek Group that overlies the Lizard formation of Albian age that is overlain by Albian to Cenomanian Beece Creek succession.

Although the age of the Falls River formation is not well constrained, the felsic to intermediate nature of the package suggests a reasonable correlation with the Taylor Creek Group volcanic unit described above. The stratigraphic and structural relationships found in the Tchaikazan River area are similar to those described by Mustard and van der Heyden (1997) in the East Waddington thrust belt. Furthermore, McLaren (1990) and Umhoefer *et al.* (1994) described a package of similar felsic to intermediate tuffs and volcanic breccias just west of the field area that yielded definitive early Albian fossils.

STRUCTURAL GEOLOGY

The study area is characterized by folded panels of rock separated by thrust faults or steeply dipping strike-slip faults. The rocks are either unmetamorphosed or of low metamorphic grade and cleavage development is localized within or near strike-slip faults or folds. Deformation within the study area has been separated into three events: (a) north- to northeast-directed large-scale thrust/reverse faulting and fault-related folding; (b) regional and local sinistral faulting; and (c) dextral strike-slip faulting.

D1 Contraction

Large north- to northeast-verging thrust/reverse faults are best displayed in the northwest, central, and eastern portions of the study area (Fig. 4). The faults dip moderately to the south-southwest and generally strike east-west. They are dissected by younger strike-slip faults except in the northwest where they continue for several kilometres to the west, outside of the mapped area (McLaren, 1990). Fault gouge and brecciated wall rock associated with thrust faults are up to several metres thick locally. D1 fold axes trend northwest-southeast and are found throughout the field area. The folds are asymmetric, verge to the north-northeast and are closed to open in form with wavelengths of approximately 100 m. Smaller, parasitic folds are common throughout the study area.

Contraction causing these structures must have been post-Albian as rocks of the Twin Creek assemblage in the central part of the study area are thrust over the Grizzly Cabin pluton, which has been dated at 101.5 ± 0.2 Ma (Appendix Table A1; Appendix Fig. A1C). This interpretation is supported by the presence of thrust faults in the northwest corner of the study area that place rocks of the Tchaikazan River formation over rocks of the Powell Creek formation. It is likely that contraction in the Tchaikazan River area is part of the East Waddington thrust belt (Fig. 3A); deformation within the belt is known to have been active by 87 Ma, possibly earlier, and finished by 84 Ma (Rusmore and Woodsworth, 1994; Umhoefer *et al.,* 1994).

D2 Sinistral Faults

In the southeast corner of the map are several zones of deformation that are interpreted to have accommodated sinistral shear. The zones are steeply dipping faults with strike lengths up to several kilometres (Fig. 4). Thickness of the fault zones range from several metres to hundreds of metres and cut through rocks of the Twin Creek assemblage and the Tchaikazan River and Falls River formations to juxtapose fault slices of each unit against one another. The amount of movement across any fault is unknown because of the lack of good marker horizons; however, it is likely that there is several hundred metres of combined offset, based on the distribution of the different stratigraphic units.

The sinistral faults are associated with both brittle and ductile structures and relatively low metamorphic conditions. The fault zones are characterized by highly sheared rock with well-developed foliations mainly defined by illite, chlorite, and calcite mineral growths. Lineations associated with sinistral slip are rare but include stretched quartz grains with shallow plunges towards the northwest. Within the largest of the sinistral faults, competent stratigraphic horizons surrounded by less competent units are isoclinally folded about vertical fold axes.

Kinematic relationships within the fault zones are interpreted from outcrop exposures where sigmoidal shear fabrics clearly indicate sinistral translation (Fig. 7). These fabrics are consistent wherever seen and are found along nearly the entire lengths of the exposed structures. Folded stratigraphic layers within some of the fault zones are asymmetric and indicate sinistral deformation. At the perimeter of several of the faults, tension veins filled with quartz and chlorite also support the sense of sinistral motion seen on nearby structures (Fig. 7). Along one fault where direction of motion is not well constrained, sedimentary layering in the host rock is folded into the fault zone so as to suggest sinistral movement. This same fault may be interpreted to offset the Grizzly Cabin pluton in sinistral fashion; however caution must be used as the pluton is not well constrained in three dimensions (Fig. 7).

These faults are significant as they represent the first documented, large sinistral faults in the region. Constraints on the timing of sinistral shearing is provided by an 89 ± 0.9 Ma date derived from illite that defines the sinistral shear fabric in the largest of the fault zones (Appendix Table A2; Appendix Fig. A2). Because of the low closure temperature of illite (~200–250°C), this age is considered to be the minimum age of deformation along the faults.

The sinistral faults in the field area are interpreted to be part of a regionally extensive sinistral system with the main locus of deformation along the Tchaikazan fault (expanded on below).

D3 Dextral Faults

The two largest structures in the mapped area are the Tchaikazan and the Twin Creek faults (Fig. 4). These are map-scale structures that cut across all other features and are believed to have formed during a latest Cretaceous to Eocene dextral strike-slip event that affected the entire southeastern Coast belt (McLaren, 1990; Schiarizza *et al.,* 1997). Numerous smaller faults that crosscut all other structures are related to these larger structures.

The Tchaikazan fault has a traceable strike length of nearly 200 km and has a suggested 7 to 8 km of dextral movement along it, based on offset portions of a distinct limestone package within the Mt. Moore formation at the northwest end of the fault (Mustard and van der Heyden, 1994). Within the study area, the Tchaikazan fault occupies large glacial valleys and its position there is, for the most part, inferred. Rocks of the Taylor Creek Group on the north side of the fault are juxtaposed against rocks of the Powell Creek and Falls River formations to the south of the fault. A rare outcrop of the fault along the Tchaikazan River is characterized by a 200 m wide zone of intense, penetratively deformed and highly altered shale and volcaniclastic rocks that probably belong to the Tchaikazan River formation. Fabrics within the fault zone have several orientations but are dominated by a vertical foliation and associated fault lineations that plunge shallowly towards the southeast.

Timing on the Tchaikazan fault is not well constrained. Schiarizza *et al.* (1997) mapped a portion of the Tchaikazan fault to the southeast of the study area where it is apparently intruded by the 92 Ma Dickson-McLure batholith (Fig. 3). However, as it is mapped in this study, the Tchaikazan fault appears to splay off the portion mapped by Schiarizza *et al.* (1997), with the strike changing sharply to the southeast (Fig. 3). This bend to the southeast at the termination of large strike-slip faults is found along almost all other major Eocene dextral faults in the Yalakom fault system (Fig. 3).

The Twin Creek fault is located in the southern portion of the study area and extends the length of the mapped region, parallel to the Tchaikazan fault. Dextral movement on this fault is not proven, but is suspected, based partly on mercury showings found along its length, which are observed within dextral strike-slip faults elsewhere in the region (McLaren, 1990; Schiarizza *et al.,* 1997). The amount of offset along the Twin Creek fault is unknown. This fault cuts the Mt. McLeod batholith, dated at 103.8 ± 0.5 Ma, and therefore must be younger than mid-Cretaceous.

Numerous smaller-scale faults found throughout the study area exhibit orientations and geometries consistent with those anticipated for a left-stepping Riedel shear and are interpreted as transfer structures that accommodated strain between the Tchaikazan and Twin Creek faults. These crosscut the 76 ± 14 Ma Tchaikazan Rapids pluton (Appendix Table A1; Appendix Fig. A1D) and thus represent the latest Cretaceous to Eocene dextral strike-slip faulting that affected much of the western margin of the Canadian Cordillera (*e.g.* Gabrielse, 1985; Struik, 1993; Umhoefer and Schiarizza, 1996).

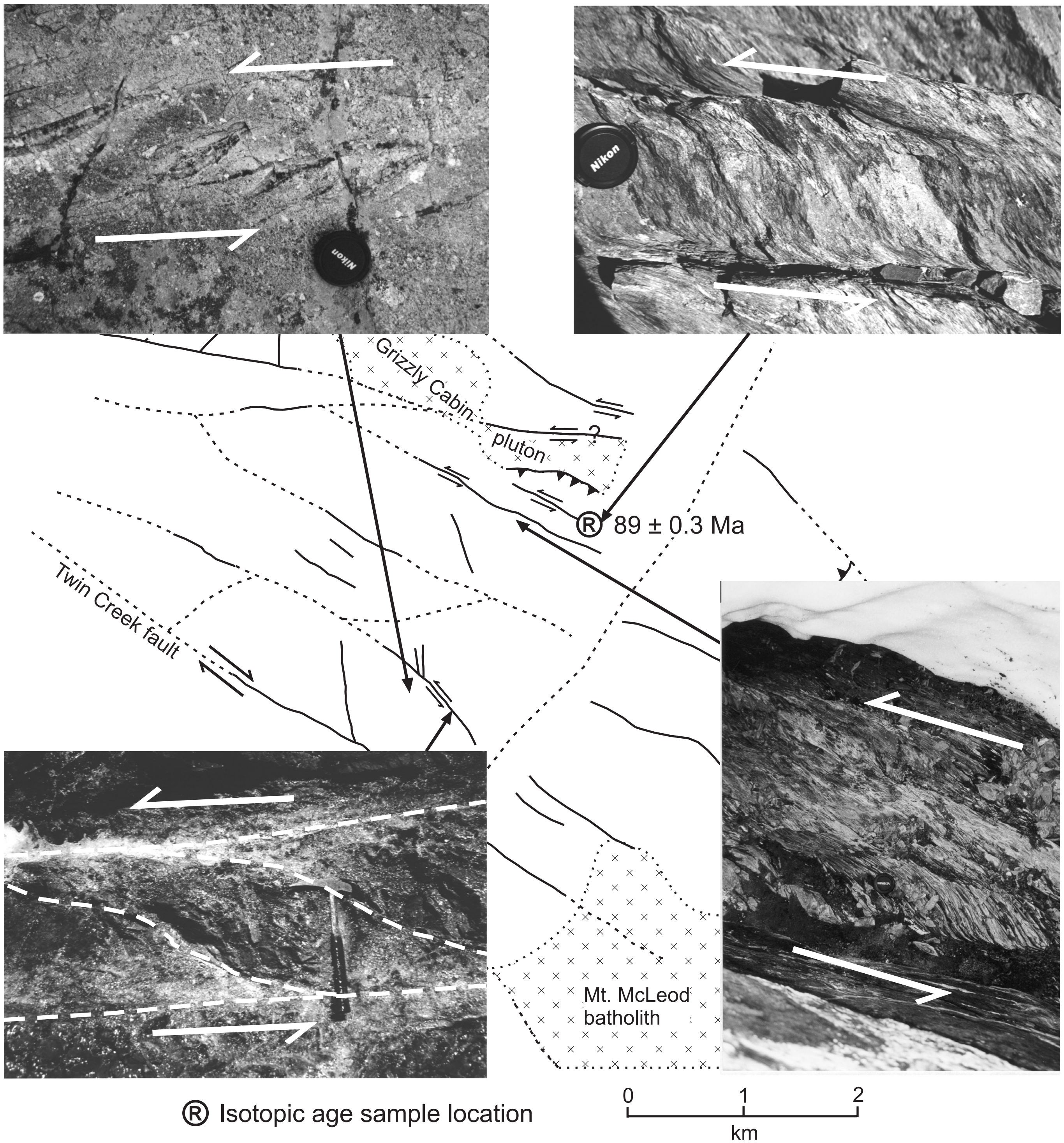

Figure 7. *Fault trace map showing the distribution of sinistral faults within the Tchaikazan River area and location of associated kinematic structures.*

DISCUSSION

Sinistral Displacement Along the Tchaikazan Fault

In the previous section, we documented the presence of early Late Cretaceous sinistral shear zones in rocks on the southwest side of the Tchaikazan fault. In this section, we present local and regional evidence suggesting that the Tchaikazan fault was the locus of significant sinistral displacement prior to its reactivation as part of a Late Cretaceous to Eocene dextral fault system. From this we infer that the sinistral shear zones documented in the Tchaikazan River area are components of a Cretaceous sinistral fault system that in part coincided with the present-day Tchaikazan fault.

The Tchaikazan fault has a strike length of almost 200 km, and extends from just east of the Tchaikazan River area northwestward to near Tatla Lake, where it apparently merges with, or is truncated by, the Yalakom fault (Fig. 8). The sense and amount of displacement on the Tchaikazan fault have been determined only along the northwestern part of the fault, where Mustard and van der Heyden (1997) suggested there was 7 to 8 km of apparent dextral offset. This displacement is compatible with the interpretation that the Tchaikazan fault forms part of a left-stepping dextral fault array that also includes the Chita Creek and Fortress Ridge faults to the east. These faults are components of the Yalakom fault system that was active mainly during early to middle Eocene time (Fig. 3A; Umhoefer and Kleinspehn, 1996; Umhoefer and Schiarizza, 1996). However, an earlier history for the Tchaikazan fault system is suggested by the presence of a fault mapped by Schiarizza *et al.* (1997) that crosses the south end of Taseko Lake and is truncated by the 92 Ma Dickson-McClure batholith a short distance east of the present study area (Fig. 3). It is this fault that we interpret to be the remnants of the sinistral fault system.

A lens of fossiliferous Lower Jurassic sedimentary rocks documented along the Tchaikazan fault near Yohetta Lake by McLaren (1990; Fig. 8) has no counterpart within the Bridge River terrane, but is readily correlated with the Lower Jurassic rocks of Cadwallader terrane, which are well exposed northeast of the Tchaikazan fault in the Chilko Lake-Tatlayoko Lake area. Schiarizza *et al.* (1997) suggested that this lens may have been translated to its present position by a minimum of 20 km of sinistral displacement along the Tchaikazan fault (the distance between the lens and the Taseko fault, the northern boundary between the Bridge

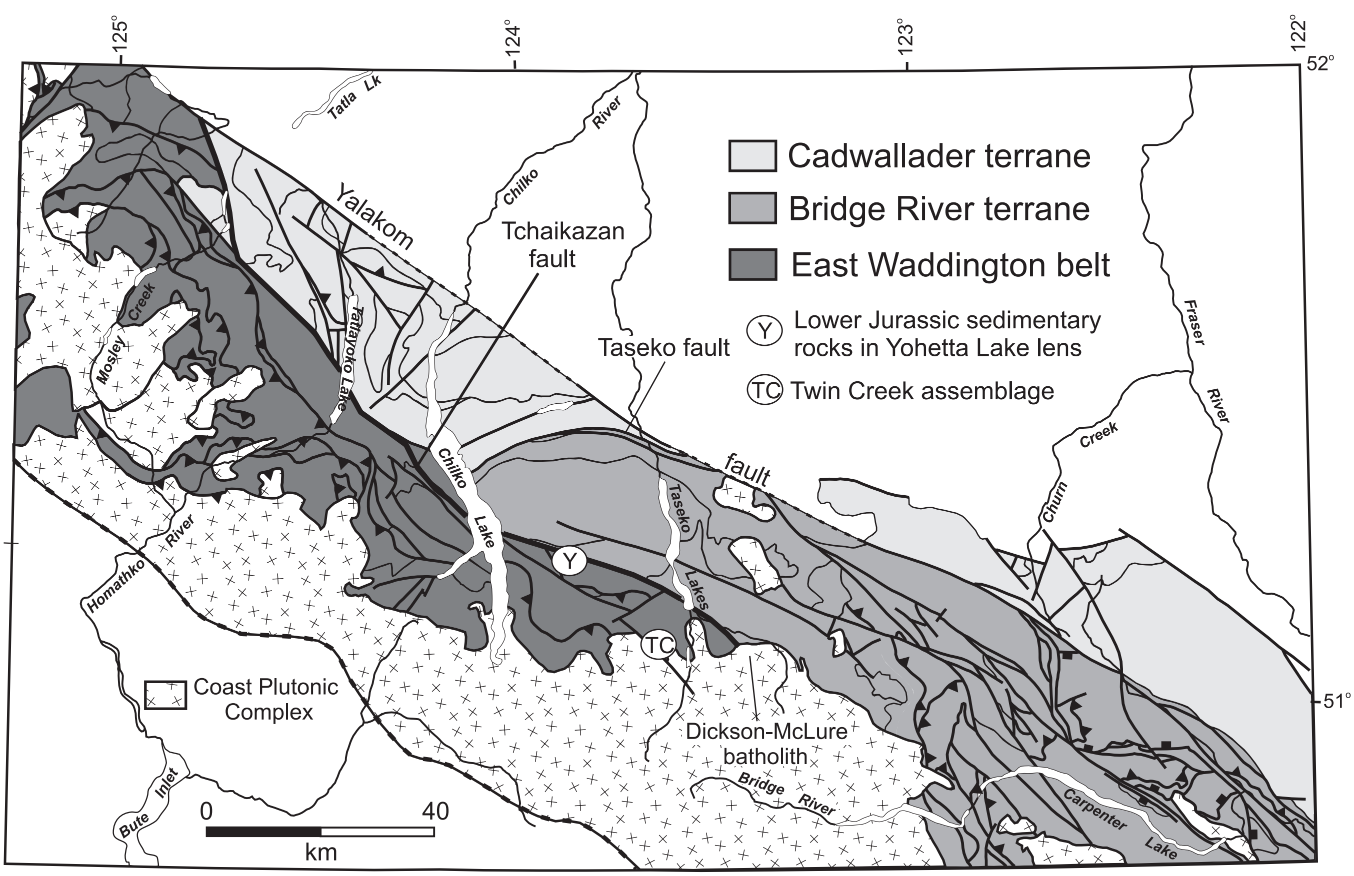

Figure 8. *Regional map showing "basement" terranes north and south of the Tchaikazan fault.*

River and Cadwallader terranes; Fig. 8). Likewise, neither the Twin Creek assemblage nor the dyke that intrudes it have counterparts within the adjacent Bridge River terrane. Both do have, however, plausible correlatives within the Cadwallader terrane near Tatlayoko Lake. These Paleozoic to Early Triassic components of Cadwallader terrane are approximately 75 km northwest of the Twin Creek assemblage exposures in the Tchaikazan River area. Allowing that similar rocks might be found in the subsurface beneath Triassic-Jurassic rocks of Cadwallader terrane anywhere northwest of the Taseko fault, a minimum of 40 to 50 km of sinistral displacement is required to match the Twin Creek assemblage of the Tchaikazan River area with the Cadwallader terrane northeast of the Tchaikazan fault (Fig. 8).

Implications for the Sinistral Displacement Model for the Southwestern Coast Belt

Simply stated, the geological elements found within the southern Coast belt can be described as: (a) a Jurassic-Cretaceous arc; (b) the East Waddington thrust belt and Gambier Group, built upon an older arc (Stikine/Cadwallader terranes and associated Twin Creek assemblage) found outboard of an accretionary complex (Bridge River terrane) overlain by fore-arc basin strata (lower Relay Mountain Group); and (c) basinal deposits reminiscent of a back-arc (upper Relay Mountain Group and Taylor Creek Group). These relationships, along with hints of sinistral faults, led Monger *et al.* (1994) to propose that during Cretaceous time part of the Jurassic-Cretaceous North American plate margin was displaced southward along a major sinistral fault system (Fig. 2C). As stated earlier, the geometric features of this model include the northern truncation of Bridge River terrane, and the repositioning of Jurassic-Cretaceous arc rocks and their basement terranes that originally formed a northern continuation of rocks found inboard of Bridge River terrane, to a position outboard of it. This geometry is exactly that observed in and adjacent to the Tchaikazan River area, where the Tchaikazan fault is interpreted to mark the position of the sinistral fault system. Relationships documented here demonstrate that the sinistral fault system developed partly within the Cadwallader terrane, the northern part of which formed along the eastern edge of Stikine terrane (Rusmore and Woodsworth, 1991; Friedman and Schiarizza, 1999). Movement along the fault system translated slices of Cadwallader and Stikine terranes, together with more outboard terranes including Wrangellia and associated Jurassic-Cretaceous plutonic and volcanic rocks of the southwestern Coast belt, to a position west of the Bridge River terrane.

In the model of Monger *et al.* (1994), the Spences Bridge arc of the southwestern Intermontane belt and the Gambier arc of the southwestern Coast belt are different segments of a single Early Cretaceous arc that was doubled as a result of southward displacement of the Gambier arc along the sinistral fault system. Their model requires that most of the sinistral movement occurred after about 100 Ma (the younger age limit of the Spences Bridge and Gambier arc systems), but prior to about 96 Ma, when the southwestern Coast belt, including the Gambier arc system, was thrust beneath Bridge River terrane and related rocks of the southeastern Coast belt (Journeay and Friedman, 1993). This timing requires that the Hauterivian to Albian arc-related volcanic and sedimentary rocks of the East Waddington thrust belt, including the Tchaikazan River and Falls River formations of the present study area, accumulated to the north of their current location as a continuation of the Spences Bridge arc. They were subsequently translated southward, together with their Cadwallader and Stikine basements, along the sinistral fault system.

The sinistral faults identified within the Tchaikazan River map area support this interpretation because they cut rocks as young as the Albian (?) Falls River formation, and one fault zone contains illite dated at 89 Ma, which probably represents a minimum age of movement. Likewise, the oldest strand of the Tchaikazan fault cuts mid-Cretaceous rocks but is truncated by the early Late Cretaceous (92 Ma) Dickson-McClure batholith. Other faults with known sinistral movement in the region also formed during mid-Cretaceous to early Late Cretaceous time, and in part overlapped with the early Late Cretaceous contractional structures that mark the final suturing of the southwestern and southeastern Coast belts (Miller, 1988; Leitch *et al.,* 1991; Greig, 1992; Hurlow, 1993; Chardon, 2003).

The model of post-100 Ma sinistral emplacement of the southwestern Coast belt requires that the Bridge River terrane and overlying Tyaughton-Methow basin did not have a western margin close enough to deposit material into the basin until after 100 Ma. Although supported by the ages of known sinistral faults in the region, this timing is not consistent with provenance and paleocurrent data from the Tyaughton-Methow basin itself. Umhoefer *et al.* (2002) documented the abrupt initiation of a western volcanic source for upper Valanginian to Hauterivian (~135 to 130 Ma) rocks of the basin (upper Relay Mountain Group), and a western volcanic source is also documented for overlying middle Aptian-early Albian (~120 to 107 Ma) sedimentary rocks within the basin (volcanic petrofacies of the Taylor Creek Group, including the Falls River formation; Garver, 1992; Garver and Brandon, 1994).

These relationships suggest that the southwestern Coast belt was outboard of the Tyaughton-Methow basin (which overlaps the northern end of the Bridge River terrane) by about 135 Ma and that, if sinistral faulting was responsible for its emplacement, significant sinistral translation had already occurred by that time (Fig. 9). Adopting this timeframe for the sinistral displacement model suggests that at least some of the Lower Cretaceous volcanic rocks within the East Waddington thrust belt were deposited after the basement terranes had already been translated to the west of the Bridge River terrane. These Lower Cretaceous volcanic rocks formed part of an active arc system that fed detritus eastward into an adjacent back-arc basin represented by the

Hauterivian through Albian part of the Tyaughton-Methow basin (Fig. 9). Such a relationship, between the Lower Cretaceous volcanic rocks of the East Waddington thrust belt and coeval sedimentary rocks within the adjacent Tyaughton-Methow basin, has been proposed by McLaren (1990), Garver (1992), and Umhoefer *et al.* (1994). The lithofacies identified within the Hauterivian through Albian rocks of the Tchaikazan River and Falls River formations are consistent

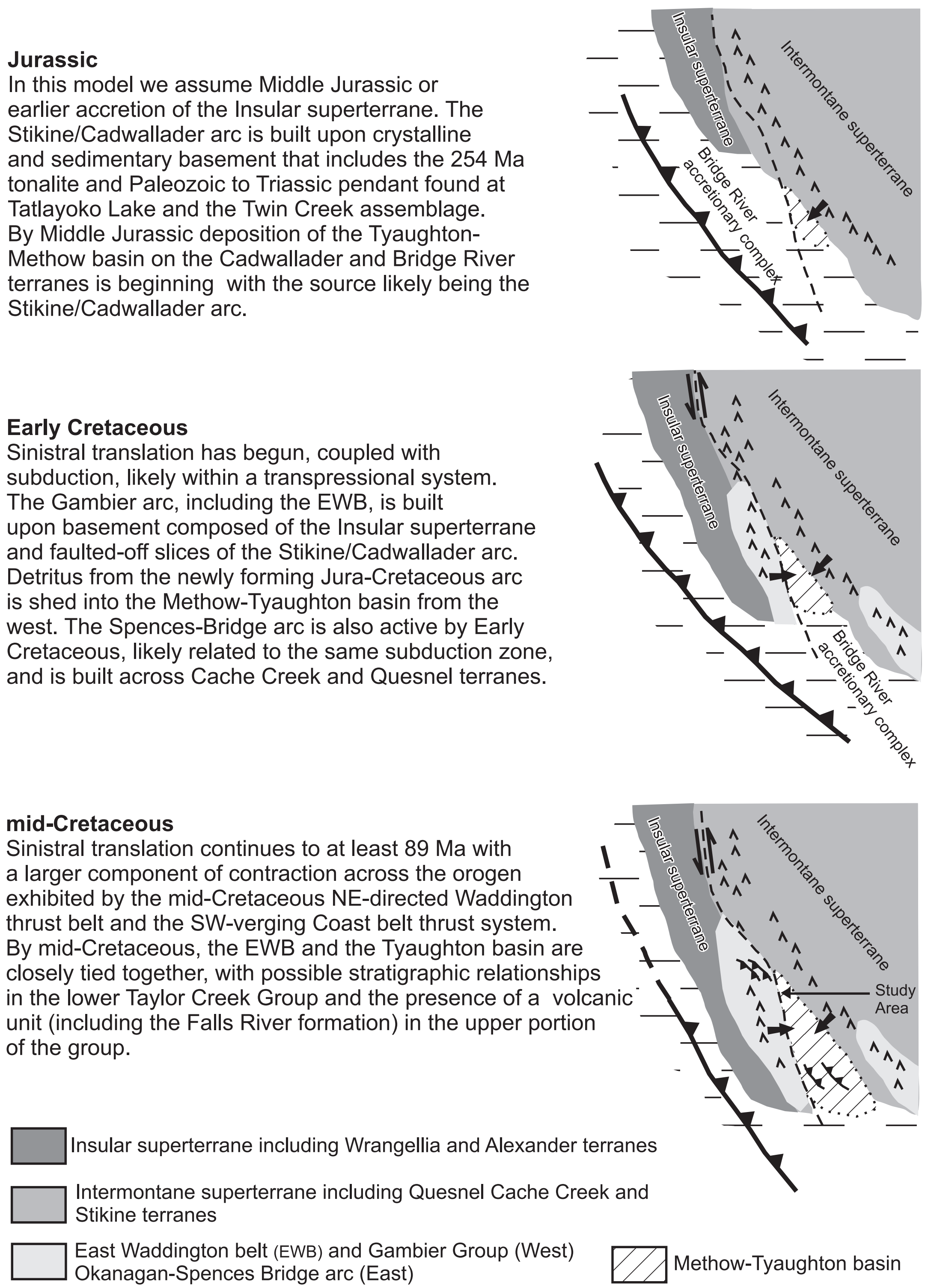

Figure 9. *Schematic diagram showing the tectonic evolution for the southern Coast belt.*

with this interpretation (Israel and Kennedy, 2000). However, they do not display such unequivocal ties to the presently adjacent Tyaughton-Methow basin that other sites of deposition are precluded.

In summary, the sinistral faults recognized in the area, together with the known distribution of Cadwallader terrane, provide strong support for the sinistral displacement model of Monger *et al.* (1994). The western volcanic source demanded by Hauterivian through Albian rocks of the Tyaughton-Methow basin led to a modified version of this model (Umhoefer *et al.,* 1994), whereby significant displacement must have occurred by Hauterivian time. This modified version of the model is preferred here, although the Hauterivian through Albian rocks within the Tchaikazan River area do not record a unique site of deposition outboard of the Tyaughton-Methow basin.

CONCLUSIONS

Detailed geological mapping in the Tchaikazan River area has documented previously unrecognized sinistral shear zones of, at least in part, early Late Cretaceous age. The study has also documented a previously unrecognized Permian or older sedimentary sequence cut by a Permian-Triassic dyke. Correlation of these rocks with Cadwallader terrane suggests that the adjacent Tchaikazan fault was the locus of at least 40 to 50 km of sinistral displacement, prior to its reactivation as an Eocene dextral strike-slip fault. These relationships are consistent with the model of Monger *et al.* (1994) for Cretaceous sinistral displacement of the southwest Coast belt and related terranes to a position outboard of the Bridge River terrane and overlying Tyaughton-Methow basin.

The mid-Cretaceous timing of sinistral displacement proposed by Monger *et al.* (1994) requires that Lower Cretaceous volcanic rocks within the Tchaikazan River formation be translated southward with their Cadwallader basement. In the modified version of Umhoefer *et al.* (2002), these Cretaceous rocks may, at least in part, have been deposited after the basement terranes had already undergone significant southward translation, thus forming part of the active arc system that shed detritus into an adjacent back-arc basin represented by Hauterivian through Albian rocks of the Tyaughton-Methow basin. Although the model of Umhoefer *et al.* (2002) is preferred, the Cretaceous rocks of the East Waddington thrust belt are not sufficiently well-understood to uniquely support it.

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APPENDIX. GEOCHRONOLOGY

Twin Creek Assemblage

A yellow/green weathered, aplite to dacitic dyke cross cuts the sedimentary rocks of the Twin Creek assemblage. It is several meters wide, has a variable strike and dip (it is probably folded), and is truncated by a fault. Samples were collected from the same locality during two consecutive field seasons (1999 and 2000) and were processed separately. In both cases, only a trace of zircon was recovered. Zircon from the 1999 sample comprised a single population of clear, colourless, equant to stubby prismatic grains. In contrast, zircon grains from the 2000 sample were heterogeneous in terms of their clarity, colour, and shape. Three unabraded fractions that represented all of the material from the 1999 sample were analysed (Table A1; Appendix Fig. A1A, fractions A–C). The results of these analyses, plotted on a standard concordia diagram, define a linear array suggesting Pb loss and provide and age estimate of 251 ± 16 Ma, based on the weighted mean of $^{207}Pb/^{206}Pb$ ages. Fractions D, E, and G from the 2000 sample are highly discordant with Precambrian $^{207}Pb/^{206}Pb$ ages. We interpret these grains as xenocrysts, likely derived from inclusions in the aplite host. Discordance is interpreted to be largely the result of Pb loss during intrusion of the dyke. A regression through these analyses projected from the interpreted magmatic age of the dyke (*ca.* 250 Ma) gives a poorly constrained upper intercept of *ca.* 1.8 Ga, which is interpreted as a reasonable estimate for the age of xenocrystic zircon in the 2000 sample.

Mt. McLeod Batholith

The Mt. McLeod batholith is a medium-grained, hornblende-rich granodiorite to diorite that intrudes rocks of the Tchaikazan River and Falls River formations. It is cut by the Twin Creek fault as well as a number of smaller structures related to latest Cretaceous to Eocene dextral strike-slip faulting. Both zircon and titanite were recovered from this sample. Zircons are clear and colourless to pale yellow or tan, stubby to elongate prisms. Titanites are clear to slightly cloudy, pale yellow to virtually colourless, and are seen commonly as blocky, wedge-shaped fragments of larger euhedral grains. Seven abraded zircon fractions and two unabraded titanite fractions were analysed (Appendix Fig. A1B, Table A1). An age estimate of 103.8 ± 0.5 Ma is based on the $^{206}Pb/^{238}U$ age for concordant zircon fraction C. Concordant titanite T1 constrains a minimum age for the rock at 101.1 ± 0.3 Ma. Fractions A and D contain old inherited zircon with possible ages of 0.6 Ga to >2 Ga. Fractions E, F and G have likely undergone Pb loss.

Grizzly Cabin Pluton

The Grizzly Cabin pluton forms an elongate, fine-grained hornblende-plagioclase porphyry intrusion that cuts rocks of the Twin Creek assemblage and Tchaikazan River formation. Three abraded zircon fractions give concordant results suggesting an age of about 102–99 Ma (Fig. A1C). We favour an interpretation in which older fraction D, which is concordant at *ca.* 101.5 Ma, records the crystallization age of the rock. However, a slightly younger age of about 99 Ma, based on concordant fractions B and C, cannot be ruled out.

Tchaikazan Rapids Pluton

The Tchaikazan Rapids pluton, located along the Tchaikazan River, is a plagioclase-hornblende porphyry exposed north of the Tchaikazan fault. It intrudes rocks assigned to the Taylor Creek Group (McLaren, 1990) and is cut by east- to southeast-verging thrust faults. Seven abraded zircon fractions give slightly discordant results that plot as a linear array (Fig. A1D). This array is interpreted to reflect the presence of inherited zircon, likely in all analysed fractions. A six point regression line (excluding fraction D, see below; MSWD-3.0) gives an upper intercept of 243 +13/-11 Ma, interpreted as an estimate for the average age of inherited zircon, and a lower intercept of 76 +13/-14 Ma, considered to be a minimum age for crystallization of the intrusion. Fraction D was excluded from the regression because it lies off the main trend, due to a slightly older average age of inheritance, and/or significant post-crystallization Pb loss. We note that there is no evidence for Precambrian inherited zircon in this rock as is the case for several rocks form the south of the Tchaikazan fault.

Ar-Ar Dates

Fault rocks along a large, sinistral shear zone in the southeast portion of the study area were collected for Ar-Ar dating. The S surface of the fault rock is defined by recrystallized illite that was used for Ar-Ar dating. Standard Ar-Ar analysis was carried out at the Geological Survey of Canada, Ottawa. The data are presented in Table A2 and plotted on a standard gas

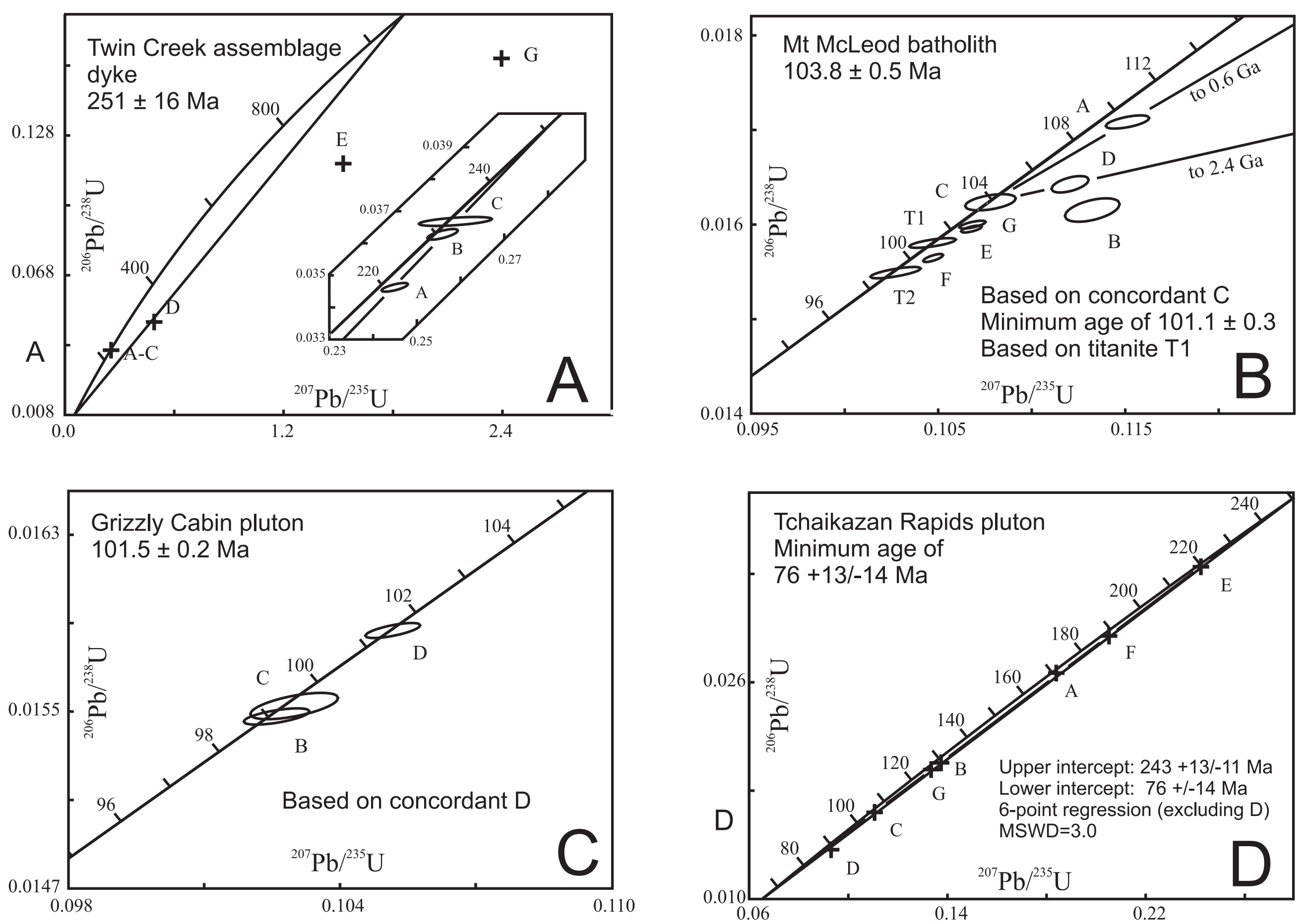

Figure A1. *Standard concordia plots showing U-Pb zircon and titanite results for samples from the Tchaikazan River area. Error ellipses are plotted at 2σ (level of uncertainty). Data represented by crosses do not reflect precision of those analyses (see Table A1 for analytical precision). (A) Dyke in Twin Creek assemblage; (B) Mt. McLeod batholith; (C) Grizzly Cabin pluton; (D) Tchaikazan Rapids pluton.*

release spectra plot (Fig. A2). The estimated age is 89 ± 0.9 Ma and may reflect the timing of formation of the illite during last phase of deformation within the shear zone. Due to the low closure temperature of illite, however, it is possible that the sinistral faulting event is older and the 89 ± 0.9 Ma age for the illite represents either a younger thermal event or cooling to the closure temperature after shearing.

Table A1. U-Pb analytical data for rocks from the Tchaikazan River area

Fraction[1]	Wt	U[2]	Pb*[3]	^{206}Pb/^{204}Pb[4]	Pb[5]	^{208}Pb[6]	Isotopic ratios (1σ, %)[7]			Apparent ages (2σ, Ma)[7]		
	(mg)	(ppm)	(ppm)		(pg)	(%)	^{206}Pb/^{238}U	^{207}Pb/^{235}U	^{207}Pb/^{206}Pb	^{206}Pb/^{238}U	^{207}Pb/^{235}U	^{207}Pb/^{206}Pb
Twin Creek assemblage aplite												
A ff,p,s,eu	0.005	701	25	363	22	11.2	0.03463 (0.20)	0.2449 (0.61)	0.05131 (0.49)	219.4 (0.8)	222.5 (2.5)	255 (23)
B ff,p,s,eu	0.010	511	19	318	39	10.8	0.03628 (0.23)	0.2559 (0.68)	0.05115 (0.54)	229.7 (1.0)	231.3 (2.8)	248 (25)
C ff,p,s,eu	0.005	814	30	231	44	10.5	0.03668 (0.19)	0.2588 (1.6)	0.05117 (1.5)	232.2 (0.9)	233.7 (6.7)	249 (68/71)
D f,p,s,eu	0.005	611	29	1205	7.7	7.2	0.04785 (0.14)	0.4895 (0.25)	0.07420 (0.17)	301.3 (0.8)	404.6 (1.7)	1046.8 (7.0)
E ff,p,eq,eu	0.004	670	80	3027	6.4	8.0	0.11605 (0.10)	1.5262 (0.17)	0.09538 (0.09)	707.8 (1.4)	941.0 (2.1)	1535.6 (3.4)
F f,p,cy,b	0.005	285	5.1	479	3.3	12.9	0.01717 (0.58)	0.1427 (1.8)	0.06025 (1.7)	109.8 (1.3)	135.4 (4.6)	612.6 (70/-74)
G ff,p,eq	0.005	317	53	1719	9.4	8.3	0.16142 (0.15)	2.4029 (0.22)	0.10796 (0.13)	964.7 (2.6)	1243.5 (3.2)	1765.3 (4.9)
Mt. McLeod batholith												
A m,p,s	0.025	148	2.6	657	6.2	12.6	0.01708 (0.20)	0.1151 (0.50)	0.04887 (0.41)	109.2 (1.6)	202.6 (1.7)	142 (19/20)
B f,p,e	0.020	105	1.7	917	2.4	11.8	0.01615 (0.38)	0.1132 (0.65)	0.05084 (0.56)	103.3 (0.8)	108.9 (1.3)	234 (26)
C f,p,s	0.024	109	1.8	949	2.8	10.8	0.01624 (0.26)	0.1078 (0.63)	0.04815 (0.56)	103.8 (0.5)	103.9 (1.2)	107 (26./27)
D f,p,s	0.024	168	2.8	1957	2.1	11.6	0.01643 (0.26)	0.1121 (0.44)	0.04948 (0.37)	105.0 (0.5)	107.8 (0.9)	171 (17/18)
E f,p,eu	0.065	192	3.1	2272	5.5	9.6	0.01595 (0.11)	0.1068 (0.26)	0.04854 (0.20)	102.0 (0.3)	103.0 (0.6)	125.9 (9.3/9.4)
F f,p,s	0.067	265	4.2	2203	7.9	10.2	0.01565 (0.13)	0.1047 (0.25)	0.04854 (0.18)	100.1 (0.3)	101.1 (0.6)	125.9 (8.5)
G f,p,s	0.063	209	3.3	1168	11	9.2	0.016 (0.13)	0.1068 (0.33)	0.04843 (0.25)	102.3 (0.4)	103.1 (0.6)	120.4 (12)
T1 f,su,b	0.560	208	3.4	350	343	11.7	0.01581 (0.16)	0.1047 (0.59)	0.04804 (0.49)	101.1 (0.3)	101.1 (0.6)	101.4 (23/24)
T2 f,su,b	0.580	212	3.4	322	398	13.7	0.01549 (0.19)	0.1027 (0.65)	0.04809 (0.53)	99.1 (0.4)	99.3 (1.2)	103.7 (25)
Grizzly Cabin pluton												
B f,p,e	0.025	187	3.1	1022	4.4	14.7	0.01548 (0.12)	0.1026 (0.35)	0.04808 (0.29)	99.0 (0.2)	99.2 (0.7)	103 (14)
C f,p	0.025	192	3.1	951	4.9	12.9	0.01552 (0.19)	0.103 (0.47)	0.04811 (0.39)	99.3 (0.4)	99.5 (0.9)	105 (18)
D f,p	0.025	247	4.0	1136	5.4	11.7	0.01587 (0.11)	0.1052 (0.29)	0.04807 (0.23)	101.5 (0.2)	101.5 (0.6)	103 (11)
99SGC-2												
A ff,p,eu	0.015	192	2.8	265	10	13.0	0.01392 (0.23)	0.0936 (1.3)	0.04876 (1.2)	89.1 (0.4)	90.8 (2.3)	136 (57/59)
B ff,p,s,eu	0.005	161	2.8	239	3.6	19.7	0.01566 (0.24)	0.1047 (2.2)	0.04848 (2.0)	100.2 (0.5)	101.1 (4.2)	123 (94/99)
C ff,p,e,eu	0.005	104	1.7	106	5.9	13.6	0.01593 (0.41)	0.1067 (4.9)	0.04857 (4.7)	101.9 (0.8)	102.9 (9.6)	127 (206/235)
Tchaikazan Rapids pluton												
A cc,p,e	0.030	272	6.9	1378	9.9	5.5	0.02666 (0.12)	0.1840 (0.26)	0.05006 (0.21)	169.6 (0.4)	171.5 (0.8)	197.8 (9.5/-9.6)
B c,p,eu	0.050	156	3.0	2072	4.7	7.3	0.02003 (0.17)	0.1375 (0.27)	0.04978 (0.21)	127.8 (0.4)	130.8 (0.7)	184.6 (9.7)
C m,p,e	0.050	131	2.1	324	22	6.9	0.01639 (0.22)	0.1107 (0.78)	0.04898 (0.67)	104.8 (0.5)	106.6 (1.6)	147 (31/-32)
D m,p,e	0.070	133	1.8	1654	4.8	7.8	0.01364 (0.19)	0.0931 (0.41)	0.04949 (0.33)	87.3 (0.3)	90.4 (0.7)	171 (15)
E c,p,eu	0.016	574	20	4937	4.0	8.9	0.03453 (0.11)	0.2425 (0.20)	0.05093 (0.12)	218.8 (0.5)	220.6 (0.8)	237.6 (5.4/-5.5)
F m,p,s	0.016	411	12	2777	4.4	8.5	0.02941 (0.12)	0.2051 (0.20)	0.05059 (0.12)	186.8 (0.4)	189.5 (0.7)	222.3 (5.5/-5.6)
G ff,m,p	0.020	227	4.3	1977	2.8	7.1	0.01955 (0.16)	0.1335 (0.26)	0.04952 (0.18)	124.8 (0.4)	127.2 (0.6)	172.4 (8.3)

[1] Upper case letter = zircon fraction identifier; T1, T2, etc, for titanites. All zircon fractions air abraded. Grain size, intermediate dimension: cc = >250mm, c = <250mm and >134mm, m = <134mm and >104mm, f = <104mm and >74mm, ff <74mm; Grain character codes: b = broken, cy = cloudy; e = elongate, eq = equant; eu = euhedral, p = prismatic, s = stubby, su = subhedral. Zircons nonmagnetic on Franz magnetic separator at field strength of 1.8A and sideslopes of 1°–5°. Titanites nonmagnetic at 0.6A and 20° sideslope, and magnatic at 1.8A and 5° sideslope. Front slope of 20°for all.

[2] U blank correction of 1pg ± 20%; U fractionation corrections were measured for each run with a double 233U–235U spike (about 0.004/amu)

[3] Radiogenic Pb

[4] Measured ratio corrected for spike and Pb fractionation of 0.0035/amu ± 20% (Daly collector), which was determined by repeated analysis of NBS Pb 981 standard throughout the course of this study

[5] Total common Pb in analysis based on blank isotopic composition

[6] Radiogenic Pb

[7] Corrected for blank Pb (1–4 pg), U (1–3 pg) and common Pb concentrations based on Stacey Kramers model Pb at the age or the 207Pb/206Pb age of the rock (Stacey and Kramers, 1975)

Table A2. Ar-Ar data, sample 99-SI-31 Whole Rock; J=.00311840 (Z6470)

Power[a]	Volume ^{39}Ar $\times 10^{-11}$ cc	^{36}Ar/^{39}Ar	^{37}Ar/^{39}Ar	^{38}Ar/^{39}Ar	^{40}Ar/^{39}Ar	%^{40}Ar ATM	*^{40}Ar/^{39}Ar	f_{39}[b] (%)	Apparent Age Ma[c]
2.4	10.2498	0.6165 ± 0.0047	0.741 ± 32.636	0.066 ± 0.003	195.844 ± 0.840	93	13.674 ± 1.178	1.1	75.33 ± 6.36
3.0	1.237	0.1265 ± 0.0012	1.185 ± 8.769	0.030 ± 0.002	52.472 ± 0.232	71.2	15.087 ± 0.355	5.6	82.94 ± 1.91
3.5	1.7398	0.0234 ± 0.0006	1.876 ± 9.425	0.013 ± 0.001	23.131 ± 0.183	29.9	16.207 ± 0.206	7.9	88.95 ± 1.10
3.9	2.8089	0.0140 ± 0.0004	1.911 ± 13.308	0.011 ± 0.001	20.417 ± 0.101	20.2	16.284 ± 0.109	12.8	89.36 ± 0.59
4.6	3.8954	0.0078 ± 0.0005	0.882 ± 6.931	0.007 ± 0.001	18.538 ± 0.069	12.5	16.222 ± 0.155	17.7	89.03 ± 0.83
5.5	4.6126	0.0062 ± 0.0003	0.542 ± 8.735	0.006 ± 0.000	18.011 ± 0.071	10.2	16.181 ± 0.087	21	88.81 ± 0.47
6.5	2.1538	0.0061 ± 0.0004	0.460 ± 14.005	0.008 ± 0.001	17.983 ± 0.137	10.1	16.176 ± 0.112	9.8	88.78 ± 0.60
12.0	5.2836	0.0077 ± 0.0003	0.452 ± 7.817	0.012 ± 0.001	18.480 ± 0.075	12.3	16.203 ± 0.104	24	88.93 ± 0.56

[a] As measured by laser in % of full nominal power (10W)
[b] Fraction ^{39}Ar as percent of total run
[c] Errors are analytical only and do not reflect error in irradiation parameter J
[d] Nominal J, referenced to FCT-SAN = 28.03 Ma (Renne *et al.,* 1994)
* Step not included in age determination
All uncertainties quoted at 2σ level

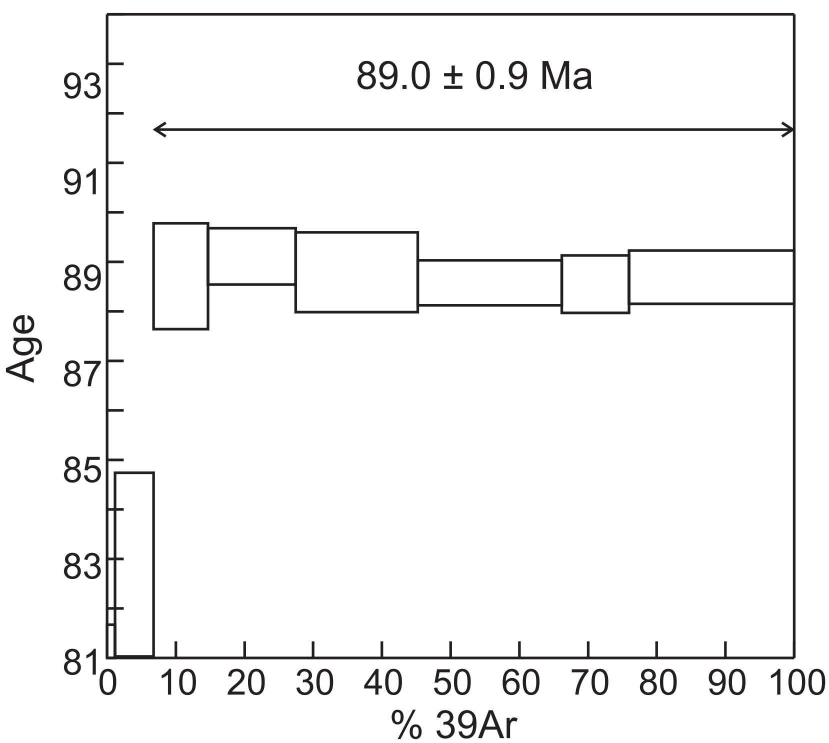

Figure A2. *^{40}Ar/^{39}Ar spectra plot of recrystallized illite from shear fabrics (see text Fig. 7) within large shear zone from the Tchaikazan River area. The age assignment is based upon the plateau segment shown by arrow.*