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**EOCENE DEXTRAL STRIKE-SLIP AND EXTENSIONAL FAULTING
IN THE BRIDGE RIVER TERRANE,
SOUTHWEST BRITISH COLUMBIA**

by

Margaret E. Coleman, Hon. B.A.

**A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfilment of
the requirements for the degree of
Master of Science**

Ottawa-Carleton Geoscience Centre

and

Department of Earth Sciences

Carleton University

Ottawa, Ontario

July, 1990

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acceptance of the thesis,

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IN THE BRIDGE RIVER TERRANE, SOUTHWEST BRITISH COLUMBIA**

submitted by Margaret E. Coleman, Hon. B.A.

in partial fulfilment of the requirements

for the degree of Master of Science

Randall K. Parrish
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ABSTRACT

The early Mesozoic Bridge River Terrane of oceanic affinity lies in the eastern Coast Mountains of southwestern British Columbia and is one of several subterranees located near the Intermontane Superterrane - Insular Superterrane boundary. Eocene strike-slip faulting and related extensional faulting and plutonism are largely responsible for the present upper crustal configuration of the Bridge River Terrane. This paper presents U-Pb geochronology and a detailed structural and geochronological analysis of Eocene deformation and magmatism of the Bridge River Terrane near Lillooet, British Columbia.

Evidence for Eocene magmatism and deformation within the Bridge River Terrane includes 48.5-46.5 Ma U-Pb zircon ages from four deformed granitic rocks, two of which are from the Mission Ridge pluton. All are cut by the Mission Ridge normal fault, which juxtaposes low-grade Bridge River Group in the hanging wall against medium-grade Bridge River Schist and associated intrusions in the footwall. The Mission Ridge fault is a low-angle east-dipping brittle normal fault with at least 10 km of down-dip displacement and a probable dextral strike-slip component.

In the Bridge River Schist, in the footwall of the Mission Ridge fault, penetrative plastic fabrics in northwest-trending, steep to shallow-dipping mylonites with northwest-southeast trending subhorizontal stretching lineations record a dextral sense of shear. Development of these fabrics pre-dates normal movement on the Mission Ridge fault and is attributed to dextral movement on the Yalakom fault system within the middle crust. Two Middle Eocene syntectonic foliated intrusions, dated by U-Pb zircon methods, have the same kinematic signature as the previously described mylonites; these constrain timing of dextral movement on the Yalakom fault system to be earlier than, contemporaneous with, and in part younger than the intrusion of the ca. 47 Ma Mission Ridge pluton.

The Mission Ridge fault is correlated with the Ross Lake fault. They were broken and offset by about 100 km of dextral movement on the north-trending Fraser fault. The Ross Lake fault hanging wall consists of the Hozameen Group, which, like the Bridge River Group, is an assemblage of low-grade oceanic rocks. The footwall of the Ross Lake fault, the Custer Gneiss, is higher grade than the Bridge River Schist in the footwall of the Mission Ridge fault but has the same lithological and kinematic signature. Mylonitic fabrics in both the Bridge River Schist and Custer Gneiss have subhorizontal stretching lineations that were generated prior to normal movement on the Ross Lake - Mission Ridge fault system and are attributed to earlier dextral motion along the Yalakom fault system.

The clear offset of these geologic features constrains all movement on the Fraser fault to be younger than 46.5 Ma. The Fraser fault is cut by the 34 Ma Chilliwack batholith.

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STATEMENT OF ORIGINAL CONTRIBUTION TO THESIS

Prior to this study reconnaissance mapping of the study area had been done. Roddick et al. (1977) identified some of the map units including the Eocene(?) sediments. Stratigraphy of the Bridge River Group, metamorphic grade of the Bridge River Group and Bridge River Schist, and a large part of the mapping of the Mission Ridge pluton was established by Potter (1983). Unpublished field maps of Jim Monger identified and roughly located the Yalakom and Marshall Creek faults.

Mapping for this thesis precisely located the traces and determined the geometry of the Yalakom and Marshall Creek faults within the study area. The Mission Ridge fault was identified, named and mapped in detail during the course of the study. The structural analysis including petrography of the Bridge River Schist was also part of this study. All aspects of the geochronological analysis excluding mass spectrometry was carried out as part of the thesis. The model which relates plastic deformation of the Bridge River Schist to dextral motion on the Yalakom fault is solely the author's idea.

INTRODUCTION

Current models for the tectonic evolution of the Canadian Cordillera consider the Intermontane and Insular superterrane as composite allochthonous terranes that accreted to the ancient margin of North America (Monger et al., 1982). The timing of accretion has generally been established; the Intermontane Superterrane was amalgamated by Late Triassic and accreted during the Jurassic, and the Insular Superterrane was assembled by Late Jurassic time and accreted to Intermontane Superterrane in the Cretaceous (Monger et al., 1982). However, uncertainties in this accretionary chronology remain because of structural and magmatic events related to younger tectonic events. One avenue to resolve these uncertainties is to study the boundary relationships between the terranes.

The study area for this thesis straddles the boundary between the Insular and Intermontane superterrane, near Lillooet, British Columbia (Figure 1). At this latitude, the boundary is characterized by mid-Cretaceous to Late Eocene north- to northwest-trending dextral strike-slip faults, the most conspicuous of which is the Fraser fault (Figure 1). Dextral strike-slip faulting in the Canadian Cordillera occurred over a protracted period of time and is in part related to transpressional collision and accretion of the Insular Superterrane with the western margin of North America. Eocene deformation, related to these strike-slip faults and normal faulting, have obscured the older Mesozoic accretionary structures. Only by first understanding these younger events can the nature of older structures be deciphered with confidence.

Figure 1.

Map of southwest British Columbia showing major lithological units and bounding faults referred to in text. CC, Cache Creek; BRT, Bridge River terrane; CAD, Cadwallader terrane; TLC, Tatla Lake Complex.

The purpose of this thesis is to present field, petrographic, geochronologic, and geobarometric data to establish (1) the geometry and kinematic relationships of the Eocene strike-slip and normal faults, (2) the age of penetrative strain in the Bridge River Terrane, and (3) timing of plutonism, strike-slip faulting, and normal faulting. These constraints require modification of recently published tectonic models.

REGIONAL GEOLOGY AND TECTONIC SETTING

As previously stated, the boundary between Intermontane and Insular superterranes in the vicinity of Lillooet is a complex zone of faults and fault-bounded tectonostratigraphic assemblages. The principal regional elements within the area of study are (from east to west, Figure 1) (1) the Intermontane Superterrane, (2) the Fraser fault system, (3) the Tyaughton-Methow basin, (4) the Yalakom fault system, (5) the Bridge River Terrane, and (6) the Insular Superterrane, including most plutonic rocks of the Coast Mountains.

INTERMONTANE SUPERTERRANE

The Intermontane Superterrane is a composite terrane that includes at least four subterrane (Stikinia, Cache Creek, Quesnellia, and Eastern) that were amalgamated by Middle Jurassic time (Monger et al., 1982). Widespread exposures of the Cache Creek and Quesnellia terranes comprise lower to middle Mesozoic strata in the southwestern Intermontane Superterrane; the Cache Creek is of oceanic origin and Quesnellia is primarily an intra-oceanic volcanic arc (Monger and Price, 1979). Overlapping the Cache Creek and Quesnellia terranes

are mid-Cretaceous volcanic and related sedimentary rocks and Tertiary non-marine sedimentary and volcanic rocks. Comagmatic granitic intrusions are Triassic to Paleogene in age.

FRASER FAULT SYSTEM

The Fraser fault is a Tertiary dextral strike-slip fault that trends north-south and, at the latitude of Lillooet, bounds the western margin of the Intermontane Superterrane. It has a dextral displacement of about 110 km (Monger, 1985). On the west side of the fault are the Bridge River Terrane, marine sedimentary rocks of the Tyaughton basin, and the Yalakom fault (Figure 1), which are all truncated by the Fraser fault. The Yalakom fault and Bridge River Group in the Bridge River Terrane are correlated on the east side of the Fraser fault with the Hozameen fault and Hozameen Group, respectively, as previously established by Monger (1985), (Figure 1). Similarly, Middle Jurassic - middle Cretaceous sedimentary rocks of the Tyaughton basin are correlated with related strata of the Methow basin east and southeast of Hope, B.C., on the east side of the Fraser fault. The Fraser fault is termed the Straight Creek fault in Washington, where this system is clearly intruded by the composite Chilliwack batholith, which includes plutons as old as 34 Ma (Vance et al., 1986; Richards and McTaggart, 1976; Engels et al., 1976).

TYAUGHTON-METHOW BASIN

The Tyaughton-Methow basin is composed of a thick sequence of Early Jurassic to Late Cretaceous marine sedimentary rocks that in part overlap the

Bridge River and other subterranees of the Intermontane Superterrane. The Tyaughton-Methow basin has been fragmented, not only by the Fraser fault, but also by somewhat earlier dextral strike-slip faulting on the Yalakom fault system. The age and provenance of different units in the Tyaughton-Methow sequence and the primary basin geometry have been, and continue to be, topics of extensive research (Selwyn, 1872; Duffell and McTaggart, 1952; Trettin, 1961; Jeletzky, 1971; Monger, 1982, 1985; Kleinspehn, 1985; Trexler and Bourgeois, 1985; O'Brien, 1986; Glover et al., 1988; Garver et al., 1989; Schiarizza et al., 1989a, 1990; Umhoefer, 1989). In the area under consideration, Tyaughton-Methow sedimentary units are juxtaposed against the Bridge River Group by the northwest-trending Yalakom fault system (Figure 2).

YALAKOM FAULT SYSTEM

The Yalakom fault is a conspicuous lineament that separates rocks of contrasting lithology and structural style. It extends from near Lillooet, where it is truncated by the Fraser fault (Figure 1), northwest about 250 km to immediately northwest of the Tatla Lake region. In the Bridge River area, the Yalakom fault forms the northeast boundary of the Bridge River Terrane.

Thirty kilometres northwest of the Bridge River canyon, adjacent to the study area, the Yalakom fault is nearly vertical and places Upper Jurassic volcanic sandstones against Bridge River Group serpentinite (Glover et al., 1988; Schiarizza et al., 1989a). Glover et al. (1988) and Schiarizza et al. (1989a) have established that there is post-mid-Cretaceous dextral movement on the Yalakom

fault system on the basis of kinematic interpretation of slickensides, fibrous mineral growth, shear bands, extensional fracture veins, and the pattern and orientation of subsidiary faults and folds.

Tipper (1969) postulated 80-90 km of right lateral offset along the Yalakom fault; more recent work suggests displacements greater than 100 km. Kleinspehn (1985) proposed 125 km of displacement, based on restoration of alluvial fan facies within the Lower Cretaceous Jackass Mountain Group and Umhoefer (1989) calculated 100 km, based on offset of the Shulaps ultramafic complex and the Petch Creek serpentinite along the correlative Hozameen fault.

BRIDGE RIVER TERRANE

The Bridge River Terrane comprises Late Permian to Early Jurassic oceanic rocks (Orchard, 1981; Potter, 1983; Cordey, 1988). There is no clear connection with either the Intermontane or the Insular superterrane, but it has been suggested by Potter (1986) and Rusmore et al. (1988) that the Bridge River Terrane formed during the Late Permian - early Mesozoic on the western margin of the Intermontane Superterrane prior to accretion of the Insular Superterrane.

A growing body of evidence supports the correlation of the Bridge River Terrane with the western Cache Creek Terrane (Figure 1). The most important evidence is their lithologic similarity and similar range of ages of radiolaria, conodonts, and fusilinids (Late Permian to Middle Jurassic; Trettin, 1980; Rafek, 1980; Orchard, 1981; Cordey et al., 1987). In addition Late Triassic K-Ar ages of Bridge River Group blueschist and blueschist metamorphism from the Cache

Creek Terrane (Garver et al., 1989; Archibald et al., 1990) are also compelling.

The Shulaps ultramafic complex is part of the Bridge River Terrane (Figure 1) and covers a large area of the Shulaps Range (Figure 2). It is bounded by the Yalakom fault to the northeast and lies structurally above most of the Bridge River Terrane rocks. The Shulaps complex has been identified as part of a dismembered ophiolite (Monger, 1977; Nagel, 1979; Wright et al., 1982; Potter, 1983, 1986; Calon et al., 1990). Similar bodies are present in Cache Creek Terrane.

Deformation within the Bridge River Terrane was generally thought to be the result of Mesozoic compression related to terrane accretion (Potter, 1986; Rusmore et al., 1988). Middle Eocene preliminary U-Pb ages on late syn-tectonic foliated granitic intrusives within the Bridge River Terrane schist (P. van der Heyden, personal communication, 1988), gave the first substantial indication that the Bridge River Terrane was deformed in part during the Eocene. Supporting data from this study imply that a significant amount of deformation in the Bridge River Terrane is a result of Middle Eocene dextral ductile shear.

INSULAR SUPERTERRANE

The Insular Superterrane is a composite terrane, amalgamated by Late Jurassic time (Monger et al., 1982). In the southern Canadian Cordillera it is composed of sedimentary and volcanic strata of late Paleozoic to Tertiary age and Cretaceous to Tertiary granitic rocks. Subterrane include Late Triassic to Early

Figure 2.

Mission Ridge, the southern Shulaps Range and surrounding region. Geological map with major faults, summarized structural data, and U-Pb zircon ages in Ma. Lines A-A', B-B', C-C', and D-D' correspond to the cross section lines in Figure 4. YF, Yalakom fault; MRF, Mission Ridge fault; MCF, Marshall Creek fault. Local relief is more than 2200 m and accounts for the arcuate trace of some of the major faults.

Cretaceous volcanic complexes and related sedimentary rocks of the Cadwallader Terrane (Rusmore, 1987); the Cascade fold belt (Roddick et al., 1979), a composite terrane of highly varied lithology ranging in age from Paleozoic to Mesozoic; the Coast Plutonic Complex, dominantly Cretaceous-Tertiary granitic rocks with pendants of sedimentary and volcanic strata of late Paleozoic to Tertiary age (Monger and Price, 1979); and Wrangellia, the most outboard terrane, comprising a Paleozoic to Jurassic assemblage of volcanic, sedimentary, and oceanic rocks (Jones et al., 1977).

GEOLOGY OF MISSION RIDGE AREA

The map units of the study area are exposed in northwest-trending fault-bounded panels (Figure 2) and are described from east to west. The faults, from east to west, are the Yalakom fault, which in this area is a 40-60° east-dipping fault with dextral displacement; the Mission Ridge fault, a major normal fault with a low to moderate (25-45°) east dip; and the Marshall Creek fault, a 50-75° west-dipping fault with normal dip-slip and possible dextral strike-slip displacement. The Yalakom fault separates Jurassic-Cretaceous sedimentary rocks of the Tyaughton basin from the Bridge River Group. Within the northern part of the field area, faulted slivers of the Hurley Formation of the Cadwallader Group lie between the Tyaughton basin rocks and the Bridge River Group. The Mission Ridge fault juxtaposes a hanging wall composed of Bridge River Group and unconformably overlying Eocene sandstone, shale, and conglomerate against schist and phyllite, derived from the Bridge River Group, and Eocene granitic rocks.

The Marshall Creek fault separates metamorphic rocks from the Bridge River Group on the west. Eocene igneous rocks are discussed separately.

LITHOLOGIC UNITS

Lillooet Group of the Tyaughton Basin

The Lillooet Group (Duffell and McTaggart, 1952) comprises Upper Jurassic - Lower Cretaceous marine sedimentary rocks and is one of numerous formations within the Tyaughton basin. The Lillooet Group is exposed in a northwest-trending panel northeast of the Yalakom fault from near Lillooet to Applespring Creek (Figure 2). It consists of at least 850 m (Duffell and McTaggart, 1952) of marine clastic sedimentary rocks of volcanic provenance deposited in the Tyaughton-Methow basin. Interbedded (1-10 cm) argillite and fine-grained sandstone layers with cross bedding, graded beds, and load structures are the predominant rock types (Figure 3A). Beds of coarse-grained greywacke with local argillaceous rip-up clasts are common. Paleontological data indicate a Late Jurassic to Early Cretaceous age (Duffell and McTaggart, 1952; Trettin, 1961; Jeletsky, 1971). An ammonite recently discovered in a section exposed near Lillooet may be Middle Jurassic (J.W.H. Monger, personal communication, 1989). The Lillooet Group is unconformably overlain by the upper Lower Cretaceous Jackass Mountain Group (Duffell and McTaggart, 1952). The northeastern limit of mapping in this study, however, lies within Lillooet Group strata (Figure 2). The Lillooet Group has been correlated with a lithologically similar Middle Jurassic volcanic sandstone unit, also unconformably overlain by the Jackass

Figure 3.

- A. Cross-bedded fine-grained sandstone and siltstone of the Lillooet Group.**
- B. Soft sediment folds in radiolarian ribbon chert from the Hozameen Group near Hope, B.C. This exposure of chert is correlative to ribbon chert in the Bridge River Group.**
- C. Mission Ridge pluton (foreground) in igneous contact with Bridge River Schist (background). View is to the east, from above the Bridge River Canyon.**
- D. Foliated syn-tectonic granitic dyke (48.5 Ma) in Bridge River Schist. View is to the east from the Bridge River canyon.**

Mountain Group, immediately northwest of the study area (Schiarizza et al., 1990).

Cadwallader Group

In the northern part of the study area, strata of the Cadwallader Group intervene between Lillooet Group and Bridge River Group within the complex Yalakom fault zone (Figure 2). The Cadwallader Group comprises mostly coarse-grained sandstone and conglomerate, and it is imbricated along several faults with the Bridge River Group southeast within the Yalakom fault zone (Figure 2). The conglomerate beds are lenticular, with an average thickness of 10 m and an average length of 50 m. Clast length/width ratios are 3/1. Pebble to 30 cm cobble size rounded clasts are supported by a micritic limestone matrix. Clasts types include macro-fossil-bearing limestone, granitic rocks, and green dacite with feldspar phenocrysts.

These lithological characteristics (Coleman, 1989) identify these strata as the Upper Triassic Hurley Formation of the Cadwallader Group as mapped by Rusmore (1987) and Schiarizza et al. (1990) northwest of the study area. Although a fault between this unit and the Lillooet Group near Applespring Creek (Figure 2) has not been identified, it is inferred on the basis of adjacent contrasting lithologies. This inferred fault is interpreted to be the easternmost splay of the imbricate fault zone, interpreted here as the Yalakom fault zone, which lies directly to the southeast (Figure 2).

Bridge River Group

The Bridge River Group, bounded by the Yalakom fault zone (including Cadwallader Group rocks) on the east and by the low-angle Mission Ridge fault to the west (Figure 2), consists of a structurally chaotic melange of ribbon chert (Figure 3B, example of ribbon chert from correlative Hozameen Group), greenstone, pillow basalts, minor greywacke, limestone olistoliths, and narrow bodies of sheared serpentinite (Coleman, 1989). It has a structural thickness of 2.5-4.5 km in this panel (Coleman, 1989; Figure 4), and petrography indicates that it is in the prehnite-pumpellyite facies (Potter, 1986). Potter (1983, 1986) refers to this very low-grade, structurally chaotic part of the Bridge River Group as the Carpenter Lake Assemblage. Ages from radiolaria found along Bridge River and Carpenter Lake range from Middle Triassic to Middle Jurassic (Potter, 1983; Cordey, 1988). Triassic conodonts are reported from the limestone olistoliths (Orchard, 1981).

Layers of grey radiolarian chert 1-5 cm thick are separated by argillite layers 1 mm to 1 cm thick. In the southern Shulaps Range chert is found in depositional contact with limestone, greenstone, and sandstone (Potter, 1983); however, in most of the study area the chert is in fault-bounded blocks of varying size, generally in fault contact with similarly deformed blocks of greenstone, basalt, sandstone, and limestone. Internal folding of chert layers within fault-bounded blocks is in part interpreted to be a result of soft sediment folding. Potter (1983, 1986) concluded that syn-depositional faulting was in part responsible for the

Figure 4.

Cross sections A-A', B-B', C-C', and D-D' are from corresponding lines in Figure 2. Patterns refer to legend of Figure 2. Note the truncation of the Middle Eocene Mission Ridge pluton by the Mission Ridge and Marshall Creek faults in cross sections B-B' and C-C'. No vertical exaggeration.

structurally chaotic aspect of the Bridge River Group. Blocks of chert have slickenside surfaces with many orientations.

Limestone is present as lens-shaped olistoliths as large as 20 m across and as layers up to 50 m thick that are laterally continuous for up to 2 km (see folded map). Some limestone layers 5-50 cm thick are interbedded with ribbon cherts. Thick layers and lenses of massive red-weathering coarse-grained sandstone and pebbly mudstone are locally present northwest of the Bridge River Canyon (Potter, 1986). Pillowed and massive greenstone in fault-bounded blocks are found locally throughout the Bridge River Group and are derived from basaltic tholeiites (Potter, 1986).

Shulaps ultramafic complex

The following description of the Shulaps complex is summarized from Calon et al. (1990) and Schiarizza et al. (1990). The Shulaps complex (Leech, 1953; Monger, 1977; Nagel, 1979; Wright et al., 1982; Potter, 1983, 1986; Calon et al., 1990) consists of variably serpentinized mantle harzburgite with minor dunite and orthopyroxenite. Structurally underlying the mantle harzburgite is an olivine cumulate-derived serpentinite melange. Volcanic and sedimentary blocks found throughout the melange, presumably derived from the Bridge River Group and the Cadwallader Group, represent incorporated pieces of the footwall over which the Shulaps complex was emplaced.

The stratigraphic order of stacking of the harzburgite and serpentinite melange map units suggests that out-of-sequence thrusting was involved in the

emplacement and imbrication of the Shulaps complex (Calon et al., 1990). Calon et al. (1990) mapped the Shulaps complex as a southwest-verging thrust system consisting of northeast-dipping duplexes. They reported kinematic indicators within the foliated serpentinites that record top-to-the-southwest sense of shear.

A suite of internally deformed and boudinaged dioritic hornblende porphyry dykes that intrude the Shulaps complex have an ^{40}Ar - ^{39}Ar age of 77 Ma (Archibald et al., 1989). This date is considered to be a reliable hornblende cooling age and indicates that the dike is not younger than Late Cretaceous (Archibald et al., 1990). Archibald et al. (1989) interpret these dikes to have been emplaced synkinematically during imbrication of the Shulaps complex. However, taking into account their deformed state and low metamorphic grade, it is probable that emplacement of the dikes occurred prior to their deformation. The cooling age may indicate that imbrication of the complex occurred after 77 Ma, contrary to Potter's (1986) Jurassic interpretation of imbrication of the Shulaps complex.

Eocene (?) sedimentary rocks

In the map area Eocene non-marine sedimentary rocks are exposed on Mission Ridge in a northwest-plunging syncline truncated on the west by the Mission Ridge fault (Figure 2). The sedimentary rocks are in probable unconformable contact with the Bridge River Group; although the actual contact is not exposed, bedding in the sedimentary rocks is conformable with the basal contact and beds are undisturbed adjacent to the basal contact. The sedimentary

rocks comprise a 1500 m thick section of well bedded conglomerate, black shale, and coarse-grained sandstone. Conglomerate consists of about 70% rounded clasts up to 15 cm across in a coarse-grained sandy matrix. The clasts are mostly lithologies of the Bridge River Group with locally abundant clasts of felsite. Evidently, none of the clasts were derived from the Bridge River schists, phyllites, or associated granitoid intrusives (described later in text) presently exposed immediately to the west (Figure 2) in the footwall of the Mission Ridge fault. Sandstones contain lithic grains of felsic volcanics, quartz, plagioclase, and minor amounts of biotite and muscovite. Black shales up to 10 m thick contain Metasequoia stem fossils. High thermal alteration index values indicate sediments were buried and heated to temperatures that caused carbonization of organic material (G. Rouse, personal communication, 1990). Only remnant, palynologic material is preserved and has been too damaged by heating for definitive palynologic dating (D. MacIntyre and A. Sweet, personal communication, 1990). At present the age of the black shale unit is constrained to mid-Cretaceous to Middle Eocene. An age of Eocene is preferred due to the non-marine nature and Metasequoia detritus.

The clast composition of sandstones and conglomerates requires that the Eocene sedimentary rocks exposed in this location were deposited relatively early in the uplift history, prior to unroofing of the higher grade rocks immediately to the west in the footwall of the Mission Ridge fault.

Bridge River Schist

The Bridge River Schist, in the footwall of the Mission Ridge fault, is a sequence of upper greenschist to lower amphibolite facies metamorphosed equivalents of the Bridge River Group intruded by abundant syn- to post-tectonic granitic to felsic porphyry intrusions. At least 3 km of structural thickness is exposed in this northeast-dipping panel. The schists are structurally truncated on the east by the Mission Ridge fault and by the Marshall Creek fault on the west (Figure 2). They are structurally overlain by the Shulaps ultramafic complex to the north (Figure 2), along the northern part of the Mission Ridge fault. The schists have undergone plastic deformation and are structurally coherent in comparison to the Bridge River Group rocks. They form the vertical cliff walls of the Bridge River canyon (Figures 3C and 3D), where 850 m of section is exposed.

The Bridge River schists are the only rocks in the Bridge River Terrane that have been plastically deformed above prehnite-pumpellyite facies. The schists include well foliated and lineated metachert, phyllite, chlorite schist, and syn- to late syn-deformational orthogneiss bodies.

The metacherts are mylonitic, characterized in outcrop by layers of quartz 2 mm to 1 cm thick, separated by micaceous pelitic laminations 1-5 mm thick (Figures 5A, 5C, and 5D, see structural geology below). The phyllites contain muscovite, biotite, and minor garnet. Chloritized foliated greenstone and greenschist (Figure 5B) occur in layers 2-15 cm thick and as boudins 2-3 m wide within the metachert and phyllite. Attenuated 1 cm to 2 m thick layers of light

Figure 5.

- A. Horizontal stretching lineations defined by quartz rods on a steeply dipping foliation surface in metachert from Bridge River Schist.**
- B. Outcrop surface is oriented parallel to the stretching lineation and perpendicular to the foliation surface. Shearbands (parallel to the pencil) in chloritized greenschist indicate a dextral shear sense.**
- C. Shearbands in metachert indicate a dextral shear sense.**
- D. Sigmoidal-shaped boudinaged marble layers within metachert indicate a dextral shear sense.**

-grey calcite marble occur locally (Figure 5D). Tectonic lenses of foliated serpentinite and talc schist are surrounded by metachert and phyllite and occur in the north end of the study area in the footwall of the Mission Ridge fault below the Shulaps complex.

Brew Group

The Early Cretaceous Brew Group occurs on Mt. Brew, south of the field area as well as along the Duffey Lake road in the footwall of the Mission Ridge fault (Figure 2), where both are down-dropped to the west by the Marshall Creek fault. The Brew Group, estimated by Duffell and McTaggart (1952) to be at least 2500 m thick, includes argillite, quartzite, conglomerate, and their metamorphosed equivalents. Along Duffey Lake Road (southernmost part of study area), metagreywacke with rip-up argillaceous clasts were observed; these characteristics of the Brew Group may suggest a correlation of the Brew Group with the Lillooet Group. The metagreywacke is of greenschist metamorphic grade, and muscovite defines the foliation.

EOCENE INTRUSIVE ROCKS

Mission Ridge pluton

The Mission Ridge pluton (Potter, 1983) is an elongate body of foliated coarse-grained hornblende-biotite-bearing granodiorite about 30 km in length. The Mission Ridge pluton is 47.4 ± 0.3 Ma based on U-Pb zircon ages, described later, from two localities in Bridge River Canyon (Figure 2). It intrudes the Bridge River Schist and is truncated on its east and west sides by the Mission Ridge and

Marshall Creek faults, respectively (Figure 2). The pluton transects the foliation in the Bridge River Schist (Figure 3C) in map view yet has a variably developed foliation with the same orientation as the foliation of the Bridge River Schist. The emplacement of the pluton is interpreted to be late syn-kinematic with respect to foliation development in the surrounding schist. This constrains at least part of the plastic deformation in the schist, which pre-dates the Mission Ridge fault, to be Middle Eocene. Foliation development within the pluton is highly variable (Figures 6A, 6B, and 6C). The contact is mylonitic and fabrics are discussed in the following section on structural geology.

Felsite

A leucocratic felsite, which is in part hornblende-phyric and which intrudes the Mission Ridge fault zone, is exposed in the central part of the area and on the east flank of the Mission Ridge pluton (Figure 2). The intrusion of the felsite occurred after the main movement on the fault; however, it is fractured by the fault and intruded the fault zone prior to the youngest movement. This unit may be comagmatic with the Rexmount porphyry, which outcrops in the Shulaps Range and farther northwest (Roddick and Hutchison, 1973; Potter, 1983; Schiarizza et al., 1989b, 1990). Its precise age is uncertain, but must be younger than ca. 46 Ma.

Figure 6.

- A.** Equigranular igneous textures in granite from the Mission Ridge pluton.
- B, C** Mylonitic textures in samples from the margin of the Mission Ridge pluton.
- D.** Euhedral hornblende, from the Mission Ridge pluton, microprobed for Al content for geobarometry.

STRUCTURAL GEOLOGY

FAULTS

Yalakom fault

Between Lillooet and Applespring Creek the Yalakom fault has a northeasterly dip of 40° - 50° (Figures 2 and 4). Rocks of the Lillooet and Bridge River groups exhibit brittle deformation fabrics at the fault boundary, which is defined by a <75 m zone of closely spaced fractures.

The Lillooet Group sedimentary rocks of the hanging wall are fractured in a narrow zone <50 m wide along the fault trace; at several localities the fault zone is characterized by narrow bands of rusty weathering fuchsite-bearing hematitic fault breccia. East of the fractured zone well-preserved bedding in the Lillooet Group is folded by shallow to moderately plunging southwest-verging folds with axial traces parallel or subparallel to the strike of the Yalakom fault and shallow to moderately plunging hinge lines (Figure 2). These folds are open to tight with axial surfaces that are moderately (40 - 60°) northeast dipping. Wavelengths of outcrop-scale folds range from 1 to 10 m and map-scale folds have wavelengths of about 50 m. These folds are thought to have formed in response to compressional movement along the Yalakom fault, because of their proximity and orientation with respect to the trace of the fault.

It is difficult to assess the effect of Yalakom faulting on the Bridge River Group. The extremely chaotic and brittlely disrupted nature of the Bridge River Group, throughout its entire mapped area, renders it difficult to identify structures

in the footwall that are distinct from those characteristic of the structural melange.

In the southern part of the study area (Figure 4A, section D-D') the fault trace is apparently a single strand. To the north it becomes a series of imbricate thrust faults (Figure 4A, sections A-A', B-B', C-C'). A thrust-fault-bounded slice of the Hurley Formation of the Triassic Cadwallader Group (Figure 2) has been mapped in a 4 km wide and 30 km long lens (Schiarizza et al., 1990) along the trace of the Yalakom fault (Figure 2). The splay of the fault that juxtaposes the Lillooet Group against the Hurley Formation is not exposed along the entire imbricate thrust zone and in places is inferred on the basis of contrasting lithology (Schiarizza et al., 1990) (Figure 2). Although Schiarizza et al. (1990) infer that the imbricate thrust splays constitute a fault zone distinct from the Yalakom fault, there is reason to believe that they are part of the Yalakom fault zone and that they developed in a transpressional setting. Thirty kilometres northwest of the Bridge River Canyon, the Yalakom fault steepens to a nearly vertical orientation (Schiarizza et al., 1990). Restraining bends or segments of strike-slip faults that have a shallow dip and record transpressional structures have been documented in other major strike-slip faults of the Cordillera (Evenchick, 1988) and are common features in well documented strike-slip faults world-wide (Christie-Blick and Biddle, 1985; Harland, 1971). The shallow dip of the Yalakom fault and the related northwest-verging folds developed in the Lillooet Group are here interpreted to have formed in response to dextral-oblique-slip motion. The

strongest arguments in favor of this view are the congruent geometries of folds in the hanging wall, the zone of imbrication, and the low-angle nature of the Yalakom fault. No igneous rocks cross-cut the Yalakom fault zone, allowing, but not requiring, these features to all be the same age. Ductile fabrics in the Bridge River Schist are attributed to dextral strike-slip movement on the Yalakom fault system (see below) and their timing constraints are discussed later.

Mission Ridge fault

The moderately northeast-dipping Mission Ridge fault (Coleman, 1989) juxtaposes rocks with distinctively different metamorphic grade and structural style and is well exposed along Mission Ridge (Figures 2 and 4). The hanging wall comprises brittlely deformed prehnite-pumpellyite grade Bridge River Group rocks and Eocene(?) sedimentary rocks that overlie the Bridge River Group at the northwest end of Mission Ridge. The Eocene(?) sedimentary rocks are folded into a northwest-plunging synform that is truncated at a moderate angle by the Mission Ridge fault (Figure 2). At the northwest end of the fault the hanging wall includes the Shulaps ultramafic complex; this segment of the fault was previously thought to be part of the imbricate Shulaps thrust fault (Potter, 1983). Footwall rocks on the west include the Mission Ridge pluton and well foliated upper greenschist facies grade schist and phyllite of the Bridge River Schist. The Mission Ridge fault truncates the foliation of the Bridge River Schist and cuts the Middle Eocene Mission Ridge pluton. The footwall rocks are structurally coherent in contrast to the sheared melange of the hanging wall Bridge River Group.

The fault geometry is precisely determined on the basis of careful mapping of good exposures of the fault zone along its trace southeast of the Bridge River Canyon (Figure 2). The dip ranges between 25° and 40° to the northeast (Figures 4 and 7A), but is steeper at the southeast end of the fault (Figure 4). The Mission Ridge fault is geometrically similar to extensional faults of metamorphic core complexes throughout the Cordillera (Armstrong, 1982; Wernicke and Burchfiel, 1982; Parrish et al., 1988; Lister and Davis, 1989).

Direct kinematic evidence for hanging-wall-to-the-northeast displacement on the Mission Ridge fault is best constrained where the fault juxtaposes hanging wall Eocene(?) sedimentary rocks against the Bridge River Schist (Figure 7B). In a narrow zone, 5 to 10 m wide, closely spaced fractures parallel to the fault zone are superimposed on the pre-existing foliation of the Bridge River Schist. Slickenside lineations on the fracture surfaces trend and plunge east-northeasterly (i.e., approximately down-dip). Outcrop-scale normal offsets of bedding in the Eocene(?) sedimentary rocks of the hanging wall within a 50 m wide zone parallel to the fault (Figure 7B) provide further evidence for the extensional nature of the Mission Ridge fault.

The Mission Ridge fault extends from its truncation at the Fraser fault (Figure 2) at least 45 km to the northwest where it bends to the west. It was traced into a zone of serpentinite and sheared rock that was formerly interpreted as the Shulaps thrust by Potter (1983, 1986). Schiarizza et al. (1990) identified a normal fault that joins the Mission Ridge fault and forms the northwest boundary of the

Figure 7.

- A. View to the southeast along Mission Ridge. Thirty degree dipping Mission Ridge fault separates hanging wall Bridge River Group rocks from the Mission Ridge pluton in the footwall.**
- B. Bedded Eocene(?) conglomerate and sandstone in the hanging wall of the Mission Ridge fault, above the Bridge River Canyon. Conglomerate beds are offset by a listric normal fault. The Mission Ridge fault is just below the frame of the photograph, where conglomerate is in fault contact with Bridge River Schist.**
- C. Foliated late-syn-tectonic granodioritic dyke (46.5 Ma). Surface is oriented perpendicular to foliation surface and parallel to the stretching lineation. C and S fabrics indicate a dextral shear sense.**
- D. Photomicrograph of orthogneiss from Bridge River Schist. C and S planes, and shearbands indicate dextral shear sense.**

Shulaps ultramafic complex (Schiarizza et al., 1990) suggesting that the entire western boundary of the Shulaps ultramafic complex is in the hanging wall of the Mission Ridge fault. Displacement on the Mission Ridge fault decreases to the northwest of the Bridge River Canyon, where there is less of a metamorphic omission. A minimum of 10 km of normal displacement on the fault is calculated in the Mission Ridge area based on pressure data and temperature estimates (see below for details).

Marshall Creek fault

The Marshall Creek fault is a major northwest-trending structure that extends from the Fraser fault, 35 km south of Lillooet (Monger and McMillan, 1984), for about 135 km northwest, where it joins the Yalakom fault (Figure 1; Tipper, 1978). In the study area, the Marshall Creek fault dips steeply ($50-75^{\circ}$) to the southwest and juxtaposes Bridge River schists against lower-grade Bridge River Group rocks (Figure 2).

At the southern end of the map area the fault truncates an east-northeast-trending low-angle fault that separates Bridge River schists and phyllites from overlying Bridge River Group (Figure 2). This low-angle fault is interpreted as the continuation of the Mission Ridge fault offset by movement along the Marshall Creek fault. Restoration of the low-angle fault from cross-section D-D' (Figure 4) gives an estimated 3.5 km normal component of displacement on the Marshall Creek fault. Farther southeast the Marshall Creek fault juxtaposes the Bridge River Schist and phyllite with the Brew Group (Figure 2). Restoration of the

Marshall Creek fault causes a problem since there is no Brew Group present east of the Marshall Creek fault; this could be due to an uncertain, but possibly significant, strike-slip component of movement on the Marshall Creek fault.

Northwest of the study area, at least 15 km of dextral strike slip on the Marshall Creek fault is inferred on the basis of offset marker units (Schiarizza et al., 1989a). The pattern formed by minor splays that link the Marshall Creek and Yalakom faults is interpreted by Schiarizza et al. (1989a) as representing an extensional duplex that transferred dextral displacement between the two faults. However, a strike-slip duplex with splays linking the two faults implies that the two faults are more or less coeval. This is not consistent with data that shows that deformation in the Bridge River Schist is associated with dextral strike-slip shear along the Yalakom fault, which is older than the Mission Ridge fault. The youngest deformation was dextral movement along the Marshall Creek fault, which offsets the Mission Ridge fault.

Cayoosh Creek fault

The contact between the Brew Group and overlying Bridge River Schist in the southeast corner of the map area appears to be a shallow northeast-dipping fault. The fault, named here the Cayoosh Creek fault, has not been mapped in detail. It is probably a thrust fault because it places older Middle Triassic - Middle Jurassic Bridge River Schist above Upper Jurassic - Lower Cretaceous Brew Group. Outcrop-scale recumbent folds within argillaceous units (Coleman, 1989) and within a conglomerate unit (Mustard, 1983) of the Brew Group may be related to

thrusting along the Cayoosh Creek fault, although the vergence of such folds is uncertain. Post-mid-Eocene strike-slip movement on the Marshall Creek fault could account for the Cayoosh Creek fault not being found in the footwall of the Mission Ridge fault east of the Marshall Creek fault.

MINOR STRUCTURES AND MYLONITIC FABRICS IN THE BRIDGE RIVER SCHIST

Mylonitic fabrics, used here to refer to planar and linear fabrics developed in rocks that have undergone strain induced grain size reduction without loss of cohesion (Brown and Murphy, 1982), are well developed in Bridge River Schist metacherts and pelites. The dominant shear foliation or C surface (Berthe et al., 1979) is defined at mesoscopic scale by compositional layering. At mesoscopic and microscopic scales layers of fine-grained ribbon quartz and feldspar are separated by fine-grained micaceous pelitic layers (Figures 5A and 5C). The micaceous layers have muscovite, biotite, chlorite, and locally-developed graphitic and opaque concentrations. In chloritic greenschist units the shear foliation is defined by aligned platy minerals including chlorite and muscovite.

Shear foliations have predominantly northwest-trending strikes and northeasterly dips (Figures 2 and 8). The shear foliation in the Seton Lake region, near the south end of Mission Ridge (Figure 2), dips moderately to steeply southwest as well as northeast (Figure 8). Late upright open folds with northwest trending axial surface traces deform the mylonitic foliation. These folds are possibly related to normal movement on the Marshall Creek fault and are thought to be responsible for the variation in foliation attitude about a horizontal axis

Figure 8.

Equal-area stereoplots of planar and linear fabric elements from the Bridge River Schist. Stereoplots A and B are from the Seton Lake region; C and D are from the Bridge River Canyon - Shulaps Range area (Figure 2.).

- pole to foliation
- + stretching lineation
- f_2 fold hinge

(Figure 8). Similarly, in the vicinity of the Marshall Creek fault zone, schists dip steeply to the southwest, where the foliation has been rotated by west-side-down normal movement on the steeply west-dipping Marshall Creek fault (Figure 2).

Stretching and intersection lineations are present on the shear foliations. Stretching lineations are best developed on the quartz-rich shear foliation surfaces, where they are defined by quartz rods and aligned aggregates of micaceous minerals (Figure 5A). In general, subhorizontal to shallowly plunging stretching lineations, on the shear foliation planes, trend northwest-southeast (Figures 8 and 5A). Stretching lineations parallel to the strike of foliation are indicative of strike-slip shear. The lineations plunge predominantly shallowly to the northwest, but a significant number, especially in the Seton Lake region, plunge shallowly to the southeast (Figure 8). The slight variation in plunge of the lineations about a horizontal axis suggests local reverse strike-slip and normal strike-slip components of movement or gentle folding.

Hinge lines of tight small-scale asymmetric folds are shallow-plunging and parallel to the stretching lineations (Figure 8). Isoclinal folds deform thinly layered metachert, with fold axes that are close to parallel with the stretching lineation. A crenulation cleavage with microfold hinge lines oriented parallel to the stretching lineation is interpreted to have formed during late stages of shearing. These microfolds are inferred to have formed with axes oriented perpendicular to the direction of maximum compression and parallel to the stretching direction.

FABRIC DEVELOPMENT IN GRANITIC BODIES THAT INTRUDE THE BRIDGE RIVER SCHIST

Concordant and discordant granitic bodies are weakly foliated to gneissic. Some of the intrusions are concordant with the shear foliation in the Bridge River Schist, whereas others cross-cut the foliation obliquely but are folded. The geometry and orientation of these folds range from open, variably oriented folds to isoclinal folds with axial surfaces parallel to the shear foliation. The granitic intrusives range from syn- to late syn-tectonic with respect to foliation development in the surrounding Bridge River Schist. The U-Pb geochronology on these granitic rocks indicates they are 46.5–48.5 Ma old demonstrating that deformation of the Bridge River Schist is in large part related to Eocene strike-slip shear and faulting and not to Mesozoic accretionary processes as was previously thought (Potter, 1986).

The deformed granitic rocks have textures indicative of progressive mylonitic deformation, including the development of S and C surfaces, and are characterized by a decrease in grain size (Berthe et al., 1979). Biotite, muscovite, and chlorite have undergone dynamic recrystallization and are oriented with long axes aligned within the shear foliation plane. Micas wrap around quartz and feldspar grains and are also recrystallized as asymmetric pressure shadows (Figure 9D).

The foliation development within the Mission Ridge pluton is highly variable. The interior of the pluton is mostly coarse-grained with equigranular igneous textures. In a narrow zone (on a scale of tens of metres) at the margin of the

Figure 9.

- A. C and S planes and shearbands in biotite - quartz schist from Bridge River Schist indicate dextral shear sense.**
- B. Rotated garnet with asymmetric pressure shadows of biotite indicate dextral shear sense.**
- C. Well developed shearbands, parallel to the stretching lineation, indicate dextral shear sense.**
- D. Feldspar with asymmetric chlorite tails in orthogneiss indicate a dextral shear sense. This orthogneiss is from the Custer Gneiss (correlative to the Bridge River Schist) near Hope (Figure 1).**

pluton there is a strain gradient with progressively stronger mylonitic fabrics toward the outer edge of the pluton (Figures 6A, 6B, and 6C). At the contact, the granodiorite is foliated and lineated and has porphyroclasts within a fine-grained matrix. In thin section, deformation fabrics reveal a combination of brittle and plastic deformation textures manifested by cracked and pulled apart feldspar grains with fine-grained recrystallized edges and by an anastomosing micaceous foliation. Chlorite is common in the foliation surrounding the feldspar porphyroclasts and formed by retrogression of biotite, during shearing, as indicated by chlorite overgrowing biotite in late stage shear bands. Mylonitic fabric elements developed within the pluton have orientations that are consistent with the fabrics in the surrounding Bridge River Schist.

KINEMATIC INDICATORS

Kinematic indicators that formed contemporaneously with the mylonitic foliation in the Bridge River Schist include rotated garnets with asymmetric pressure shadows (Figure 9B, Simpson and Schmidt, 1983), and S surfaces defined by "fish" shaped fine-grained quartz aggregates (Berthe et al., 1979) at an oblique angle to micaceous layers that define the C surfaces. Stretching lineations are oriented parallel to the C surfaces. The angle between C and S surfaces is 45° or less (Figure 9A and 9B), which indicates clockwise rotation of S surfaces. S surfaces record incremental stages of the x-y plane of the finite strain ellipsoid (Berthe et al., 1979, Figures 9A, 9B, 9C, and 9D). Clockwise (dextral) shear sense was recorded by orientation of C and S surfaces from ten field stations from

within the Bridge River Schist. This indicates an upper-member-to-the-southeast sense of shear.

Rotated garnets with asymmetric pressure shadow tails of biotite (Figure 9B) indicate that during peak metamorphic conditions, of lower amphibolite grade, shear sense indicators record movement of upper member to the southeast (dextral).

In the orthogneiss, S surfaces are defined by asymmetrically oriented quartz and feldspar porphyroclasts with fine-grained recrystallized margins and asymmetric tails within a mylonitic matrix (Figures 7C, 7D, and 9D). Asymmetric augen feldspar and quartz grains are visible in outcrop and in thin section. In several examples feldspar grains display 30°-40° brittle extensional microfaults (Figure 7D) that give a shear sense consistent with other kinematic indicators in the same thin section. Similarly minor shear bands that offset micaceous layers have formed micro-drag folds that also give a consistent shear sense.

Shear bands (e.g., Platt and Vissers, 1980; White et al., 1980) are abundant throughout the Bridge River Schist and are visible at macroscopic and microscopic scales of observation (Figures 5B, 5C, 9A, 9B, and 9C). The shear bands are defined by a weakly developed cleavage oriented 20°-40° from the dominant shear foliation. The shear-bands are discontinuous and they curve into and merge with C surfaces. In thin sections, micas curve into the zones that define the shear-bands or are cut off by microfaults (Figures 9A, 9B, and 9C; Platt and Vissers, 1980). Minerals are finer grained within these zones and have probably undergone

dynamic recrystallization. The sense of shear derived from the shear-bands (upper member to the southeast) is almost invariably consistent and was recorded from 20 field stations within the Bridge River Schist (Figure 2). Conjugate sets of shear-bands are developed but are extremely rare. In zones of bulk simple shear, a single set should form parallel to the bulk shear direction (Platt and Vissers, 1980).

The occurrence of chlorite as a retrograde product of biotite in shear band zones provides evidence that these shear bands formed during latter stages of mylonitization (Platt and Vissers, 1980; White et al., 1980). This is further supported by the simple observation that the shear bands deform the mylonitic foliation and are therefore a later structure. Textural relationships of kinematic indicators with the peak and retrograde metamorphic minerals suggest that during mylonitic foliation development, dextral shearing lasted through retrograde conditions at greenschist facies, at which grade the rocks were quickly quenched, preserving metamorphic and mylonitic textures and kinematic indicators.

GEOCHRONOLOGY

It is necessary to constrain the age of the dextral strike-slip fabric in the Bridge River Schist to evaluate its tectonic significance. Four igneous rocks from the footwall of the Mission Ridge fault were sampled for U-Pb zircon age determinations. Sample locations are outlined on Figure 2; three of the four samples are from the Bridge River canyon area; a fourth is from the east end of Seton Lake. Analytical methods are outlined in Appendix 1 and follow those developed by Krogh (1973, 1982) and Parrish et al. (1987). Analytical results are recorded in Table 1 and Figure 10. Zircon fractions from three of the four samples were abraded using air abrasion techniques similar to those developed by Krogh (1982).

MISSION RIDGE PLUTON

The Mission Ridge pluton was sampled from two locations (Figure 2). Sample MC-89-1 is a biotite-hornblende-bearing granite with medium-grained equigranular igneous texture. Sample MC-89-3 is a granodioritic mylonite with large (1 cm) plagioclase porphyroclasts.

Zircons analyzed from these samples consisted of elongate prismatic crystals. Three zircon fractions analyzed from sample MC-89-3 overlap in a cluster slightly below concordia at 47.5 Ma (Figure 10). Three of four fractions from sample MC-89-1 overlap below concordia at 47.3 Ma, and the fourth analysis plots below concordia at 48.3 Ma. As measured, the analyses are not concordant. The slightly discordant analyses intersect concordia only after corrections are made for ^{230}Th

TABLE 1. U-Pb Zircon Data for Mission Ridge Pluton and Associated Intrusions

	fraction, wt.	U	Pb	Tn ^d	In ^d	206Pb ^e	Pbc ^f	208Pb	206Pb/-1SE ^g	206Pb ^h	207Pb/-1SE ^g	207Pb ^h	207Pb	207Pb Age (Ma)	207Pb Age ^h
size ^a	mg	ppm	ppm U	rock	min.	204Pb	pg	%	235U	238U	corr.	corr.	corr.		
MC-89-1, Mission Ridge Pluton, Terzaghi Dam, Weekly Foliated, Late Synkinematic															
A +62a	.131	707	5.17	5.4	.3376077	2060	21	9.4	.007353±0.10%	.00736877	.04778±0.13%	.04713±0.06%	.0470273	55.6 ± 2.9	50.6 ± 2.9
B +62a	.131	687	5.11	5.4	.3432323	2131	20	9.5	.007474±0.09%	.00748975	.04662±0.12%	.04718±0.06%	.0470610	58.4 ± 2.8	53.3 ± 2.9
C +74a	.117	647	4.80	5.4	.3865669	2127	17	10.6	.007555±0.09%	.00737062	.04779±0.12%	.04712±0.05%	.0470263	55.5 ± 2.3	50.6 ± 2.9
D +62a	.195	731	5.39	5.4	.3721236	2407	28	10.2	.007347±0.11%	.00736266	.04767±0.13%	.04706±0.06%	.0469598	52.2 ± 3.0	47.2 ± 2.9
MC-89-2, Bridge River Canyon Dyke, Strongly foliated Mylonite															
A -62	.003	3102	23.4	4	.3232021	3485	36	9.0	.007617±0.11%	.00763246	.04957±0.13%	.04720±0.05%	.0471006	59.3 ± 2.2	54.3 ± 2.9
B -62	.052	3051	22.9	4	.3391166	2885	27	9.4	.007541±0.10%	.00755639	.04904±0.12%	.04716±0.05%	.0470670	57.5 ± 2.4	52.6 ± 2.9
MC-89-3, Mission Ridge Pluton, Bridge River Canyon, Strongly foliated Mylonite															
A +105a	.084	922	6.72	5.4	.3206854	914	40	9.0	.007372±0.11%	.00738762	.04787±0.19%	.04709±0.13%	.0469904	53.8 ± 6.1	48.7 ± 2.9
B +74a	.085	978	7.23	5.4	.3510037	2507	16	9.7	.007409±0.09%	.00742473	.04814±0.11%	.04713±0.05%	.0470274	55.6 ± 2.2	50.6 ± 2.9
C +62a	.083	904	6.75	5.4	.3878580	1842	19	10.6	.007406±0.10%	.00742160	.04814±0.12%	.04716±0.06%	.0470422	56.4 ± 2.8	51.4 ± 2.9
MC-89-4, Seton Lake Dyke, Foliated Mylonite															
A +62a	.069	1720	12.8	3.95	.4739751	1281	43	12.7	.007207±0.11%	.0072218	.04680±0.16%	.04709±0.10%	.0469990	53.9 ± 4.6	49.2 ± 2.9
B +74a	.035	1577	11.5	3.95	.3736047	2547	10	10.3	.007235±0.10%	.00725023	.04703±0.12%	.04715±0.05%	.0470428	56.6 ± 2.6	51.4 ± 2.9
C +149a	.069	1107	8.84	3.95	.1909628	1766	30	5.5	.008373±0.10%	.00838900	.05461±0.13%	.04731±0.07%	.0472137	64.7 ± 3.3	60.0 ± 2.9

Errors are 1 std. error of mean in % except 207/206 age errors which are 2 std. errors in Ma.
SIZES (i.e., +62) refer to aspect of zircons in microns; the letter a attached to sizes indicates fraction was abraded.
Radiogenic Pb.
Th/U of whole rock; analyses performed by ICPMS, courtesy of the Geological Survey of Canada. Detection limit is 0.1 ppm.
d/h/u of mineral. Th calculated from radiogenic 208Pb.
Measured ratio, corrected for spike and fractionation.
f Total common Pb in analysis corrected for fractionation and spike.
g Corrected for blank Pb and U, common Pb; errors quoted are 1 standard error of the mean in percent.
h Corrected for initial Th enrichment; correction procedure is described in Appendix 2.

Figure 10.

Concordia plots from U-Pb zircon analyses obtained from 4 granitic samples. Open ellipses represent uncorrected analyses. Solid ellipses represent analyses after corrections have been made for Th disequilibrium for reasons discussed in Appendix 2.

disequilibrium (described in Appendix 2). The discordance pattern of the three clustered analyses cannot be attributed to inheritance because of the very tight clustering and overlapping of three analyses of zircons of different sizes. If discordance were a result of an inherited component, separate analyses for different size fractions would contain varying amounts of inheritance; one would expect separate analyses to plot in a linear array with upper and lower intercepts indicating the ages of the inherited component and the magmatic component, respectively.

A single analysis from sample MC-89-1 plots slightly below concordia at 48.2 Ma. This older slightly discordant fraction, which has a corrected $^{207}\text{Pb}/^{206}\text{Pb}$ age of 53.3 ± 2.9 Ma, may have an older inherited component or may represent a 55-50 Ma zircon that experienced minor Pb loss.

Three analyses from MC-89-3 overlap slightly below concordia at 47.5 Ma. Corrections for Th disequilibrium restore the analyses to a concordant position at 47.5 Ma.

The two clusters of analyses from the two samples of the Mission Ridge pluton (MC-89-1 and MC-89-3) restore to concordant positions at 47.5 ± 0.2 Ma and 47.3 ± 0.2 Ma, and together they indicate that the Mission Ridge pluton is 47.4 ± 0.3 Ma old.

FOLIATED DYKES

Two foliated dykes were dated, the Bridge River Canyon dyke (MC-89-2) and the Seton Lake dyke (MC-89-4). The Bridge River Canyon dyke is concordant

with the foliation of the Bridge River Schist, and intrusion of the dyke is interpreted to be syn-kinematic with foliation development in the schist (Figure 3D). The dyke is a highly strained mylonitic L-tectonite with horizontal to subhorizontal mineral lineations oriented parallel to the stretching lineations in the surrounding Bridge River Schist.

The Seton Lake dyke cross-cuts foliation of the Bridge River Schist. The dyke is itself foliated and orientated subparallel to the foliation in the surrounding schist. Intrusion of the dyke is interpreted to be late syn-kinematic. The dyke is mylonitic with C and S fabrics that indicate the foliation formed in a southeast-directed (dextral) shear zone (Figure 7C).

Two of three zircon analyses from the Seton Lake dyke (MC-89-4) overlap at 46.5 Ma, intersecting concordia after ^{230}Th correction. A single analysis plots below concordia at 54 Ma and remains discordant after ^{230}Th correction. This fraction contains zircons that are much larger and have a different morphology than the zircons from the two 46.5 Ma fractions. These anomalous zircons are probably xenocrysts and this age most likely reflects averaging of two discrete populations: older xenocrysts >55 Ma and younger zircons morphologically similar to those from the 46.5 Ma concordant fractions.

The two zircon fractions from the Bridge River canyon dyke (MC-89-2) were the only unabraded fractions analyzed. After ^{230}Th correction one analysis is barely concordant at 48.5 Ma, while the other analysis remains discordant below concordia at 49 Ma. The concordant point is interpreted as the crystallization age,

48.5 $\pm$ 0.1 Ma. This could be a slight underestimate since the $^{207}\text{Pb}/^{206}\text{Pb}$ age, after correction is 52.9 $\pm$ 2.6 Ma. The reasons for discordance of the other fraction is more complex than initial ^{230}Th deficiency. A contributing factor to discordance could be radiation damage due to high uranium content. These fractions contained three times the ppm U than concordant fractions analyzed from the Mission Ridge pluton.

If the interpreted 48.5 $\pm$ 0.1 Ma age of the syn-kinematic Bridge River canyon dyke is correct, this indicates that there was magmatism during dextral strike-slip shearing immediately prior to intrusion of the 47.4 $\pm$ 0.3 Ma Mission Ridge pluton. The 46.5 $\pm$ 0.2 Ma age of the late syn-kinematic mylonitic Seton Lake dyke, which also has dextral kinematic indicators, provides evidence that dextral strike-slip faulting and magmatism was still active after intrusion of the Mission Ridge pluton. The Mission Ridge pluton is therefore interpreted to have intruded the Bridge River Schist during dextral strike-slip faulting.

In summary, ductile dextral shearing was occurring both prior to 48.5 Ma and after 46.5 Ma. These intrusions, particularly the Mission Ridge pluton, define the westernmost location of Middle Eocene magmatic rocks of southern British Columbia and are coeval with volcanic rocks in the Kamloops Group east of the Fraser fault.

GEOBAROMETRY

AL-IN-HORNBLENDE GEOBAROMETER

The Al content of hornblende from the Mission Ridge pluton (undeformed)

was used as a geobarometer to determine the depth of crystallization of the magma. Hammarstrom and Zen (1986) and Hollister et al. (1987) showed theoretically and empirically that for some calc-alkaline plutons the aluminum content of magmatic hornblende is controlled by pressure. They also derived equations that determined the pressure of phenocryst equilibration from Al content in hornblende. Johnson and Rutherford (1989) have refined the equation for determining pressure from Al content in hornblende through experimental calibration. They derived the equation:

$$P = -3.46(+/-0.24) + 4.23(+/-0.13)(Al^T)$$

In this equation P is pressure in kilobars and Al^T is total Al content. The uncertainty associated with applying this calibration depends on the specific Al^T content of the hornblende. If Al^T content is within a 95% confidence limit, the maximum error is +/- 0.6 kbar at 8 kbar and slightly less (+/- 0.5 kbar) at lower pressures. The Mission Ridge pluton has the appropriate equilibrium mineral assemblage of quartz + orthoclase + plagioclase(An_{30}) + hornblende + biotite + sphene + magnetite required for this geobarometer.

ANALYTICAL TECHNIQUES

Euhedral hornblende rims (Figure 6D) were analyzed on a Cambridge Microscan 5 electron microprobe at Carleton University operated at 20 kilovolt accelerating potential and a specimen current of 9.0 nanoamperes. U.S.N.M. microprobe standard kakanui hornblende was used as the calibration standard. Hornblende was not analyzed for H_2O content, which accounts for the

approximately 98 wt.% totals (Table 2). There is 0.1% uncertainty of relative total Al content, which is from microprobe analysis. Structural formulae for hornblende were calculated on the basis of 23 oxygens.

RESULTS

Table 2 shows that in euhedral hornblende total Al varies from 1.56 to 1.60%. This translates into $P = 3.14-3.31 \pm 0.5$ kbar. Another grain had distinct anhedral shape and chemical zoning. The rim composition is that most likely in equilibrium with all essential mineralogical phases, and its total Al is 1.50-1.54%, yielding pressures of 2.9-3.03 kbar. Taking these estimates, the crystallization pressures are calculated at $2.9-3.03 \pm 0.5$ kbar. This pressure is interpreted as that present during the 47.5 Ma crystallization of the Mission Ridge pluton.

TABLE 2: Microprobe Analyses of Hornblendes from Mission Ridge Pluton
for Al-in-Hornblende Geobarometer

Run P(kbar)	Euhedral Grain						Anhedral Grain			
	Rim				Core		Core		Rim	
	M1.1 3.2	M1.2 3.2	M1.3 3.3	M1.4 3.2	M1.5 3.1	M1.6 3.1	M2.1 0.8	M2.2 1.2	M2.3 2.9	M2.4 3.0
SiO ₂	44.70	44.22	43.75	44.06	44.14	43.89	47.78	46.94	44.22	43.88
Al ₂ O ₃	8.98	8.85	8.98	8.76	8.71	8.64	5.81	6.12	8.38	8.52
TiO ₂	1.57	1.58	1.60	1.52	1.64	1.53	0.74	0.74	1.25	1.30
MgO	11.07	10.85	10.86	10.91	10.74	10.88	12.07	11.59	10.81	10.45
FeO	17.67	17.81	18.22	17.68	17.59	17.50	17.98	17.71	18.10	18.15
MnO	0.56	0.52	0.57	0.52	0.59	0.52	0.97	0.83	0.78	0.82
Cr ₂ O ₃	0.08	0.06	0.09	0.05	0.13	0.08	0.14	0.11	0.11	0.10
NaO ₂	1.72	1.61	1.62	1.27	1.34	1.20	1.04	1.21	1.56	1.52
CaO	11.48	11.66	11.39	11.37	11.48	11.46	11.51	11.29	11.39	11.38
K ₂ O	0.97	0.96	1.02	0.89	0.76	0.75	0.57	0.58	0.83	0.90
Total	98.80	98.12	98.10	97.03	97.12	96.45	98.61	97.12	97.83	97.02
Cations per 23 Oxygen, Total Fe as FeO										
Si ^{IV}	6.672	6.660	6.610	6.692	6.696	6.700	7.105	7.085	6.716	6.701
Al ^{IV}	1.328	1.340	1.390	1.308	1.304	1.300	0.895	0.915	1.284	1.299
Al ^{VI}	0.253	0.231	0.210	0.260	0.254	0.255	0.123	0.174	0.216	0.235
Ti	0.177	0.179	0.181	0.174	0.187	0.176	0.083	0.084	0.143	0.150
Mg	2.463	2.436	2.446	2.470	2.429	2.476	2.676	2.608	2.447	2.378
Fe	2.206	2.243	2.302	2.246	2.232	2.235	2.236	2.236	2.299	2.319
Mn	0.071	0.066	0.073	0.067	0.076	0.067	0.123	0.106	0.100	0.106
Cr	0.009	0.007	0.010	0.006	0.015	0.009	0.017	0.013	0.013	0.013
Na	0.498	0.471	0.473	0.375	0.395	0.356	0.301	0.355	0.460	0.451
Ca	1.836	1.882	1.845	1.851	1.865	1.874	1.834	1.826	1.854	1.863
K	0.184	0.184	0.198	0.172	0.146	0.146	0.108	0.111	0.160	0.176

STRUCTURAL SYNTHESIS

RESTORATION OF MISSION RIDGE FAULT

Uplift of the Bridge River Schist was accommodated by extensional faulting along the Mission Ridge fault, that clearly truncates mylonitic foliation in the Bridge River Schist, and is demonstrably younger than 46.5 Ma intrusions. Depth calculations for the contrasting grades of metamorphism of the hanging wall and footwall rocks of the Mission Ridge fault make it possible to calculate normal displacement on the Mission Ridge fault and construct pre-46.5-Ma restored cross sections (Figure 11).

For footwall rocks, temperature ranges for the metamorphic grade of the Bridge River Schist and pressure estimates based on Al content of hornblende from the late syn-kinematic Mission Ridge pluton are used to determine the geothermal gradient of the upper crust and the depth of the schists during peak metamorphic conditions. A minimum temperature of 425°C from a range of 425-525°C was inferred for upper greenschist facies assemblages containing stable chlorite, biotite, and garnet (Winkler, 1979). Pressure during peak metamorphism is assumed to be somewhat higher than the 2.9-3.03 $\pm$ 0.5 kbars calculated for the Mission Ridge pluton, based on the assumption that the Bridge River Schist experienced some uplift and cooling prior to emplacement of the late syn-kinematic pluton. Conditions of 4 kbar and 425°C are inferred for Bridge River Schist during its ductile deformation.

To determine depth, an average density for continental crust of 2670 kg m⁻³

Figure 11.

Cross sections from Figure 4 restored to 47.5 Ma, prior to normal movement on Mission Ridge and Marshall Creek faults. Dotted line shows location of future Mission Ridge fault (see text for discussion).

47.5Ma restored x-sections

(Bott, 1982) yields a pressure gradient of 3.8 km/kbar. Using this pressure gradient the Bridge River Schist at 4 kbar and 425°C was at a depth of 15.2 km. According to the calculated continental geotherms of Chapman (1986), this temperature and this pressure plot on an equilibrium geotherm with a surface heat flow of 90 mW m⁻¹. Although this is a high heat flow it is within the range expected for magmatic belts. The hanging wall rocks (Bridge River Group) were at or below conditions of prehnite-pumpellyite facies, which indicates a maximum temperature range of 200-300°C (Winkler, 1979); this translates to a maximum depth range of 6-10 km at the time of metamorphism, assuming the same value of heat flux as inferred above. These calculated depths require a minimum range of 5.3-9.2 km of vertical omission for juxtaposition of the contrasting metamorphic grade of the hanging wall and footwall rocks. The vertical omission created by normal movement on the 30°-dipping Mission Ridge fault translates to a minimum range of down-dip displacement of 10.4-18.4 km. Restoring a minimum of 10.2 km of down-dip displacement on the Mission Ridge fault places the Yalakom fault directly above the plastically deformed Bridge River Schist prior to 46 Ma (Figure 11). If the permissible larger displacements are used, the footwall rocks restore even closer to the down-dip location of the Yalakom fault structures.

EOCENE DEXTRAL OBLIQUE-SLIP

Structural and geochronologic data support a model for regional dextral strike-slip faulting prior to normal movement on the Mission Ridge fault. U-Pb geochronology of the Mission Ridge pluton and associated dykes and the

structural relationships of these intrusions to the mylonitic foliation within the Bridge River Schist indicate that there was dextral strike-slip shear before 48.5 Ma and that there was additional strike-slip faulting and magmatism from 48.5 to 46.5 Ma. This is consistent with the conclusions of Glover et al. (1988) and Schiarizza et al. (1989a) from northwest of the map area in the Cadwallader - Bridge River Terrane area regarding post-mid-Cretaceous right lateral offset on the Yalakom fault system.

Although there is no direct evidence linking Middle Eocene strike-slip movement on the Yalakom fault to the southeast-directed mylonites of the Bridge River Schist, the Yalakom fault is the only post-mid-Cretaceous dextral strike-slip fault in the vicinity to the east of the schists. Restoration of movement on the Mission Ridge fault requires placing the schists in a position very near the down-dip location of the Yalakom fault. There seems to be no other alternative in which to explain the significant dextral ductile shear within the schists. The Yalakom fault is therefore inferred to be the strike-slip fault active during the Middle Eocene that generated dextral ductile fabrics in the Bridge River Schist in the middle crust.

Structures in the hanging wall of the Yalakom fault that could be related to compression include southwest-verging folds with axial surfaces parallel to the fault zone and imbricate fault slices (Figure 2). Schiarizza et al. (1990) also report southwest-verging folds in the hanging wall of the Yalakom fault northwest of the study area in the Yalakom River area. These folds die out to the northeast of the

Yalakom fault zone (P. Sciarizza, 1989 personal communication). Although timing of these structures is not well constrained, their orientation is consistent with a component of shortening at a high angle to the fault trace. Because these folds are spatially related to the Yalakom fault, I presume that they formed during dextral displacement.

In the footwall of the Yalakom fault the axis of a large syncline in Eocene(?) sedimentary rocks on Mission Ridge (Figure 2) is parallel to the trace of the Yalakom fault. The same fold is truncated by the Mission Ridge fault. The orientation of the fold provides evidence for shortening in upper-crustal-level rocks prior to extensional faulting. If these sedimentary rocks are Eocene, this shortening must also be Eocene in age. I interpret the upper level compressional structures to have formed simultaneously with dextral fabrics in deeper level footwall mylonites of the Bridge River Schist.

Similar compressional features have been documented in other intra-orogenic transcurrent fault settings including the San Andreas fault (Wilcox et al., 1973; Harding, 1976; Mount and Suppe, 1987) and in Caledonian Spitsbergen (Harland, 1971; Lowell, 1972). In both these examples, folds with axes nearly parallel to the fault zones, have been related to transpression. There are two existing interpretations for their formation. In one model, initially en echelon folds with axes oblique to the principal displacement zone rotate into parallelism under continued strike-slip. An alternative model explains fold orientations by strain partitioning in a transpressive regime into simple shear (with oblique folds) and

shear zone normal pure shear (with shear zone parallel folds) according to relative competence (Harland, 1971).

Recent data from the San Andreas fault (Mount and Suppe, 1987), including break-out orientations in boreholes, trends of Pliocene to Holocene fold axes, and fault plane solutions, support a model for transpression in which transpressive shear along a subduction zone is partitioned to strike-slip and dip-slip deformation operating simultaneously and largely independently.

The strain partitioning model for accommodation of transpression, however, remains somewhat controversial. Harding (1988, p.1152) states that "the oblique angle between en echelon folds and adjacent wrench faults has a wide range of values (10° - 30°) and is commonly smaller than the angle produced by models of simple shear (Wilcox et al., 1973)". Additional study is required to determine which model is appropriate for the present orientation of the folds parallel to the Yalakom fault. However, the presence of imbricate thrust faults parallel to the fold axes and the main fault zone (Figure 2) is supporting evidence of strain partitioning, if in fact these structures were formed during dextral strike-slip faulting.

Regardless of which model applies, the folds in the Yalakom fault hanging wall, the synform in the footwall Eocene sedimentary rocks, and the deeper level footwall mylonites with dextral strike-slip kinematic indicators within the Bridge River Schist are characteristics consistent with a dextral transpressional setting. Much of the mylonitic development is constrained to be Middle Eocene in age

but strike-slip movement on the Yalakom fault system could have started as early as Late Cretaceous.

An unusual aspect of the Yalakom fault within the study area is its shallowly-dipping geometry at the upper crustal level. Intra-plate strike-slip faults commonly are vertical in the upper crust and flatten at middle crustal levels into detachment horizons (Royden, 1984; Lemiski and Brown, 1988). However, the geometry of the Yalakom fault and its subjacent ductile zone of shear (after restoring normal movement on the Mission Ridge fault) is shallowly dipping at the surface, where it is a brittle fault, and moderately dipping below the brittle-plastic transition, where orientation of foliation of the upper greenschist grade Bridge River Schist generally has an inferred shallow to moderate northeasterly dip (Figure 3) after restoration.

CONCLUSIONS

- (1) Middle Eocene and younger deformation dominates the structural configuration of the Bridge River Terrane in the Mission Ridge region.
- (2) Intrusion of the Middle Eocene Mission Ridge pluton was coeval with dextral strike-slip shear in Bridge River Schist; this system of shear is interpreted to have been produced by dextral faulting on the Yalakom fault.
- (3) Dextral strike-slip faulting along the Yalakom fault system during the Middle Eocene occurred in a transpressional setting, based on the presence of imbricate thrust slices along the fault trace, compressional fault-parallel folds in the hanging wall, folding of Eocene(?) sedimentary rocks on Mission Ridge, and Middle

Eocene dextral kinematic indicators in the Bridge River Schist.

- (4) The Mission Ridge fault is a normal fault with at least 10 km of down-to-the-east-northeast displacement. It truncates the Middle Eocene Mission Ridge pluton and the Bridge River Schist (formed by Middle Eocene dextral strike-slip shear).**
- (5) Extensional faulting along the Mission Ridge fault is bracketed by dextral movement on both the Yalakom and Marshall Creek faults and is probably kinematically related to regional strike-slip faulting.**
- (6) The Fraser fault truncates the Mission Ridge, Yalakom, and Marshall Creek faults, indicating that 80-110 km of dextral displacement is constrained to the period after 46 Ma and before 34 Ma (intrusion of Chilliwack batholith).**

DISCUSSION

RELATIONSHIP OF STRIKE-SLIP FAULTING TO EXTENSIONAL FAULTING IN SOUTHWEST BRITISH COLUMBIA

Timing and geometric relationships suggest a link between regional dextral strike-slip shear and extensional movement along the Mission Ridge fault. As discussed above, east-northeast-directed normal movement along the Mission Ridge fault is younger than dextral strike-slip fabrics in the Bridge River Schist but older than dextral strike-slip along the Marshall Creek fault. In other words, the Mission Ridge fault was active as a normal fault while in a regional northwest striking dextral strike-slip regime in Middle Eocene time.

At the northwest end of the Yalakom fault an Eocene extensional fault has been documented at the western boundary of the Tatla Lake metamorphic complex (Freidman and Armstrong, 1988; Figure 1). Hanging wall to the west ductile normal faulting (55-47.5 Ma) followed by east-directed brittle normal faulting unroofed amphibolite grade mylonitic gneisses. U-Pb dating in that area constrained extensional faulting mainly to Early and Middle Eocene time (55-47 Ma), and later folding was related to post-47-Ma dextral motion along the Yalakom fault (Friedman and Armstrong, 1988).

It is probable from the chronology of tectonic events in the Bridge River Terrane and the Tatla Lake complex that extensional faulting in this region of the Cordillera during Middle Eocene time was kinematically linked and was a direct result of dextral strike-slip faulting on the northwest-trending Yalakom fault system. Tectonic settings that could accomodate normal faulting by creating a

zone of transtension, during strike-slip faulting, include a releasing bend in the main strike-slip fault trace or a change in relative plate boundary motions.

SUMMARY OF EOCENE TECTONIC EVENTS IN THE BRIDGE RIVER TERRANE

As early as Middle Eocene (48.5 Ma) and probably starting in Late Cretaceous time, there was significant dextral motion on the Yalakom fault system, which continued to sometime after 46.5 Ma. During this time interval mylonites with dextral kinematic indicators formed at a depth of 6-10 km within Bridge River Terrane rocks, accompanied by intrusion of the Mission Ridge pluton at 47.5 Ma and granitic dykes at 48.5 and 46.5 Ma. At upper crustal levels, formation of compressional structures during the Middle Eocene including folds in upper plate Tyaughton-Methow sedimentary rocks, a fold in lower plate Eocene(?) sedimentary rocks, and imbricate thrust fault splays, all parallel to the Yalakom fault trace, provides evidence that dextral displacement was transpressional during the Middle Eocene within the study area.

The Bridge River Schist mylonites and associated intrusions were exhumed by post-46.5-Ma extensional faults. Most of the extension in the Bridge River Terrane was accommodated by > 10 km of down-dip displacement on the Mission Ridge fault followed by further dextral strike-slip movement (8 km) on the Marshall Creek fault, which also had a minor component of down to the west normal movement (3 km). All three faults (Yalakom, Mission Ridge, and Marshall Creek) are truncated by the Late Eocene Fraser fault (Figure 1).

REGIONAL CORRELATION AND TIMING OF EOCENE FAULTS OFFSET BY THE FRASER FAULT SYSTEM

The sequence of faults and lithological panels in the Mission Ridge area is offset 80-100 km by dextral strike slip on the Fraser fault. Correlative geology east of the fault extends from near Hope, British Columbia, to south of the Canada-U.S.A. border (Figure 1). Monger (1985) correlated the Yalakom fault with the Hozameen fault because both faults form a distinct boundary between the Jurassic-Cretaceous Tyaughton-Methow marine sedimentary rocks to the east and the Permian-Triassic Bridge River - Hozameen Terrane oceanic assemblage to the west. Correlation of the other northwest-trending structures is less certain.

Restoration of 80-100 km on the Fraser fault matches the Bridge River Schist with the Skagit (Custer) Gneiss (Figure 12). The Skagit Gneiss, in the vicinity of Hope is composed of amphibolite grade pelite and metachert laced with abundant orthogneiss and pegmatite. East of the Skagit Gneiss, low-grade rocks of the Hozameen Group are correlative with the Bridge River Group (Monger, 1985), and are juxtaposed against the higher grade Skagit Gneiss by the east-dipping Ross Lake fault. Farther to the south Haugerud (1985) estimated 20 km of down-to-the-east normal movement on the Ross Lake fault.

Ross Lake fault - Mission Ridge fault correlation

Based on reconnaissance mapping done as part of this study, the Ross Lake fault in the vicinity of Hope, British Columbia, is correlated with the Mission Ridge fault because of similarities in fault geometry, lithology, and structural style of hanging wall rocks and lithological and kinematic signature of footwall rocks.

Figure 12.

Middle Eocene configuration of major lithological units and northwest trending faults. About 85 km of displacement on the Fraser - Straight Creek fault system has been restored by matching the Mission Ridge and Ross Lake faults.

**Reconstruction for after 46.5 Ma and
before Fraser fault displacement**

The Ross Lake fault dips moderately 40° - 60° to the east as does the foliation of the footwall schist and gneiss. Subhorizontal northwest-trending stretching and mineral lineations lie in the footwall. Dextral kinematic indicators (C and S planes and shear bands) indicate that ductile deformation occurred in a dextral strike-slip shear zone, similarly to Bridge River Schist deformation.

It is not certain whether the bulk of strike-slip movement occurred along the Hozameen fault zone or along the Ross Lake fault prior to extensional movement. In order for the Ross Lake - Mission Ridge fault correlation to be consistent with the previously proposed Middle Eocene Yalakom fault model, the dextrally deformed mylonites of the Skagit Gneiss must be a mid-crustal level of a Late Cretaceous - Middle Eocene dextral shear zone, exhumed by post-46.5-Ma extensional movement on the Ross Lake fault.

The difference in metamorphic grade between the Skagit Gneiss (amphibolite facies) and Bridge River Schist (upper greenschist facies) can be explained by a decrease in the amount of normal displacement on the Ross Lake - Mission Ridge fault system to the northwest. This is consistent with an apparent decrease in normal displacement on the Mission Ridge fault towards the northwest within the Bridge River Terrane.

Geochronological data from the Bridge River Schist and Skagit Gneiss are similar but not identical. In the Mission Ridge area, dextral strike-slip motion in the Bridge River Schist started prior to 48.5 Ma and lasted past 46.5 Ma.

Comparable results from the Ross Lake fault zone include a 48 Ma U-Pb age on

a syn-kinematic intrusion into orthogneiss (Hoppe, 1982) and younger strike-slip motion indicated by a 46 Ma U-Pb age on concordant orthogneiss from the Skagit Gneiss (P. van der Heyden, personal communication, 1989). A 50 Ma U-Pb age on a pluton, which cross-cuts a strand of the fault zone (Miller and Bowering, 1988), is inconsistent with the other age determinations of younger syn-kinematic intrusions but may suggest that different "along-strike" segments of the fault zone were not all active simultaneously. In any case, the bulk of the geochronologic data from the correlated fault zones are consistent with a Middle Eocene tectonic setting involving dextral shear with syn-kinematic magmatism.

Taking into account the Mission Ridge - Ross Lake fault correlation, the northwest-trending zone of middle to upper crust affected by Middle Eocene dextral shear on the Yalakom fault system has a length of about 400 km (with Fraser fault restoration, Figure 12). Although the amount of Middle Eocene dextral offset on the Yalakom fault system has not been unequivocally determined, the degree to which middle to upper level crustal rocks were deformed implies that it was significant. This has serious implications for the existing models for Eocene transtension in the Cordillera that relate regional extension to strike-slip faulting.

IMPLICATIONS FOR PRICE-CARMICHAEL MODEL FOR EOCENE TRANSTENSION IN THE CORDILLERA

Major intra-orogenic transcurrent faults of the Canadian Cordillera record relative northwest counter-clockwise motion of Cordilleran lithosphere from Late Cretaceous through Eocene time (Monger and Price, 1979). The Tintina -

Northern Rocky Mountain Trench system has a length of 2500 km, along which about 450 km of Late Cretaceous through Early Eocene dextral displacement has been estimated (Templeman-Kluit, 1979; Roddick, 1967; Gabrielse, 1985). Dextral displacement along the Northern Rocky Mountain Trench appears to terminate at its southern end: there is evidence of only minimal transcurrent motion on the Southern Rocky Mountain Trench (Leech, 1962; Price et al., 1972; Harrison, 1972; Harrison et al., 1974; Benvenuto and Price, 1979; Price, 1981; McMechan, 1981; McMechan and Price, 1982; Murphy, 1990). It has been suggested that the displacement on the Tintina - Northern Rocky Mountain Trench was in part transferred to the Fraser fault system (Gabrielse, 1985; Price and Carmichael, 1986). Price and Carmichael (1986) proposed a geometrical model that treats the Tintina - Northern Rocky Mountain Trench and Fraser fault zones as separate en echelon concentric, small circle fault segments of a composite intra-continental transform fault zone. At the Southern Rocky Mountain Trench this model partitions the 450 km of displacement from the Northern Rocky Mountain Trench into oblique convergence in the southern Rocky Mountains during Late Cretaceous - Paleocene time, with the remainder taken up by Early to Middle Eocene dextral strike-slip on the Fraser fault system.

This model also explains the zone of Eocene extension in southeast British Columbia and northern Washington as an area of west-northwest to east-southeast horizontal stretching in the zone of en echelon overlap between the Tintina - Northern Rocky Mountain Trench and the Fraser fault zones. Price and

Carmichael (1986, p. 470) state that "Early Eocene change from transpression to transtension in the southern Cordillera may be a result of a small change in regional plate kinematics and/or the initiation of the Fraser fault zone".

Timing constraints on extensional faulting in the southern Omineca belt of southeast British Columbia and northern Washington (Parrish et al., 1988) and on dextral movement of the Fraser fault (from this study) preclude the latter possibility. Major extensional faulting in the southern Omineca belt occurred from 58 to 45 Ma (Parrish et al., 1988), and the 80-100 km of dextral offset on the Fraser fault system took place between 46.5 and 34 Ma. These timing constraints make it very unlikely for the major displacement on the Fraser fault to be linked to the cause of extension in the Omineca belt. It is more probable that dextral motion on the Yalakom fault (pre-48.5-Ma to post-46.5-Ma) accommodated displacement transferred from the Tintina - Northern Rocky Mountain Trench. Whether or not these displacements are kinematically or dynamically related to extension in the southern Omineca belt remains to be determined.

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APPENDIX 1

Analytical techniques

Zircons were extracted from four samples using standard crushing and grinding techniques. A series of steps to separate minerals by density were implemented to obtain heavy mineral separates. A Roger's table was used for "wet shaking" followed by heavy liquid separation using methylene iodide.

Magnetic separation was done with a FrantzTM LB-1 separator. Minerals were then separated into different size fractions by sieving with ethyl alcohol, and final zircon selections were made by hand picking in ethyl alcohol.

All fractions of zircons (except fractions from sample MC-82-2, which consisted of zircons too small and fragile to survive abrasion) were abraded with pyrite using an air abrasion device similar to that developed by Krogh (1982). After abrasion, zircons were leached in lukewarm 3N HNO₃ for 15 minutes. Final mineral selection was made by hand picking. The remaining steps were done in a clean lab with filtered air.

Zircon fractions were acid washed in lukewarm 3N HO₃ for 20 minutes after which they were rinsed in acetone, dried in clean air, and weighed using a microbalance. Grains were transferred to teflon microcapsules (Parrish, 1987) and a mixed ²⁰⁵Pb-²³³U-²³⁵U isotopic tracer (Parrish and Krogh, 1987) was added.

Dissolution of zircon was carried out by methods modified from Krogh (1973). Additions of 0.25 ml of HF were made to the zircon samples within the teflon microcapsules, which were then heated in ovens within steel-jacketed pressure

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MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS
STANDARD REFERENCE MATERIAL 1010a
(ANSI and ISO TEST CHART No. 2)

vessels at 240-250°C for 30 hours. After cooling these solutions were evaporated.

To prepare the samples for column chemistry, 3.1 N HCl was added and samples were put in a 210°C oven for 14 hours. U and Pb were then separated by ion exchange elution chemistry using BioRad AG1x8, 200-400 mesh, CL⁻ form anion exchange resin. The remaining U and Pb elution steps were done as outlined by Parrish et al. (1987). U and Pb isotopic compositions were measured on a Finnigan-MAT 261 variable multicollector mass spectrometer. Blank levels of U and Pb were 6 and 11 pg, respectively. U-Pb errors were calculated by direct propagation of errors (Roddick, 1987), and plotting on concordia diagrams was done using software written by J.C. Roddick of the Geological Survey of Canada.

APPENDIX 2

²³⁰Th deficiency corrections

It has been recognized for some time that accessory minerals that are younger than about 100 Ma, including zircon, monazite, and xenotime, show anomalous U-Pb systematics (Mattinson, 1973; Scharer, 1984; Copeland et al., 1988; Parrish, in press). Mattinson (1973) noted that young zircons have unusually high ²⁰⁷Pb/²⁰⁶Pb ratios. He also observed that the deviation of ²⁰⁷Pb/²⁰⁶Pb ratios for young zircons consistently decreases with increasing age, and from this he concluded that the anomalous ²⁰⁷Pb/²⁰⁶Pb ratios were a result of an initial deficit of ²⁰⁶Pb. ²³⁰Th is an intermediate daughter product of the ²³⁸U-²⁰⁶Pb decay chain with a 7.52×10^4 year half-life. Mattinson noted that "exclusion of ²³⁰Th from zircon during

crystallization will result in a deficiency of ^{206}Pb equivalent to the amount of ^{230}Th excluded".

The opposite is true for monazite. Monazites have been shown to have initial enrichment in ^{230}Th (Scharer, 1984) and thus have excess ^{206}Pb and "start life" above concordia. Monazites are affected by ^{230}Th to a higher degree than zircons and Scharer (1984) described a method for correcting ^{206}Pb ratios based on the deviation of Th/U content of the mineral analyzed from the Th/U content of the magma (whole rock).

The corrections required for deficient or excess ^{206}Pb are outlined by Scharer (1984) and have been used to obtain corrected $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{206}\text{Pb}$ ages for all the zircon analyses. Corrected ratios and ages are recorded and plotted in Table 1 and Figure 10. Although corrections in $^{206}\text{Pb}/^{238}\text{U}$ ages are minor, about -0.1 Ma, $^{206}\text{Pb}/^{207}\text{Pb}$ age corrections are significant, about -5 Ma (Table 1). Additional uncertainty in corrected $^{207}\text{Pb}/^{206}\text{Pb}$ ages as a result of the correction procedure has not been included. After correction, the analyses shift towards concordia, and most analyses become concordant (Figure 10). The fact that some of the analyses do not completely restore to concordia after Th corrections may be due to minor amounts of inheritance or may result from the measured Th/U of the whole rock not being equivalent to the Th/U of the magma.

Corrections for Th disequilibrium

The following corrections made for initial ^{230}Th deficit follow those described by Scharer (1984) and Parrish (in press).

The correction uses a fractionation factor f

$$f = (\text{Th}/\text{U})_{\text{mineral}} / (\text{Th}/\text{U})_{\text{magma}}$$

which defines the degree of Th-U fractionation that has taken place between the mineral and the magma from which it crystallized. In this study whole rock U and Th analysis from ICP-MS was done to estimate the latter. To obtain Th/U ratios for the zircons Th content was calculated from the amount of radiogenic ^{206}Pb in each analysis from the age equation:

$$^{232}\text{Th} = ^{206}\text{Pb} / (e^{L_{232} t} - 1)$$

where L_{232} = Th^{232} decay constant and $t = ^{207}\text{Pb}/^{235}\text{U}$ age

The f factor is then used in an equation to calculate the corrected $^{206}\text{Pb}/^{238}\text{U}$ ratio:

$$(^{206}\text{Pb}/^{238}\text{U})_{\text{corrected}} = (^{206}\text{Pb}/^{238}\text{U})_{\text{measured}} - (f - 1) L_{238}/L_{230}$$

from which the corrected $^{207}\text{Pb}/^{206}\text{Pb}$ ratio is calculated by the expression:

$$(^{207}\text{Pb}/^{206}\text{Pb})_{\text{corrected}} = 1/137.88 (^{207}\text{Pb}/^{235}\text{U})_{\text{measured}} / (^{206}\text{Pb}/^{238}\text{U})_{\text{corrected}}$$

Application of these corrections require the following assumptions outlined by Scharer (1984):

- (1) The magma was in radioactive equilibrium before crystallization.
- (2) Th/U ratio of the whole rock still reflects Th/U ratio of the magma from which the mineral crystallized.
- (3) $^{207}\text{Pb}/^{235}\text{U}$ age of the zircon analyses approximates the age of crystallization.

122° 28'

50° 51'

122° 16'

THIS
MAP
PRO
COT
191

122°16'
50°98'

GEOLOGY OF THE MISSION RIDGE AREA

BY M.E. COLEMAN

NTS 92-J/9, 10, 15, 16

A'

B

C

B

B

C

D

BRG

REEK

BRG

JKLG

LEGEND

STRATIFIED ROCKS

- EOCENE(?)
TES Conglomerate, sandstone, and siltstone
- UPPER JURASSIC TO LOWER CRETACEOUS
LILLOOET GROUP
JKLG Argillite, fine-grained sandstone, and coarse-grained volcanic sandstone
- BREW GROUP
JKbg Argillite, quartzite, conglomerate, and their metamorphosed equivalents
- UPPER TRIASSIC
CADWALLADER GROUP
Hurley Formation
Thin- to thick-bedded sandstone, calcarenite and shale; lesser amounts of limestone volcanic conglomerate and volcanic sandstone; minor greenstone and

INTRUSIVE ROCKS

- EOCENE(?)
TEr Leucocratic felsite, in part hornblende phytic
- MIDDLE EOCENE
TEmr MISSION RIDGE PLUTON: hornblende-biotite-bearing granodiorite

SYMBOLS

- Geological contact (defined, approximate, assumed) - - - - -
- Thrust fault, teeth in direction of dip (defined, approximate, assumed) - - - - -

2
km

SCALE 1:50000

URCH

Thin- to thick-bedded sandstone, calcarenite and shale; lesser amounts of limestone, volcanic conglomerate and volcanic sandstone; minor greenstone and greenstone breccia

Thrust fault, teeth in direction of dip (defined, approximate, assumed)

2
km

LEGEND

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Hurley Formation

URCH Thin- to thick-bedded sandstone, calcarenite and shale; lesser amounts of limestone-volcanic conglomerate and volcanic sandstone; minor greenstone and greenstone breccia

PERMIAN TO JURASSIC

BRIDGE RIVER GROUP

BRG Undivided ribbon chert, argillite and pillowed to massive greenstone, with lesser amounts of limestone, gabbro, diabase, sandstone, pebble conglomerate and serpentinite

LS Limestone

BRIDGE RIVER SCHIST

BRS Undivided metachert, phyllite, green chloritic schist, orthogneiss, and minor amounts of marble, biotite-quartz schist, talc schist, chert, argillite, greenstone and limestone.

AGE UNKNOWN

SHULAPS ULTRAMAFIC COMPLEX

SM SERPENTINITE MELANGE UNIT: serpentinite with blocks of ultramafic rock, gabbro, diorite, pillowed and massive greenstone

S Serpentinite

INTRUSIVE ROCKS

EOCENE(?)

TEr Leucocratic felsite, in part hornblende phyrlic

MIDDLE EOCENE

TEmr MISSION RIDGE PLUTON: hornblende-biotite-bearing granodiorite

SYMBOLS

Geological contact (defined, approximate, assumed) - - - - -

Thrust fault; teeth in direction of dip (defined, approximate, assumed) - - - - -

Normal fault (solid circle on down thrown side) - - - - -

Bedding - - - - -

Shear fracture - - - - -

Foliation - - - - -

Stretching lineation - - - - -

Crenulation lineation - - - - -

Arrow indicates direction of movement of upper member of shear couple - - - - -

Mesosopic fold axis, anticline, syncline - - - - -

Arrows indicate relative sense of strike-slip movement - - - - -

Sample location of U-Pb zircon age determination - - - - -

Contact of Mission Ridge pluton modified from Potter (1983)

END

1|5|0|4|9 1

FIN