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**Late Cretaceous - early Tertiary tectonic evolution of the
southern Omineca Belt, Canadian Cordillera**

by

SHARON D. CARR, M.Sc.

**A thesis submitted to the Faculty of
Graduate Studies and Research in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy, Department of Earth Sciences**

Carleton University

Ottawa, Ontario

October, 1990

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in partial fulfillment of the requirements for
the degree of Doctor of Philosophy.**

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October, 1990**

ABSTRACT

The present crustal architecture of the southern Omineca Belt in the Canadian Cordillera is a product of Eocene extension and crustal thinning superimposed on a crust that was thickened and deformed during Paleozoic and Jurassic to Late Paleocene compression. Amphibolite-facies rocks exposed as gneiss complexes within the Shuswap metamorphic complex, in the southern Omineca belt, were buried during compression and were exhumed in the lower plates of low- to moderate-angle plastic-brittle Eocene extensional faults.

Polydeformed gneisses of the Thor-Odin - Pinnacles area, within the Shuswap complex, are bounded at the base by the Monashee décollement, a deep-seated north-easterly directed Mesozoic-Paleocene thrust fault and are bounded at the top by crustal-scale Eocene normal faults: the Columbia River fault on the east and the Okanagan Valley - Eagle River fault system on the west. The metamorphic rocks host extensive plutons, stocks and sheets of the syn- and post-tectonic Late Paleocene - Early Eocene Ladybird granite suite. K-Ar hornblende and U-Pb zircon and titanite ages indicate that both metamorphic and igneous rocks were hot in the Paleocene and cooled rapidly in the early Tertiary; rapid cooling resulted from extensional denudation.

Field relationships of the Ladybird granite and U-Pb zircon and monazite geochronology place timing constraints on compressional and extensional shear zones. The timing of the onset of compressional deformation is uncertain; however, U-Pb ages of deformed granitic rocks indicate that thrusting on the Monashee décollement and F3 folding were ongoing in the Late Cretaceous-Paleocene. The last thrust motion on the Monashee décollement occurred in the latest Paleocene, and the shear zone had stopped by 58 Ma. Crustal scale normal faults were active in the Early Eocene indicating that crustal extension either overlapped or closely followed the compressional regime.

All geological and geochronological data are consistent with an anatectic crustal origin for the Ladybird granite; the suite was generated during the final stages of thrusting, perhaps due to decompression melting as the mid-crustal rocks were carried up a thrust ramp and unroofed and/or due to the introduction of hydrous fluids into the system. *In situ* magma and hot intrusions probably played an important role in the nucleation of extensional shear zones. The extensional regime then facilitated the intrusion of vast late-syn-kinematic to post-tectonic plutons.

The metamorphic rocks within the Thor-Odin - Pinnacles area are divided into two tectonostratigraphic packages: the Fawn Lake assemblage, which forms a 0-3 km wide belt in the immediate hanging wall of the Monashee décollement and the Gold Range assemblage, which extends over a >1200 km² area and tectonically overlies the Fawn Lake assemblage. The Fawn Lake assemblage is thought to be correlative with the semipelite-amphibolite division of the Horsethief Creek Group of the Upper Proterozoic Windermere Supergroup. It is bounded at the top by an unannealed Late Paleocene or Early Eocene shear zone, the Slate Mountain shear zone, which cuts down section in the Fawn Lake assemblage from west to east and may be an extensional transfer zone related to the Columbia River normal fault.

The Gold Range assemblage is correlated with Cambrian to Jurassic stratigraphy of the Hamill Group, Badshot Formation, Lardeau Group, Milford Group, Kaslo Group, Marten conglomerate and Slocan Group. The southern part of the Gold Range assemblage is intruded by the leucocratic potassium feldspar megacrystic hornblende bearing Whatshan batholith. It is 77 Ma based on U-Pb zircon geochronology and is variably deformed; a well developed foliation and superposed folds in exposures near Lower Arrow Lake indicate that amphibolite-facies metamorphism and at least two phases of deformation must be Late Cretaceous or younger.

The predominant foliation (S2), northerly verging tight to isoclinal F2 folds and the northeasterly directed Monashee décollement formed progressively during D2 and are generally synchronous with the peak of metamorphism. Open to tight, westerly plunging F3 folds formed as metamorphic conditions were waning. A vergence reversal in F3 folds, is coincident with the axis of a structural depression between Thor-Odin and Pinnacles culminations and is attributed to the wedge-like effect of underthrusting of blind thrust sheets imaged in LITHOPROBE seismic reflection data.

D2 and D3 structures are overprinted by a post-metamorphic D4 crenulation cleavage and by D5 broad open folds or warps. These structures may be coeval with crustal-scale plastic-brittle Eocene extensional faults. The Beaven fault, a normal fault on the west side of the Pinnacles culmination is a brittle and/or plastic structure that is interpreted to be the eastern continuation of the west-dipping and westerly directed Okanagan Valley - Eagle River fault system and has been down-dropped by younger steep normal faults such as the Cherryville fault.

The culmination of penetrative contractional deformation and the accompanying metamorphic peak attained within gneisses of the Shuswap metamorphic complex occurred during the Cretaceous-Paleocene. A substantial part of the motion on the Monashee décollement occurred at this time as part of a Cretaceous-Paleocene thrust system that transferred shortening eastward to the Foreland Belt. Rocks that were at higher structural levels show little evidence of Cretaceous-Paleocene deformation indicating that contractional strain was partitioned within the crust during the youngest part of the compressional history of the southern Omineca Belt. Rocks in the Thor-Odin - Pinnacles area and Valhalla complex cooled rapidly at rates of $\sim 25^{\circ}\text{C}/\text{Ma}$ during the early Tertiary, consistent with denudation on crustal-scale normal faults known to be active in the Eocene.

ACKNOWLEDGEMENTS

This contribution results from 7 months of field study integrated with U-Pb zircon and monazite geochronology carried out at the G.S.C. geochronology laboratory in Ottawa and comprises part of a Ph.D. research program carried out at Carleton University under the supervision of R. L. Brown. The project was funded by LITHOPROBE Supporting Geoscience Grant number 85, NSERC Operating Grant A2693 to R. L. Brown, the Geological Survey of Canada, EMR Research Agreement 227/04/88 and Carleton University. I would like to acknowledge NSERC and OGS scholarships, Geological Society of America research grants in 1987 and 1988 and travel funding from Carleton University and the Graduate Students Association. I am grateful to Dick Brown and Randy Parrish for advice and discussion and particularly to Randy for his patience in teaching U-Pb geochronology, for providing access to the G. S. C. geochronological facilities in Ottawa and for sharing unpublished geochronology and field data from southern British Columbia. I thank Peter Read for providing unpublished maps of the Columbia River fault and the Beaven fault and Vicki Coleman and Brad Johnson for field assistance. I would like to acknowledge Klaus Santowski and Dale Loveridge of the G. S. C. who provided mass spectrometry and data reduction, the G. S. C. K-Ar lab for K-Ar data and Dan Marshall for help with computers and recalcitrant machines. Thanks to Vicki Coleman, Brad Johnson, Lisel Currie, Dave Parkinson, Diane Carlson and Dave Klepacki, as well as many others, for sharing their observations and experience and for stimulating discussion.

ORIGINAL CONTRIBUTION

During seven months of field work from 1986-1989 I mapped the 1:50,000 Mount Fosthall sheet 82L/8 and adjoining margins of 82 L/1, 82 L/9, 82 K/4, 82 K/12 (Map 1). I also did reconnaissance mapping adjacent to the Monashee Highway between the Columbia River and Okanagan River valleys. Zircons, monazites and titanites from 15 samples were dated utilizing the U-Pb method. I performed all the stages of rock crushing and grinding, mineral separation and mineral selection for all samples; I performed chemistry on all zircon and monazite fractions except for titanite fractions from four rocks which were run by technicians at the G.S.C. laboratory. Mass spectrometry and K-Ar analyses were performed by technicians at the G.S.C.

I have benefitted from discussions with fellow students and colleagues but take full responsibility for the data and interpretations presented in this thesis.

METHOD OF PRESENTATION

This thesis is presented as a series of papers so as to facilitate their publication as journal articles. I apologize for any redundancy that arises from this paper format.

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CHAPTER 1

Tectonic setting and U-Pb geochronology of the early Tertiary Ladybird leucogranite suite, Thor-Odin - Pinnacles area, southern Omineca Belt, British Columbia

Abstract

The Thor-Odin - Pinnacles area is a structural culmination in the Shuswap complex of the southern Omineca Belt of the Canadian Cordillera. It comprises amphibolite-facies rocks that were deformed during Mesozoic-Paleocene compression and were exhumed in the footwalls of Eocene normal faults during crustal extension. The Ladybird leucogranite suite coincides with the extended terrane in the southern Omineca Belt. It is generally restricted to a mid-crustal level which lies in the hanging walls of deep-seated thrust faults and the footwalls of extensional faults.

Field relationships of the leucogranites and U-Pb geochronology place timing constraints on compressional and extensional shear zones. The last thrust motion on the Monashee décollement occurred in the latest Paleocene, and the shear zone had stopped by 58 Ma. Crustal-scale normal faults were active in the Early Eocene, indicating that crustal extension closely followed the compressional regime.

All geological and geochronological data are consistent with an anatectic crustal origin for the Ladybird granite. The granites apparently post-date the thermal peak of metamorphism (Carr, Chapter 3) and were generated during the final stages of thrusting, perhaps due to decompression melting as the mid-crustal rocks were carried up a thrust ramp and unroofed and/or due to the introduction of hydrous fluids into the system. *In*

situ magma and hot intrusions probably played an important role in the nucleation of extensional shear zones. The extensional regime then facilitated the intrusion of vast late-syn-kinematic to post-tectonic plutons.

U-Pb systematics reveal that zircons in high-temperature shear zones may have suffered high-temperature Pb loss, perhaps due to deformation- or fluid-enhanced diffusion, and that monazite systematics from samples from high-grade terranes are complex. Apparently magmatic monazite populations contain crystals of different ages that do not coincide with zircon ages and apparently do not represent either crystallization ages or a cooling ages.

Introduction

Intracontinental extensional tectonics plays an important role in orogenesis and uplift in collisional orogenic belts. Perhaps the best known of the extended terranes include the Cordilleran metamorphic core complexes of western North America (Crittendon et al. 1980; Coney 1980, 1987; Armstrong 1982; Wernicke et al. 1987) and the Himalayas (Burg et al. 1984; Burchfiel and Roydon 1985; Roydan and Burchfiel 1987; Sebrier et al. 1985; Herren 1987; Mercier et al. 1987); however, syn- or post-thrusting extensional shear zones have also been identified in the Andes (Dalmayrac and Molnar 1981; Mercier 1981; Dalziel and Brown 1989), the Alps (Behrmann 1987, 1988; Selverstone 1988; Ratschbacher et al. 1989) and in Precambrian belts such as the Grenville Province (Carlson et al. 1990; van der Pluijm et al. 1990). Extensional shear zones that were active during compression and/or shortly afterwards are recognized as an important mechanism for denudation and crustal uplift (England and Thompson 1984; Sandiford and Powell 1986; Ruppel et al. 1988). Extensional denudation has been invoked in deeply eroded orogenic belts, where the erosional level does not preserve direct evidence of extensional structures, in order to explain P-T-t paths preserved in metamorphic rocks (Sandiford and Powell 1986; Anovitz and Chase 1990).

An important element of extended terranes in collisional orogenic belts is the presence of syn-tectonic leucogranites such as those in some of the Cordilleran metamorphic core complexes in western North America (Anderson and Rowley 1981; Haxel et al. 1984; Carr et al. 1987; Parrish et al. 1988; Holder and McCarley Holder 1988; Miller and Barton 1989) and in the Higher Himalayas (Dietrich and Gansser 1981; Le Fort 1981; Searle and Fryer 1986; Stern et al. 1989). The Shuswap complex, in the southern Omineca Belt of the Canadian Cordillera, comprises rocks that were buried during Mesozoic to Paleocene compression and were exhumed during Eocene crustal extension on plastic-brittle low- to moderate-angle normal faults (Parrish et al. 1988, and references therein; Figure 1.1). Leucogranites of the Ladybird suite coincide with the extended terrane in the southern Omineca Belt. The emplacement of this diachronous Late Paleocene to Eocene igneous suite coincided with the end of thrusting and coincided with and outlasted crustal extension. Ladybird granite occurs as syn-kinematic sheets, in both compressional and extensional shear zones, and as late-kinematic to post-kinematic stocks, plutons and batholiths. U-Pb zircon dating of various phases constrains the timing of the tectonic transition from compression to extension in the southern Omineca Belt. Thrusting was ongoing in the latest Paleocene, was over by 58 Ma and was closely followed by the onset of extension in the Early Eocene. The purpose of this paper is to present geological relationships and U-Pb geochronology from the Thor-Odin - Pinnacles area (Figure 1.1), a structural culmination within the Shuswap complex, that constrain this early Tertiary tectonic transition. The implications of these data for the origin of leucogranites in collisional orogenies are also discussed.

Regional geology

The Mesozoic and Tertiary tectonic history of the southern Canadian Cordillera includes protracted compression and accretion of outboard terranes to the western margin of North America, crustal thickening, strike-slip faulting and crustal extension (Price and

Mountjoy 1979; Monger et al. 1982; Gabrielse 1985; Brown et al. 1986; Parrish et al. 1988). The Omineca Belt (inset Figure 1.1, see Okulitch 1984), the high-grade hinterland of the Rocky Mountain Foreland Belt, coincides with the overlap of the accreted terranes and the rocks of the North America paleo-margin.

In the southern Omineca Belt, early Tertiary crustal-scale extension was important resulting in ~30% extension across the 300 km wide belt (Parrish et al. 1988).

Amphibolite-facies rocks, exposed as culminations within the Shuswap complex (Kettle - Grand Forks, Monashee, Okanagan, Priest River, Valhalla; Figure 1.1), were exhumed by generally north-trending outward-dipping normal fault systems (Columbia River, Granby, Greenwood, Kettle, Newport, Okanagan Valley - Eagle River, Purcell Trench, Valkyr - Slocan Lake). The east-dipping Valkyr - Slocan Lake, Kettle, and Columbia River fault systems were active in the Early Eocene and are older than the west-dipping Okanagan, Greenwood and Granby fault systems, which are Middle Eocene (Parrish et al. 1988, and references therein; Carr and Parkinson 1989).

The present configuration of the southern Omineca Belt can be described in terms of three crustal zones that experienced different deformation and thermal histories and were juxtaposed by regionally extensive shear zones (Carr 1989; Figure 1.1). During the Jurassic to Paleocene compressional phase, a thick composite sheet of internally deforming rocks was transported eastward over basement on the Monashee décollement (Journey 1986; Journey and Brown 1986, and references therein; Brown and Journey 1987). In the Eocene extensional phase this allochthon was dissected by low- to moderate-angle normal faults (Figure 1.1; Parrish et al. 1988). Amphibolite-facies rocks of the lower part of the allochthon (Middle Crustal Zone) in the footwall of these normal faults were uplifted and juxtaposed against higher crustal level, cooler rocks (Upper Crustal Zone) of the allochthon. Three crustal zones are exposed at the surface (Figure 1.1): the Upper Crustal Zone generally lies in the upper plate of north-trending normal faults, the Middle Crustal Zone occurs in the footwall of the normal faults, and the

deepest crustal level, the Basement Zone, is exposed in Frenchman Cap and Thor-Odin culminations and the Malton complex as tectonic windows beneath the Middle Crustal Zone.

The Thor-Odin - Pinnacles area consists of amphibolite-facies polydeformed rocks bounded by the Columbia River fault in the east and the Okanagan Valley - Eagle River fault system in the west (Figures 1.1, 1.2 and 1.3). The area straddles the southern exposures of basement rocks, in the footwall of the Monashee décollement in Thor-Odin culmination, and extends southward into the Late Cretaceous Whatshan batholith. Basement rocks consist of Precambrian migmatitic paragneisses and granitoid gneisses (Reesor and Moore 1971; Wanless and Reesor 1975; Read 1979a, 1980; Parrish and Armstrong 1983; Duncan 1982, 1984; Evenchick et al. 1984; Parrish and Ross 1989, 1990; Parkinson 1990). The term basement is used loosely as crystalline basement rocks are unconformably overlain by Proterozoic to Cambrian cover gneisses; the cover rocks are infolded and imbricated within the crystalline basement (Höy and Goodwin 1988; Parrish and Scammell 1988; Scammell and Brown 1990, and references therein). Polydeformed Proterozoic to Mesozoic sillimanite +/- muscovite bearing gneisses and schists of the Middle Crustal Zone, that lie between the Monashee décollement and overlying normal faults, are intruded by the Ladybird granite. Analogous Middle Crustal Zone high-grade rocks and Ladybird leucogranite in Valhalla complex lie in the hanging wall of the Gwillim Creek shear zones, which are part of a Late Cretaceous to Paleocene thrust system, and in the footwall of the Valkyr - Slocan Lake normal fault system (Carr et al. 1987; Parrish et al. 1987a; Parrish et al. 1988).

Previous work in the region includes the following (Figure 1.2). Jones (1959) identified the high-grade Shuswap complex, major boundaries, metamorphic breaks and low-grade stratigraphy during regional mapping. Mapping of units and the interpretation of Thor-Odin culmination as a mantled gneiss dome was published by Reesor and Moore (1971); metamorphism and the large fold in Pinnacles were described by Reesor and

Froese (1968; 1969). The Columbia River fault, klippen of low-grade rocks and the southern part of the Beaven fault were mapped by Read (1979a, 1979b). Duncan (1984) dated basement rocks and interpreted the evolution of Thor-Odin culmination in terms of fold interference. Parrish et al. (1988) presented geochronological and structural arguments that are consistent with exhumation of the Thor-Odin - Pinnacles area in the Paleogene due to crustal extension.

Results of this study include the following. Two tectonostratigraphic assemblages and their internal structural and metamorphic history were identified in the hanging wall of the Monashee décollement in the Thor-Odin - Pinnacles area. The Fawn Lake and Gold Range assemblages are correlated, respectively, with part of the Late Proterozoic Windermere Supergroup exposed north of the Monashee complex and Cambrian-Mesozoic stratigraphy similar to that of the Kootenay Arc (Carr, Chapter 2). The assemblages are separated by a Paleocene or Eocene shear zone, the Slate Mountain shear zone, interpreted as an extensional transfer zone that is kinematically linked with the Columbia River fault. U-Pb dating of deformed and folded (F3) granitoids of the Late Cretaceous Whatshan batholith and the Late Paleocene - Early Eocene Ladybird granite suite indicates that a substantial amount of compressional deformation at thermal-peak conditions within the high grade gneisses of the Shuswap metamorphic complex occurred during the latest Cretaceous and Paleocene (Carr, Chapter 3). Faults between Pinnacles and Vernon were elucidated and are interpreted as part of the westerly-directed Okanagan Valley normal fault system.

The Monashee décollement

The Monashee décollement (Figures 1.1 and 1.2) is a westerly rooted, northeast-directed ductile thrust fault with a displacement on the order of 80-100 km which is arched over the Thor-Odin culmination (Read and Brown 1981; Journeay 1986; Scammell 1986; Journeay and Brown 1986; Bosdachin 1988; Harrap 1990; Coleman

1990; Parrish et al. 1988 [for a review]; Brown et al. 1990, and references therein). In the Thor-Odin culmination, the Monashee décollement is annealed, is up to 2 km thick and is characterized by strong mylonitic fabrics, sheath folds and transposed layering (Coleman 1989). On the southwest flank of Thor-Odin, the shear zone is a duplex with imbricated slices of basement and supracrustal gneisses (Coleman 1989; see Figure 1.2). In Frenchman Cap culmination, the shear zone has had a protracted two-stage history (Journey 1986; Journey and Brown 1986). U-Pb dating of late- and post-kinematic pegmatites (Journey and Parrish 1989) indicate that the youngest motion on the shear zone occurred in the Paleocene. The décollement is part of a Mesozoic to Paleocene thrust system which feeds into the sole thrust of the Rocky Mountain Foreland Belt to the east (inset, Figure 1.1; Parrish et al. 1987a; Journey and Parrish 1989; Brown et al. 1990).

The Monashee décollement is recognized in seismic reflection data from the southern Canadian Cordilleran LITHOPROBE transect and corresponds to a zone of strong seismic reflections (Carr and Brown 1990; Cook et al. 1990). On the southwest side of Thor-Odin culmination it dips southwesterly for 40 km and flattens into the lower crust under the Okanagan Valley. Structural mapping and U-Pb geochronology on the southern flank of the Thor-Odin culmination (discussed on page 19) indicates that the Monashee décollement was still in motion at 62 Ma (SC1028, Tables 1.1 and 1.2) and 59 Ma (SC951, Tables 1.1 and 1.2). Movement on the shear zone had terminated by 58 +/- 0.3 Ma, based on the U-Pb zircon age of a pegmatite that crosscuts the Monashee décollement (SC570, Tables 1.1 and 1.2).

Normal fault systems

The Columbia River and Okanagan Valley - Eagle River fault systems are plastic-brittle low- to moderate-angle Eocene normal faults (Figure 1.1). There is a significant metamorphic contrast between the hanging wall (Upper Crustal Zone) and footwall

(Middle Crustal and Basement Zones) of these fault systems. The upper plate is generally at lower grade (chlorite +/- biotite +/- staurolite) than the predominantly high-grade (sillimanite - potassium feldspar - melt or sillimanite-muscovite) lower plate, although there are some local exceptions to this (Figure 1.3). More importantly, metamorphism in the upper plate is Mesozoic and, in general, cooling of pre-Eocene rocks below the K-Ar closure temperature of micas and hornblende occurred in the Mesozoic, whereas rocks in the Middle Crustal Zone were at high grade in the Late Cretaceous and Paleocene and cooled in the early Tertiary (Fox et al. 1977; Mathews 1981; R. L. Armstrong unpublished data file, 1984; Archibald et al. 1983; Schiarizza and Preto 1987; Parrish et al. 1988, and references therein; Hunt and Roddick 1988; Carr, Chapter 2; Sweetkind and Duncan 1989). The 161.6 +/- 0.5 Ma Galena Bay stock (Parrish and Armstrong 1987) and the 173 +/- 5 Ma Kuskanax batholith crosscut isograds in the hanging wall of the Columbia River fault (Read and Wheeler 1976; Parrish and Wheeler 1983), placing a minimum age of Middle Jurassic on the metamorphism. In contrast, rocks in the Thor-Odin - Pinnacles area were hot until the early Tertiary as 62-55 Ma Ladybird intrusions apparently do not impose contact metamorphism on country rocks, and in some areas both Ladybird granite and country rock were deformed together under amphibolite-facies conditions. The early Tertiary thermal history is documented through mineral dating of micas and feldspar from the South Fosthall pluton (Parrish et al. 1988), Late Cretaceous and Paleocene U-Pb metamorphic zircon and titanite dates (Carr, Chapter 2) and early Tertiary K-Ar biotite dates from the region (Baadsgaard et al. 1961; Mathews 1983; R. L. Armstrong unpublished data file; 1984; Parrish et al. 1988; Hunt and Roddick 1988; Carr, Chapter 2).

Columbia River fault

The trace of the east-dipping Columbia River fault extends for 200 km and displacement decreases towards the north and south ends where the fault dies out (Figure

1.1). North of Revelstoke on the eastern margin of Frenchman Cap, the Columbia River fault is interpreted as a predominantly brittle structure (Campbell 1971; Lane 1984; Lane et al. 1989), and early plastic motion may have been transferred eastward to the Standfast Creek fault (Parrish et al. 1988). In the Thor-Odin - Pinnacles area the footwall of the fault is a plastic mylonite zone with a brittle overprint. Deformation in the hanging wall is predominantly brittle. Locally the fault is an irregular corrugated surface with grooves and scoop-shaped ramps and flats; however, regionally the fault zone dips 30° to the east based on three-point solutions of the fault trace.

The Early Eocene age of the fault is well constrained by a 55.1 ± 1.5 Ma U-Pb date on the deformed South Fosthall pluton and by 53.9 ± 0.8 Ma, 56.0 ± 0.9 Ma and 59.7 ± 1.2 Ma Rb-Sr dates of syn-kinematic minerals (Parrish et al. 1988). The displacement, in the Thor-Odin area, based on metamorphic offset, is estimated at 20-30 km (Read 1979b; Parrish et al. 1988).

Okanagan Valley - Eagle River fault system

The Okanagan Valley fault (Parkinson 1985; Bardoux 1985; Parrish et al. 1985) and its northward continuation, the Eagle River detachment (Journey and Brown 1986; Johnson 1989) is a low-angle, west-dipping plastic-brittle shear zone with a strike length of over 250 km. Between the Okanagan Valley and Pinnacles (Figure 1.2), the detachment has been down-dropped and dissected by younger steep (?) normal faults (Carr and Brown 1989; Figure 1.2).

Amphibolite facies mylonites in the footwall of the Okanagan Valley - Eagle River fault system are progressively overprinted by greenschist-facies mylonites and brittle fabrics, whereas predominantly brittle structures occur in the hanging wall (Parkinson 1985; Bardoux 1985; Parrish et al. 1988; Johnson 1989). In the Vernon area (Figure 1.1), the fault zone dips 8° - 25° to the west (Carr and Brown 1989). It has been seismically imaged on Line 11 of the LITHOPROBE reflection survey and appears to be listric and

flattens into the middle crust (Carr and Brown 1990). Mylonitic fabrics in a 52 Ma rhomb feldspar porphyry dyke and a 47 Ma leucocratic granitic dyke in the sheared footwall of the fault in the southern Okanagan Valley indicate that at least some of the plastic motion on the fault is Middle Eocene (Parkinson 1985; Parrish et al. 1985).

Stratigraphy and structure of the Middle Crustal Zone in the Thor-Odin - Pinnacles area

The Middle Crustal Zone in the Thor-Odin area consists of predominantly sillimanite - potassium feldspar - melt and sillimanite-muscovite bearing gneisses and schists that were intruded by a vast amount of Late Paleocene - Eocene Ladybird granite plutons, stocks and pegmatite (Figures 1.2, 1.3 and 1.4). The stratigraphy of the Middle Crustal Zone can be broadly divided into the Fawn Lake and Gold Range assemblages, which are separated by the Paleocene or Eocene Slate Mountain shear zone which may be an extensional transfer zone (Carr, Chapter 2). The ~3 km thick Fawn Lake assemblage, in the immediate hanging wall of the Monashee décollement, consists of semi-pelitic and psammitic gneisses with up to 30% amphibolite and up to 30% pegmatite. These rocks are probably correlative with part of the late Precambrian Windermere Supergroup (Brown et al. 1978; Raeside and Simony 1983; Pell and Simony 1984; Johnson 1989; Scammell 1990) based on lithologic similarity (Carr, Chapter 2). The Gold Range assemblage extends from the southern flank of Thor-Odin culmination in the north (Plate 1.1a) to the Whatshan batholith in the south (Figure 1.2). These rocks are probably metamorphic equivalents of Cambrian to Triassic stratigraphy (Carr 1989, Chapter 2) exposed in the Kootenay Arc to the east (Little 1960; Fyles 1967; Read 1973; Read and Wheeler 1976; Höy 1977a, 1977b; Reesor 1973; Klepacki 1983, 1985; Klepacki and Wheeler 1985).

The Middle Crustal Zone underwent polyphase deformation under amphibolite-facies conditions. There is also evidence of a protracted deformation history which

predated the metamorphic peak and the formation of the predominant foliation; however, primary layering and pre-metamorphic structures have been transposed obscuring the details. There are ultramafic boudins at three different stratigraphic and structural levels which may represent parts of ophiolite sequences, but no contact relationships are preserved. Although few outcrop-scale isoclinal folds (F1?), of uncertain age, were observed throughout the area and none were observed in pelitic schists, it appears that at least one phase of deformation occurred at lower amphibolite facies, prior to the peak of metamorphism.

The main metamorphic foliation contains thermal-peak sillimanite - potassium feldspar - melt or sillimanite-muscovite mineral assemblages throughout most of the area and has been designated S2 (Plate 1.1b). S2 is synchronous with high-grade D2 shearing on the Monashee décollement (Coleman 1989; this study). S2 is generally subparallel to parallel with axial planes of tight north-verging folds (F2) and fold hinges are subparallel to the sillimanite stretching lineation (L2). S2 is refolded by more upright F3 folds which are also syn-metamorphic but generally postdate the metamorphic peak (Plate 1.1c and 1.1d). Second order parasitic F3 folds have an amplitude of ~5 km and generally control the map pattern and distribution of rocks exposed at the surface south of the Monashee décollement. There is a structural depression between Thor-Odin and Pinnacles culminations and the F3 form surface dips gently to the southwest on the southern flank of the Thor-Odin culmination and dips northeast in the Pinnacles area, thus the stratigraphic level of exposure does not vary much across the area. A crenulation cleavage (F4), penetrative in pelitic rocks, is biotite bearing and postdated the metamorphic peak as did broad warps (F5). F4 and F5 minor folds are best developed in the Pinnacles area. The Columbia River and Okanagan Valley fault systems (D6) apparently post-date regional folding and are themselves dissected by steep, north-trending brittle faults (D7) with displacements on the order of tens of metres to 1-2 km (Figure 1.2). The Columbia River and Okanagan Valley fault surfaces undulate; this may

be primary or it may be a result of displacement by the younger generation of steep faults.

The Ladybird granite

The Ladybird granite suite comprises biotite +/- muscovite +/- garnet +/- sillimanite bearing leucocratic quartz monzonite to granite batholiths, stocks, sheets and pegmatites. The total areal extent of the Ladybird suite is in the order of 1000 km² and is generally confined to the Middle Crustal Zone above deep-seated thrust faults and in the footwall of normal faults (Figure 1.1). There is no known extrusive equivalent to the Ladybird suite. Field relationships, its composition and the presence of inherited Precambrian Pb in zircons are consistent with an anatectic crustal source for the Ladybird suite. Most of the larger plutons and sheets of leucogranite in the hanging wall of the Monashee décollement are younger than motion on the shear zone, but are not present in underlying basement that is exposed in the Monashee complex; this paradoxical relationship implies that they did not intrude from immediately below and granite must have been emplaced laterally or developed *in situ*.

The Ladybird suite was originally mapped as the "Valhalla series" by Little (1957, 1960, 1961) and the "Silver Star intrusions" by Jones (1959). The first U-Pb zircon dates were obtained from intrusions in Valhalla complex where syn- to post-kinematic granites in the Valkyr shear zone range from 59 +/- 1 to 56 +/- 1.5 Ma (Carr et al. 1987; Parrish et al. 1988). The results of subsequent mapping and geochronology in the southern Omineca Belt (this study; Parrish, unpublished data 1988, 1989) indicate that the Ladybird granite ranges in age from Late Paleocene to Middle Eocene (Table 1.1; Parrish et al. 1988), is extensive throughout the Middle Crustal Zone of the Shuswap complex and probably extends as far north as the Adams River area (Sevigny et al. 1989). The Ladybird granite has the same composition and tectonic setting as the early Tertiary Keller Butte suite of the Colville batholith in the Okanogan dome, northeast Washington

(Carlson 1984; Carlson and Moye 1987; Holder and McCarley Holder 1988).

Geochemistry from Adams River granites and the Keller Butte suite indicate that they were derived from partial fusion of continental crust (Sevigny et al. 1989; Holder and McCarley Holder 1988).

In the Thor-Odin - Pinnacles area, Ladybird intrusions and pegmatite are ubiquitous; they intruded over a ~10 Ma period in the Late Paleocene to Early Eocene (Table 1.1) and were diachronous with respect to deformation (Plate 1.2a). Some dykes occur at deeper levels in basement rocks, but the Ladybird suite is predominantly confined to the Middle Crustal Zone; no Ladybird intrusions have been found in the Upper Crustal Zone. The only named intrusive body, the South Fosthall pluton, previously thought to be Paleozoic (Okulitch 1985), has been dated at two locales yielding 55 +/- 1.5 Ma and 55 +/- 0.1 Ma ages (U-Pb zircon and monazite; Parrish et al. 1988). The largest volume of Ladybird includes the South Fosthall pluton and occurs on the south flank of the Thor-Odin culmination in the hanging wall of the Monashee décollement (Figure 1.4). Part of this zone was mapped by Reesor and Moore (1971) in terms of < 50% or > 50% pegmatite. Stratigraphy is more or less intact between granitoid bodies and as sheets within the granitic rocks; marker units and stratigraphic packages can be mapped between the pegmatite and granite sheets. Stockwork and thick pegmatite sheets are predominant in the central and eastern part of Pinnacles culmination. The lowest volume of Ladybird occurs in rocks that coincide with staurolite bearing rocks in the Middle Crustal Zone (Figures 1.3 and 1.4). In these areas, Ladybird rocks occur as isolated stocks and dykes rather than as sheets or plutons.

Strain variation

The Ladybird intrusions postdate much of the regional deformation in the Middle Crustal Zone and therefore have a different finite strain than the country rock. They are variably strained depending on their spatial and temporal relationship to the Monashee

décollement and the Columbia River and Okanagan Valley normal fault systems and can be used as a qualitative gauge of Paleocene and Early Eocene strain. For example, Parrish et al. (1988) acquired 55 Ma U-Pb dates for the South Fosthall pluton from the east side of the area, in the footwall of the Columbia River fault, and from the west side on Sugar Mountain (Figure 1.4). The granite on the east side is a strongly deformed mylonite, whereas the granite of the same age on the west side is undeformed. The limit of the Early Eocene ductile strain can be mapped out within the pluton (Figure 1.4) and indicates that extensional faulting at ~55 Ma was limited to the eastern flank of the Thor-Odin and Pinnacles culminations and was associated with the Columbia River fault.

The variation in strain throughout the Ladybird suite can be grouped into four categories shown as Zones A, B, C and D on Figures 1.4 and 1.5. Zone A fabrics are annealed sillimanite bearing mylonites that occur in a ~5 km thick zone in and above the Monashee décollement and were deformed during thrusting. Zone B fabrics are unannealed lower amphibolite to greenschist-facies mylonites or protomylonites that occur in the footwall of the Columbia River fault on the eastern side of the area and were deformed during extension. Unannealed Zone C leucogranites have weakly to moderately developed amphibolite-facies protomylonitic fabrics and occur predominantly on the eastern side of the Thor-Odin - Pinnacles area. These fabrics probably formed while the Columbia River fault was active and represent distributed strain in the footwall. Igneous Zone D fabrics occur in post-tectonic pegmatites, which occur at all structural levels, and in post-tectonic stocks, which occur at the highest structural levels, particularly on the western side of the Thor-Odin - Pinnacles area. U-Pb geochronology samples are described in the context of the regional strain variation (see Figure 1.6 and Appendix I for sample locations). Detailed U-Pb interpretations are discussed in a subsequent section (see Table 1.1 for a summary of age interpretations and Table 1.2 for analytical data).

Zone A

Highly sheared rocks in the Monashee décollement range in thickness from approximately 0.5-5 km and have a northeasterly directed shear sense on the southwest flank of Thor-Odin and an easterly directed shear sense on the southern flank. The northeasterly directed shear sense is the regional orientation; the easterly directed fabrics were transposed by the Columbia River fault. In the hanging wall of the Monashee décollement, there is a regional strain gradient associated with the shear zone where a ~5 km wide zone of highly strained gneiss and schist is transposed into parallelism with the décollement (Figure 1.4). F2 folds and sillimanite - potassium feldspar bearing mylonitic fabrics in this zone are syn-kinematic with the Monashee décollement. Kinematic indicators such as C- and S-fabrics (Berthé et al. 1979) and rotated porphyroclasts yield a shear sense consistent with that of the Monashee décollement (Figure 1.4). In thin section, subgrains and grain boundaries are annealed indicating that metamorphism outlasted strain. Zone A Ladybird intrusions in this hanging-wall strain zone occur as concordant or folded sheets, discontinuous lenses, boudins and crosscutting dykes (Plates 1.2b, 1.2c, 1.2d, 1.3a and 1.3b).

Three syn-kinematic samples from the strained zone were dated. Sample SC1020 is a 10-50 cm thick mylonitized and boudinaged granite sheet from the north flank of Mount Fosthall shown in Plate 1.2c. Sillimanite is present in the mylonitic stretching lineation, and an easterly directed sense of shear is interpreted from the rotation of the S-surface with respect to the C-surface (Berthé et al. 1979). The U-Pb age is 62.1 +/- 0.3 Ma; therefore, the strain is the same age or younger. Sample SC951 is a coarse leucosome from a mylonitized migmatite (Plate 1.2d) from north of Margie Lake about 1 km structurally above the Monashee décollement. This sample yields an age of 59.0 +/- 0.3 Ma; therefore, shearing was ongoing at 59 Ma or younger. Sample SC1122 (>58 Ma), from the shear zone itself, is a coarse-grained sillimanite bearing pegmatite that is folded by a tight F2 fold (Plate 1.3a). Sillimanite occurs in the axial planar cleavage.

Zone B

Mylonitic fabrics are observed in the South Fosthall pluton, and in stocks and pegmatite bodies along the eastern side of the area in a 5 km thick zone in the footwall of the Columbia River fault (Figure 1.4). Granitic rocks are mylonitic with a well developed east-plunging stretching lineation (Plates 1.3c and 1.3d). The interpretation of C- and S-foliations, rotated porphyroclasts, shear bands, and vergence of syn-mylonite folds throughout the zone yield an easterly directed sense of shear (Berthé et al. 1979; Simpson and Schmidt 1983; Platt and Vissers 1980; Lister and Snoke 1980; Platt 1984; Passchier and Simpson 1986). Lower amphibolite-facies mineral assemblages in this zone consist of quartz, plagioclase, potassium feldspar, < 15% biotite +/- muscovite and +/- garnet. No sillimanite is present in the Ladybird suite in Zone B although it is present in the country rock. In contrast to fabrics in the Monashee décollement, mylonitic fabrics in the footwall of Columbia River fault are unannealed (Plate 1.3d). Within 1 km of the fault trace, the lower amphibolite-facies protolith assemblage is overprinted by syn-kinematic chlorite-muscovite-sericite bearing greenschist-facies mylonitic and cataclastic fabrics. Fabric relationships and Rb-Sr dates of greenschist-facies muscovite fish (which grew below their ~500^o C closure temperature) in the mylonitic South Fosthall pluton are 53.9 +/- 0.8, 56.0 +/- 0.8 and 59.7 +/- 1.2 Ma (Parrish et al. 1988) indicating that the fault was active in early Eocene time.

Zone C

Weakly deformed granitoid rocks are generally confined to the central part of the area, particularly on the eastern flank of the Thor-Odin - Pinnacles area and in most cases represent distributed strain in the footwall of the Columbia River fault (Figure 1.4). Zone C rocks exhibit a mesoscopic foliation and stretching lineation and unannealed protomylonitic fabrics in thin section. The mineral assemblage is quartz, plagioclase, potassium feldspar, < 10% biotite, +/- muscovite and +/- garnet; there is no sillimanite or

chlorite in this zone. The east-west oriented stretching lineation is more strongly developed than the foliation (Plates 1.4a and 1.4b).

SC570 is a weakly foliated 55.5 $\pm$ 0.5 Ma pegmatite from north of Whatshan Lake typical of Zone C. Sample SC855, from Pinnacles Peaks, is weakly deformed 54 $\pm$ 0.3 Ma hornblende bearing granite sill (Tables 1 and 2) which crosscuts three phases of folding in Pinnacles (Plate 1.4d). Since this 54 Ma rock is deformed, plastic strain at the Pinnacles Peaks locality was ongoing at this time or younger.

Sample SC534 from a sheet of weakly deformed pegmatite yielded a 60.5 $\pm$ 0.5 Ma age (Tables 1.1 and 1.2). Since 55 Ma rocks which intrude the same region were not deformed during extension, the fabric in SC534 probably formed during compressional deformation related to thrusting on the Monashee décollement.

Zone D

Predominantly igneous fabrics are common on the west side of the area, particularly on the west side of the South Fosthall pluton near Sugar Lake, and in sheeted pegmatite cliffs in Pinnacles peaks (Figure 1.4). Mineral assemblages are the same as for Zone C. In the Sugar Lake area, the granite is locally deformed by discrete 0.2-3 m wide westerly directed shear zones which are thought to be associated with the Okanagan fault. In general, Zone D granitoids are not penetratively deformed (Plate 1.4c). They post-date the thrusting and folding and are in an unstrained zone structurally below regional extensional structures.

At Cariboo Alp, a set of undeformed Zone D pegmatite dykes crosscut all fabrics in the Monashee décollement (Plate 1.3b). U-Pb zircon results from sample SC570 yield a 58 $\pm$ 0.5 Ma age, therefore movement on the Monashee décollement had ceased by 58 Ma.

Geochronology

Analytical techniques

Mineral separates were obtained from rock samples weighing about 20-25 kg. Standard crushing, grinding, Rogers Gold™ table, heavy liquid and Frantz™ magnetic separation techniques were utilized. Zircons were sieved in alcohol, and small populations of 1-30 clear crack-free grains were selected for analysis; some fractions were abraded (Krogh 1982; see Table 1.2). Clear euhedral pale monazite fractions of 1-8 crystals were selected. Zircon and monazite samples were spiked with a mixed ^{205}Pb - ^{233}U - ^{235}U tracer (Parrish and Krogh 1987) and dissolved in teflon micro-capsules (Parrish 1987). Mineral dissolution, ion exchange column chemistry, mass spectrometry, error propagation and data reduction were done following procedures described by Krogh (1973), Parrish et al. (1987b) and Roddick (1987). Isotopic compositions of Pb and U were measured on a Finnigan-MAT 261 variable multicollector mass spectrometer as described by Roddick et al. (1987). Procedural U blanks were less than 2 pg for zircon and monazite analyses. Pb blanks generally ranged from 7 to 20 pg for zircon, although some are higher due to accidental contamination during the chemistry procedure (Table 1.2). The total analyzed common Pb in monazites (Table 1.2) is attributed to initial Pb in the crystals and inclusions contained within the crystals. Common Pb corrections were done assuming model Pb compositions derived from the growth curve of Stacey and Kramers (1975) using ca. 60 Ma model Pb. Decay constants are those recommended by Steiger and Jäger (1977).

Errors in U/Pb ratios reflect one standard error (Table 1.2), and error ellipses on concordia plots are 2 standard errors. An analysis is considered to be concordant if the error ellipse overlaps concordia; the mean intersection of the error ellipse with concordia is interpreted as the age of the rock unless mentioned otherwise. Zircon discordance in the Ladybird suite generally reflects multiple ages of inheritance (this study; Parrish et al.

1988): consequently analyses, especially for small numbers of crystals, do not fall on a discordia line. Therefore, the statistical methods used to calculate fit of data on discordia chords are not necessarily valid and are not used to estimate errors in this study. Errors attached to the interpreted age correspond to the deviation of the ellipse from the mean (Parrish et al. 1987b).

Young monazites commonly show "reverse discordance" and plot above the concordia curve (Schärer 1984; Schärer et al. 1985; Parrish 1990). This is attributed to the effect of U and Th chemical fractionation during accessory crystal growth (Schärer 1984), stemming from the fact that monazite, unlike zircon, strongly partitions Th relative to U. ^{230}Th is an intermediate daughter in the ^{238}U - ^{206}Pb decay chain. The ^{230}Th enrichment of monazite during crystal growth results in the production of ^{206}Pb in excess of what would be present if the ratios of ^{230}Th and ^{238}U in monazite and the parent magma were the same. The presence of this "unsupported ^{206}Pb " contributes to the total amount of radiogenic ^{206}Pb in the crystal. This results in radiogenic $^{207}\text{Pb}/^{206}\text{Pb}$ ratios today which are too low, $^{207}\text{Pb}/^{206}\text{Pb}$ ages which are too low and can be negative and monazites which plot above the concordia curve. Conversely, fractionation of U over Th occurs during zircon growth, leaving zircon with a deficiency of Th relative to the magma. This results in a deficit of daughter ^{206}Pb ; the $^{207}\text{Pb}/^{206}\text{Pb}$ ratios are too high and the zircons plot below concordia, although the effect for zircon is slight. The effects of Th-U fractionation in zircon and monazite are important in young rocks as the percent of radiogenic ^{206}Pb contribution from ^{230}Th forms a significant proportion of the total radiogenic ^{206}Pb (Parrish 1990); this effect decreases with increasing age and becomes inconsequential in rocks older than ~150 Ma (Parrish 1990).

In this study, the $^{206}\text{Pb}/^{238}\text{U}$ ratios, and subsequent age calculations of zircon and monazite fractions, were corrected for Th fractionation using the procedures outlined in Schärer (1984) and Parrish (1990). It is assumed that the Th/U ratio measured from the

whole rock (Table 1.3) represents the Th/U ratio of the magma, although this assumption may not necessarily be valid (see discussion in U-Pb systematics section).

Age interpretations

Zircons and monazites from six samples of the biotite bearing Ladybird leucogranite suite and one hornblende bearing granite were analysed (Figure 1.6, Tables 1.1, 1.2 and 1.4). On all tables and concordia plots zircons are designated by letters and monazites by numbers, and the single quote symbol on concordia diagrams (Figures 1.7-1.15) and Table 1.2 indicates the thorium corrected $^{206}\text{Pb}/^{238}\text{U}$ analyses.

Zircons from Ladybird samples are generally similar in morphology and are generally of very high clarity and quality. They predominantly occur as colourless faceted euhedral crystals with sharp terminations. The crystals are usually tetragonal prisms modified by pyramids and have length to width ratios of 2:1 to 4:1. This morphology is generally regarded as being indicative of a magmatic origin. Cores are visible in the centre of many crystals as small cloudy inclusion ridden zones. The clearest most crack-free crystals with small or no apparent cores were chosen for analysis. The presence of an inherited Pb component clearly shows up in samples SC855, SC570 and SC951; other samples, such as SC530, SC1028 and SC1122 do not have an inherited Pb component, and many of these were strained at high grade.

Monazites range in colour from clear pale green or yellow to dark cloudy brownish yellow. They occur in fragments or as euhedral crystals, interpreted to represent an igneous morphology, and generally contain numerous inclusions. The palest, most inclusion free euhedral crystals were chosen for analysis. The monazite analyses all plot above concordia (Schärer 1984; Barth et al. 1989; Parrish 1990); therefore, $^{207}\text{Pb}/^{235}\text{U}$ ages are generally used to represent the age of the monazite, since they are not affected by excess ^{206}Pb . Monazite systematics are not straightforward, particularly in samples from shear zones. Monazite ages are generally younger than zircon ages, many samples

have more than one age of monazite, and the monazite ages may not necessarily represent the age of the rock (Table 1.5). In some cases, monazite ages coincide with each other but not with the zircon age, and in other cases different monazite fractions yield different ages. These patterns are discussed in the following section on U-Pb systematics. Age interpretations are discussed for each sample in order from the least complex U-Pb zircon systematics to most complex.

Sample SC1028 is a sillimanite bearing mylonitic granite strained in the hanging wall of the Monashee décollement (Plate 1.2c, Zone A of Figure 1.4). The three zircon fractions analysed are concordant and overlap each other and concordia at 62.1 ± 0.3 Ma (Figure 1.7). These zircons do not have an inherited Pb component and of all the samples analysed, have the lowest concentrations of uranium (average 700 ppm Pb). The error on fraction A' is large because of common Pb contamination during the spiking procedure. Both the uncorrected and Th corrected monazite analyses plot above concordia and the 55.1 ± 0.3 and 57 ± 0.3 Ma $^{207}\text{Pb}/^{235}\text{U}$ ages are younger than the zircon age (Table 1.5).

Sample SC855 is a Zone C weakly deformed hornblende bearing crosscutting granitic sill (Plate 1.4d). The 54.3 ± 0.5 Ma age is based on concordant fraction B' (Figure 1.8). Discordant fractions A' and C' indicate the presence of inherited Pb. The fractions with inheritance do not lie on a discordia chord perhaps because they have different ages of inheritance or have suffered different amounts of Pb loss.

Sample SC534 is a weakly strained pegmatite (Zone C, Figure 1.4). Zircon fractions D' and E' indicate an inherited Pb component (Figures 1.9 and 1.10). The 55.5 ± 0.3 Ma age interpretation is based on the near concordance of fraction C' (Figure 1.10). The $^{207}\text{Pb}/^{235}\text{U}$ ages of monazite fractions 1' and 3' are 55.4 ± 1.8 Ma and 55.4 ± 0.6 Ma and within error coincide with the interpreted zircon age of 55.5 Ma; however, the 56.6 ± 0.7 Ma $^{207}\text{Pb}/^{235}\text{U}$ age of monazite fraction 2' is 1 Ma older (Table 1.5).

Sample SC570 is a post-tectonic Zone D pegmatite dyke that crosscuts all fabric in the Monashee décollement (Plate 1.3b). Fractions A', F' and C' exhibit inheritance and/or Pb loss and the 58.0 +/- 0.3 Ma age interpretation is based on concordant fraction B' (Figure 1.11). There is a 5.9 Ma range in $^{207}\text{Pb}/^{235}\text{U}$ monazite ages; three are older and one is younger than the interpreted age of the rock. Fractions 3', 4' and 6' are 61.1 +/- 0.2, 62.0 +/- 0.4 and 61.2 +/- 0.9 Ma respectively, whereas, fraction 1' is 56.1 +/- 0.9 Ma (Table 1.5).

Sample SC951 is a sillimanite bearing migmatite in the hanging wall of the Monashee décollement (Plate 1.2d, Zone A Figure 1.4). Clear euhedral needles of zircon with some visible cores (fractions A' and C', Figure 1.12) and stained cracked, cloudy euhedral zircons with visible cores (fractions D', E' and F') were analysed separately in case they represented two different populations of zircons. Analyses revealed that the different morphologies belong to only one population. The stained cracked group underwent Pb loss probably due to diffusion along cracks. The 59 +/- 0.3 Ma age interpretation is based on concordant fraction G', a single slightly imperfect crystal. Fractions G', A' and C', the best crystals, lie at the lower end of an array of discordia chords, indicating a component of inherited Pb. Two monazite fractions yield 57.7 +/- 0.3 and 56.0 +/- 0.4 Ma $^{207}\text{Pb}/^{235}\text{U}$ ages, which are younger than the 59.3 +/- 0.3 Ma zircon age (Table 1.5).

Sample SC530 is a weakly foliated, ~10 m thick sheet of coarse-grained pegmatite within a ~3 km thick sheet of variably strained pegmatite that was deformed during high-grade compressional deformation (Zone C, Figure 1.4). All zircon fractions were abraded. Fractions J' and K' overlap concordia at 60.5 +/- 0.5 Ma and are interpreted to represent the age of the rock (Figures 1.13 and 1.14). The other five zircon fractions are concordant or near concordant between 60.5 Ma and 59 Ma. This pattern of discordance may be a result of high-temperature Pb loss (see following discussion). Monazite

$^{207}\text{Pb}/^{235}\text{U}$ ages are younger than the zircon age; fractions 2' and 3' agree and are 56.3 ± 0.4 Ma and 56.2 ± 0.3 Ma and fraction 4' is 59.2 ± 1.4 Ma (Table 1.5).

Sample SC1122 is a 0.3-3 m wide, sillimanite bearing folded pegmatite sheet in highly sheared rocks in the immediate hanging wall of the Monashee décollement (Plate 1.3a, Zone A of Figure 1.4). The discordance pattern is similar to SC530 (Figure 1.15); near concordant zircons lie just below the concordia curve between 51.5 and 52.5 Ma. All fractions were abraded. These data do not allow a precise age interpretation to be made, except that the igneous age is >52.5 Ma, and a very low zircon yield precludes further work. From field relationships the rock must be older than 58 Ma, as the fabrics in SC1122 are the same as those crosscut by the 58 Ma dyke SC570. The zircons have probably undergone high-temperature Pb loss. The $^{207}\text{Pb}/^{235}\text{U}$ ages of all four monazite analyses agree (51.5 ± 0.8 , 51.2 ± 0.6 , 51.4 ± 0.5 and 51.0 ± 0.6 Ma) but are 8 Ma younger than the youngest possible age for the rock. Both zircons and monazites have the highest concentrations of U of all the Ladybird samples; zircons average 6600 ppm and monazites 25,000 ppm (Table 1.2), and perhaps this has lowered the resistance of the crystal to Pb loss.

U-Pb systematics

Inheritance

Most zircon fractions analysed for this study have inherited radiogenic Pb and the pattern of discordance indicates multiple ages of inheritance, which range from 1000 Ma to 2500 Ma. This is consistent with previous studies of the Ladybird granite (Parrish et al. 1988) and is also consistent with a crustal-melting origin for the Ladybird suite. There is no evidence to suggest a significant inherited Pb component in the monazite fractions such as that reported by Copeland et al. (1989), except possibly sample SC570.

High-temperature Pb loss

Zircons are generally refractory and the presence of cores of inherited radiogenic Pb in magmatic zircons indicates that the crystals are resistant to diffusion at magmatic temperatures; however, there are indications from this study that high-temperature Pb loss may be common in zircons from high-grade shear zones. The leucogranite samples (SC530 and SC1122), that were strained during motion on Monashee décollement and remained hot afterward, have an unusual discordance pattern. Zircon analyses are slightly discordant and are spread along the discordia curve (Figures 1.14, 1.15 and 1.16), a pattern indicative of Pb loss. In the case of SC530, this could be due to high temperatures accompanied by shearing. From SC1122, geological relationships indicate that shearing ceased by 58 Ma, but Pb loss clearly continues to 52 Ma. This implies that Pb diffusion may be enhanced during deformation perhaps by the presence of dislocations within the crystal or by fluids and/or by radiation damage in high-uranium crystals especially while at high temperatures.

The cracked zircons in SC951 clearly show substantial Pb loss. Fractions E and F underwent substantial Pb loss that is younger than 59 Ma (Figure 1.12). Uncracked zircon fractions from the same rock do not exhibit this pattern of discordance. This example clearly shows that Pb loss can be correlated with the presence of cracks and can be accounted for by diffusion along crystal defects.

Effect of abrasion

It is common practice to abrade "old" zircons (Krogh 1982) to decrease the possible effects of surface correlated Pb loss. Few, if any, published studies have used abrasion in "young" rocks. Most of the zircon fractions in this study were abraded (Table 1.2) and in comparison to unabraded fractions, a larger proportion of abraded fractions are concordant. This implies that it may be wise to abrade young zircons as a general procedure.

Thorium disequilibrium

In 70% of the nearly concordant zircons, those without significant inheritance or Pb loss, Th corrections shifted the error ellipse upward to overlap concordia; therefore, the correction was generally useful (see Figures 1.1-1.15). All 18 monazite fractions analysed initially showed reverse discordance. Th corrections resulted in the under-correction of 10 fractions which remained above concordia, the over-correction of 5 fractions which moved below concordia and correction to concordia of only 3 fractions. In the cases where the data corrected to concordia, the correction did not apply equally as well to all the fractions of samples in question (SC530 and SC570). These data indicate that the zircon data are not as sensitive to the corrections as monazites and suggest that the corrections, particularly for monazite, are not necessarily valid or particularly useful. The assumptions that the measured Th/U ratio of the rock represents the Th/U ratio of the magma, and that this ratio represents the Th/U available to accessory minerals during crystallization may not be met (Schärer 1984, Parrish 1990). The Th/U ratios of SC534 and SC1028 are much higher than the other samples and higher than values reported for other leucogranites (Schärer 1984; Videt et al. 1982) indicating that there may have been leaching of U during either metamorphism or weathering (Stuckless et al. 1981; Schärer et al. 1986). In any case, the $^{207}\text{Pb}/^{235}\text{U}$ ages are used to interpret the ages of the monazite fractions and this does not change regardless of the ^{206}Pb correction.

Monazite systematics

Monazite results from each of six variably deformed Ladybird leucogranites (Table 1.5) indicates that monazite systematics in young rocks are complicated and that monazite ages may not necessarily represent the magmatic age of the rock or a meaningful cooling age. Ladybird samples either contain monazite populations with either more than one apparent $^{207}\text{Pb}/^{235}\text{U}$ age or ages that are reproducible but are not in agreement with the zircon data (Table 1.5). A review of published monazite analyses

reveals that this is apparently common for young rocks (Parrish and Armstrong 1987; Parrish and Bell 1987; Parrish and Tirrul, 1989; Parrish 1990).

Samples SC534 and SC570 have monazite in which $^{207}\text{Pb}/^{235}\text{U}$ ages of some fractions are older than the zircons and the interpreted age of the rock (Table 1.5). One of three monazite fractions in SC534 and three of four fractions in SC570 are older than the rock. Both of these samples are from post-tectonic intrusions; therefore, the older monazite fractions are interpreted to represent xenocrystic monazites that were entrained by the magma during intrusion.

Four samples (SC530, SC951, SC1028 and SC1028) have monazite fractions of more than one age that are younger than the age of the rocks, as interpreted from zircons (Table 1.5). All four monazite fractions from SC1122 are in agreement with each other but are at least 8 Ma younger than the age of the rock. The faceted morphology of the monazite crystals selected for analyses in SC1122 is interpreted as being igneous, therefore a metamorphic origin is tentatively ruled out. These younger ages could represent a cooling age when the rocks cooled below the monazite closing temperature (Parrish and Tirrul 1989; Parrish 1990).

Parrish and Tirrul (1989) reported a case from the Himalayan Baltoro leucogranite where the U-Pb ages of monazites are younger than those of zircons and the interpreted age of the rock. They suggested that the discordance pattern in the Baltoro granite was a result of high-temperature partial diffusional Pb loss. They proposed that Pb loss occurred at temperatures of $650^{\circ}\text{--}700^{\circ}\text{C}$; similar to the estimated closure temperature of monazite, during slow cooling of the high-grade country rocks. This explanation does not seem satisfactory for the Ladybird leucogranites because the country rock apparently cooled rapidly during Early Eocene extension (Carr et al. 1987; Parrish et al. 1988; Carr, Chapter 3). Partial Pb loss would not account for the consistent 51.3 Ma ages of all four monazite fractions in SC1122. It is possible, however, that high-temperature partial or total Pb loss could have been a result of diffusion enhanced by either local temperature

increases or fluid influxes which accompanied slightly younger granite and pegmatite intrusions. This is reasonable for "older" 62 to 58 Ma phases of the Ladybird suite (SC530, SC570, SC951, SC1028 and SC112) since we know that the region was intruded by ~55 Ma plutons and pegmatite sheets (Figure 1.2, Table 1.1). This explanation is plausible for all samples except for SC1122; perhaps these 51.3 Ma monazite ages somehow reflect a Pb loss effect brought during emplacement of the 51.5 Ma Coryell suite which is extensive throughout the southern Omineca Belt and locally plutons are exposed near Lower Arrow Lake and on the western flank of Valhalla complex (Figure 1.1, Little 1957, 1960; Carr et al. 1987; Parrish et al. 1988).

In summary, the monazites do not unequivocally represent an igneous or cooling age in any of the six leucogranitic samples studied. It is probable that monazite ages which are 1-4 Ma older than the zircon ages (SC534 and SC570, Table 1.2) may represent xenocrystic monazites incorporated as post-tectonic pegmatites intruded through slightly older granite, pegmatite and other metamorphic rocks. Monazite ages which are younger than the zircon ages may be a result of temperature- or fluid-enhanced diffusional Pb loss that was triggered during the intrusion of younger granitoid phases. High uranium concentrations may have made monazite crystals more susceptible to high-temperature Pb loss.

Discussion

Origin of the Ladybird leucogranite suite

It is likely that the Ladybird leucogranite suite formed from melted crustal material. This is supported by the mineralogy and field relationships of the granites and the presence of inherited Pb in zircons. There are very few Ladybird intrusions below the Monashee décollement in the exposed Basement Zone in Thor-Odin culmination. The décollement was inactive at 58 Ma, the bulk of the granites in the Middle Crustal Zone

are ~55 Ma, and they did not rise through the Basement Zone; therefore, the granites must have either intruded laterally along strike or have been generated *in situ*.

Granitic melts can be generated from quartzo-feldspathic crustal rocks at temperatures common in regional metamorphism (Brown and Fyfe 1970; Wyllie 1977; Allegré and Ben Othman 1980; Whitney 1988), and increased temperature, decreased pressure or increased P_{H_2O} are often invoked to trigger melting in solid crust (Wyllie 1977). The generation of heat early in the history of the Mesozoic-Paleocene thrust systems, subsequent uplift by ramping, unroofing and decompression melting and/or the introduction of fluids may have played an important role in generating the Ladybird granite suite.

Decompression melting

During thrusting, the rocks of the Middle Crustal Zone, which now host the Ladybird granite, formed the lower part of the allochthonous sheet carried eastward by the Monashee décollement. Journeay (1986; Journeay and Brown 1986) and Scammell (1986) showed that the Monashee décollement, on the flanks of the Frenchman Cap culmination, had a movement history on the basis of structural relationships, the overprinting of syn-kinematic low-pressure mineral assemblages on syn-kinematic high-pressure assemblages and the preservation of inverted metamorphic isograds in the footwall. In the Thor-Odin - Pinnacles area, the Monashee décollement is imaged in LITHOPROBE seismic reflection data (Carr and Brown 1990; Cook et al. 1990; Brown et al. 1990). The décollement is near the surface on the southern flank of Thor-Odin culmination and ramps down into the middle crust under the Okanagan Valley. Movement of the hanging wall up this ramp in the Late Cretaceous - Paleocene combined with unroofing by erosion or denudation faulting could have triggered decompression melting within the allochthonous sheet if $P_{H_2O} < P_{TOTAL}$. Although data on fluid composition is not directly available, this model is consistent with the spatial distribution pattern of Ladybird intrusions with time; the magmatic front migrated from east to west

between 62 and 52 Ma. The oldest phases of the Ladybird granite occur in the eastern part of the Omineca Belt (Valhalla complex) or are at the deepest structural levels near the base of the Middle Crustal Zone. The youngest phases are located in the western exposures of the Middle Crustal Zone in the footwall of the Okanagan Valley fault (Parrish and Bardoux, unpublished data, 1988).

Increased hydrous fluid pressure

At ambient temperatures close to that of melting, the introduction of fluids decreases the melting temperature of rocks and could trigger melting (Whitney 1988). Fluids may have helped trigger melting and may have become available to the system either by liberation during dehydration reactions (Brown and Fyfe 1970; Patiño Douce et al. 1990), perhaps as the second sillimanite isograd was exceeded, or by the transport of fluids along the Monashee décollement and associated thrust faults. The first theory is testable by doing further work on the metamorphic and thermal history in the region. The presence of fluids in shear zones is well known from studies on mineral and whole rock chemistry, isotopic composition and metamorphic reactions (Beach and Fyfe 1972; White and Knipe 1978; Beach 1976, 1980; Brodie 1980; Allison and Kerrich 1981; Watts and Williams 1983; Kerrich and Rehrig 1987). The theory that fluids were introduced to the system is supported by a study on metamorphic zircons (Carr, Chapter 2). Two amphibolite samples from the southern flank of Thor-Odin yield U-Pb dates on metamorphic zircons that are Late Paleocene; the onset of metamorphic zircon growth is attributed to the introduction of fluids (Carr, Chapters 2 and 3).

Relationship of intrusion to extension

The bulk of the Ladybird intrusions, which occur between Valhalla complex and the Okanagan Valley (Figure 1.1), are ~55 Ma and postdate the onset of the easterly dipping

extensional faults (Columbia River - Valkyr - Slocan Lake); however, early intrusions may have localized extensional shear zones and facilitated extension by melt enhanced softening.

Ductile shear zones are thought to nucleate in areas of mechanical or thermal inhomogeneity (Poirier 1980). The Columbia River and Valkyr - Slocan Lake shear zone are coincident with sheetlike granites in their footwalls. Magma partial melts or plutons could have played an important role in the nucleation of crustal-scale normal faults by enhancing structural or strain-rate softening, that would in turn lead to strain localization and shear zone formation. Once underway, extension facilitated the intrusion of extensive batholiths of Ladybird granite.

Conclusions

The Late Paleocene to Early Eocene Ladybird leucogranite suite is a vast previously unrecognized intrusive suite which coincides with the region of maximum extension in the southern Omineca belt. It is generally confined to a particular crustal level; it occurs in the Middle Crustal Zone above deep-seated thrust faults and below normal fault systems. It occurs as syn-kinematic sheets in both compressional and extensional shear zones and as late-kinematic to post-kinematic stocks, plutons and batholiths.

Timing constraints are placed on the transition between compression and extension in the southern Omineca Belt by U-Pb zircon dating of syn-tectonic Ladybird intrusives in shear zones in the Thor-Odin - Pinnacles area. Thrusting on the Monashee décollement thrust system was ongoing in the latest Paleocene based on 62-59 Ma U-Pb ages of pegmatite and migmatite deformed in the shear zone (Table 1.1) and thrusting was finished by 58 +/- 0.5 Ma based on U-Pb zircon age of a crosscutting pegmatite. The transition from compression to extension in the Thor-Odin - Pinnacles area and Valhalla complex occurred at 58 +/- 1 Ma. Extension was underway between 58 and 56 Ma in Valhalla complex (Carr et al. 1987). The Columbia River normal fault deforms ~55 Ma

granites; this timing relationship is consistent with Rb-Sr dates of syn-kinematic muscovite in the footwall of the Columbia River fault (Parrish et al. 1989). The 58 ± 1 Ma transition between compression and extension coincides with estimates for the end of thrusting in the Rocky Mountain Foreland Belt (Price and Mountjoy 1970; Donelick and Beaumont 1990).

Comparison of U-Pb zircon systematics in rocks which have undergone various degrees of strain indicate that the systematics are relatively straightforward in weakly deformed and undeformed samples and are more complex in granites which were deformed at high-grade and/or have high U concentrations. The samples deformed at high grade show evidence of high-temperature Pb loss perhaps due to temperature- or fluid-enhanced diffusion during deformation. The presence of a component of inherited radiogenic Pb in most zircon fractions is consistent with an origin of crustal anatexis for the Ladybird granite.

Monazite analyses indicate that monazite systematics in young rocks are complex and that monazite dates do not necessarily represent the magmatic age of the rocks or a cooling age (Table 1.5). Monazites with ages older than the age of the rock, interpreted from concordant zircon analyses, occur in post-tectonic intrusions and are thought to be inherited xenocrystic monazites. Monazites with ages younger than the age of the rock are thought to have lost Pb at high temperatures as a result of fluid- or temperature-enhanced diffusion during the intrusion of slightly younger (1- 4 Ma) phases of the Ladybird suite. The correction procedure to accommodate unsupported ^{206}Pb derived from excess ^{230}Th in monazite is of questionable usefulness, perhaps due to invalid assumptions made to derive the Th/U ratios available to the monazite during growth.

The constraints on crustal geometry, timing of regional compressional and extensional structures and timing of Ladybird leucogranite plutonism in the southern Omineca Belt are consistent with the following model. The mid- to upper crust was heated during protracted compression and crustal thickening. The onset of anatexis during the

final stages of thrusting may have been triggered by decompression of the allochthonous Middle Crustal Zone as it was transported up a crustal ramp in the hanging wall of the Monashee décollement and unroofed by erosion and tectonic denudation or by fluxing of the Middle Crustal Zone by fluids introduced along the shear zone system or liberated during dehydration reactions. This model is testable by comparing the pressure and temperature conditions of the country rock and granitic rocks to determine conditions of granite emplacement, and by studying the geochemistry of the granitic suite and possible protoliths to determine the origin of the melts.

Crustal melts probably played an important role in the nucleation of the extensional shear zones. The extensional regime then facilitated intrusion of vast late to post-kinematic plutons.

The uplift and exposure of the Ladybird granite suite throughout the extended terrane in the southern Omineca Belt is ultimately a result of extension; however, the granites themselves are mainly a product of the pre-existing compressional regime.

TABLE 1.1: SUMMARY OF U-Pb SAMPLES AND AGES

Sample number	Rock type	Location	Description	U-Pb age (Ma)
SC530	Ladybird Suite pegmatite	Sitkum Creek	weakly foliated sheets tens of metres thick, Fabric Zone C.	60.5+/-0.5
SC534	Ladybird Suite pegmatite	Whatshan River	very weakly foliated composite sheets, Fabric Zone C.	55.5+/-0.3
SC570	Ladybird Suite pegmatite	Cariboo Alp	undeformed 30 cm thick dyke, crosscuts fabric in country rock, Fabric Zone D.	58.0+/-0.3
SC855	hornblende bearing granite	Pinnacles	weakly foliated 10 cm wide sill, crosscuts folds in country rock, Fabric Zone C.	54.3+/-0.5
SC951	migmatite leucosome	North of Margie Lake	coarse grained, highly strained 50 cm wide concordant sill, Fabric Zone A.	59.0+/-0.3
SC1028	Ladybird Suite granite	Mount Fossilhall	highly strained, boudinaged 30 cm wide sill, Fabric Zone A	62.1+/-0.3
SC1122	Ladybird Suite pegmatite	Cariboo Alp	sillimanite bearing, 10-80 cm wide sill folded by F2, Fabric Zone A	unknown > 58 Ma

TABLE 1.2: U-Pb ANALYTICAL DATA

Fraction ¹ Wt.	U	Pb* (ppm)	$\frac{206\text{Pb}}{204\text{Pb}}$ [#]	Pb _c ^a 208Pb** (pg)	(%)	$\frac{206\text{Pb}}{238\text{U}}$	$\frac{207\text{Pb}}{235\text{U}}$	Corr. coeff.	$\frac{207\text{Pb}}{206\text{Pb}}$	$\frac{207\text{Pb}}{206\text{Pb}}$ ^{^^} Age (Ma)	$\frac{207\text{Pb}}{206\text{Pb}}$ ^{\$\$} Age(Ma)		
SC 530													
A	0.104	1602	13.7	6712	14	2.9	0.009212	0.009196±0.12%	0.05995±0.13%	0.96	0.04728±0.04%	63.2±1.7	59.2
B, n=1	0.038	1440	12.9	3396	10	5.6	0.009421	0.009407±0.12%	0.06140±0.13%	0.93	0.04733±0.05%	66.1±2.2	62.5
C	0.086	1899	16.4	4178	23	3.4	0.009270	0.009255±0.19%	0.06040±0.20%	0.97	0.04733±0.04%	66.1±2.0	62.2
D	0.043	1786	14.9	3064	14	2.2	0.009075	0.009059±0.11%	0.05909±0.12%	0.92	0.04731±0.05%	64.8±2.3	60.6
H,abr	0.028	1718	15.3	2235	15	5.2	0.009381	0.009366±0.09%	0.06106±0.12%	0.86	0.04728±0.06%	63.6±2.8	59.4
J,abr	0.053	1338	11.8	1169	37	4.0	0.009439	0.009424±0.10%	0.06139±0.13%	0.88	0.04724±0.06%	61.5±3.0	57.7
K,abr	0.041	1386	12.0	410	88	1.9	0.009448	0.009432±0.13%	0.06121±0.33%	0.69	0.04707±0.26%	52.7±12.3	48.7
2, n=7	0.210	3933	198	1882	255	83.7	0.008832	0.009023±0.17%	0.05697±0.20%	0.91	0.04579±0.08%	-13.2±3.8	38.1
3, n=1	0.033	4289	208	1379	58	83.3	0.008754	0.008937±0.12%	0.05692±0.15%	0.86	0.04619±0.08%	7.5±3.7	57.1
4, n=7	0.104	6829	239	555	791	75.7	0.009275	0.009383±0.56%	0.06005±0.64%	0.91	0.04642±0.26%	19.3±12.7	47.0
SC 534													
C	0.212	2054	16.4	7373	33	2.9	0.008650	0.008634±0.30%	0.05627±0.30%	0.99	0.04727±0.03%	63.0±1.6	58.3
D	0.083	2244	19.9	8516	13	3.0	0.009543	0.009526±0.12%	0.06640±0.13%	0.96	0.05055±0.03%	220.4±1.5	216.3
E	0.110	2101	19.5	5614	26	4.6	0.009801	0.009785±0.11%	0.07098±0.13%	0.96	0.05261±0.04%	312.0±1.6	308.0
1, n=10	0.226	5108	205	2598	250	80.3	0.008729	0.008731±0.81%	0.05592±0.82%	0.99	0.04645±0.06%	21.0±3.0	21.4
2, n=5	0.247	4177	201	1097	546	83.1	0.008957	0.008963±0.29%	0.05732±0.33%	0.91	0.04639±0.13%	17.7±6.4	19.2
3, n=1	0.056	4604	229	1523	96	84.0	0.008763	0.008770±0.24%	0.05605±0.26%	0.95	0.04635±0.08%	15.9±3.7	17.8
SC 570													
A	0.068	1489	12.7	3448	18	1.2	0.009365	0.009349±0.10%	0.06114±0.12%	0.94	0.04743±0.04%	70.9±2.0	66.8
B, n=1	0.092	689	5.66	1379	27	1.0	0.009052	0.009036±0.12%	0.05889±0.16%	0.84	0.04727±0.09%	63.0±4.2	58.6
C	0.057	1567	14.0	2481	23	1.7	0.009781	0.009765±0.10%	0.06572±0.12%	0.90	0.04882±0.05%	139.0±2.5	135.1
F	0.060	1369	11.9	2366	21	1.5	0.009533	0.009517±0.10%	0.06350±0.12%	0.88	0.04839±0.06%	118.5±2.7	114.5
1, n=4	0.094	6592	184	2399	146	71.3	0.008769	0.008860±0.37%	0.05680±0.38%	0.98	0.04650±0.06%	23.6±3.0	48.2
3, n=1	0.038	3289	143	1376	56	79.8	0.009488	0.009443±0.11%	0.06202±0.14%	0.88	0.04665±0.07%	31.2±3.2	69.8
4	0.035	2895	175	843	77	85.3	0.009574	0.009809±0.13%	0.06299±0.19%	0.77	0.04657±0.12%	27.3±5.8	85.1
6	0.063	2996	171	592	203	84.6	0.009456	0.009678±0.13%	0.06217±0.29%	0.71	0.04659±0.22%	28.3±10.6	83.8

TABLE 1.2: U-Pb ANALYTICAL DATA (concluded)

Fraction ¹	wt. U (mg)	Pb* (ppm)	$^{206}\text{Pb}/^{204}\text{Pb}$ (ppm)	Pb _c ² (pg)	^{208}Pb (‰)	^{238}U	^{206}Pb (ppm)	$^{207}\text{Pb}/^{235}\text{U}$	Corr. coeff.	$^{207}\text{Pb}/^{206}\text{Pb}$	$^{207}\text{Pb}/^{206}\text{Pb}$ Age (Ma)	$^{207}\text{Pb}/^{206}\text{Pb}$ Age (Ma)
SC1122												
A,abr	0.034	5399	40	5564	17	0.3	0.008173	0.003157±0.11%	0.93	0.04719±0.05%	58.7±2.1	53.9
B,abr	0.025	6574	46	8248	10	0.3	0.008087	0.008071±0.10%	0.95	0.04717±0.04%	57.9±1.7	53.0
C,abr	0.035	7753	56	10945	13	0.2	0.008017	0.008000±0.12%	0.97	0.04718±0.03%	58.2±1.5	53.2
1,n=1	0.035	20247	278	1167	317	46.9	0.008007	0.008082±0.11%	0.76	0.04642±0.13%	19.5±6.4	41.9
2,n=3	0.037	27454	359	4665	113	44.5	0.007977	0.008043±0.11%	0.94	0.04651±0.04%	24.3±2.0	43.9
3,n=2	0.030	20111	271	3945	77	45.9	0.008000	0.008071±0.10%	0.95	0.04643±0.04%	20.1±1.7	41.3
4(n=1)	0.041	32740	393	6533	106	39.2	0.008036	0.008066±0.12%	0.96	0.04619±0.04%	7.8±1.7	22.9

¹Letters are zircon fractions; numerals are monazite fractions; abr=2-6 hours of abrasion; single crystal analyses (n=1).

²Radiogenic Pb, corrected for spike, fractionation, blank and common Pb.

³Measured ratio, corrected only for spike and fractionation.

⁴Total common Pb in analysis.

⁵Radiogenic ^{206}Pb , expressed as % of total radiogenic Pb.

⁶ $^{206}\text{Pb}/^{238}\text{U}$ corrected for unsupported Pb from ^{230}Th .

⁷ $^{207}\text{Pb}/^{206}\text{Pb}$ age recalculated from Th corrected $^{206}\text{Pb}/^{238}\text{U}$.

⁸Uncertainties are 1-sigma %.

⁹Uncertainties are 2-sigma in Ma.

TABLE 1.3: WHOLE ROCK THORIUM AND URANIUM ANALYSES

Sample Number	Th ppm	U ppm	Th/U
SC530	0.7	0.5	1.4
SC534	36.7	3.0	12.2
SC570	0.9	0.7	1.2
SC855	13.5	5.6	2.4
SC951	0.6	1.0	0.6
SC1028	26.8	1.9	14.7
SC1122	5.9	11.0	0.5

Analyses performed by ICPMS courtesy of the Geological Survey of Canada.
Detection limit is 0.1 ppm.

TABLE 1.4: U-Pb GEOCHRONOLOGY SAMPLE LOCATIONS

Sample number	Description
SC530	300 m cliff of coarse, weakly foliated pegmatite with biotite books, located above Sitkum Creek logging road between Twin Peaks and Sitkum Plateau (82 L/8), elevation 4830', UTM 407170E-5584180N
SC534	very weakly foliated medium-grained pegmatite with biotite books, 13 km north of Whatshan Lake (82 L/1), elevation 3100', UTM 423900E-561200N
SC570	coarse, discordant pegmatite dyke, ~30 cm wide, trends northerly and dips steeply to the east, post-tectonic, cuts imbricated basement and cover gneisses, cuts annealed mylonitic fabrics associated with the Monashee décollement, Cariboo Alp (82 L/9), elevation 7300', UTM 415600E-5597650N
SC855	weakly foliated, hornblende-biotite bearing 20-30 cm wide sill of leucocratic granite in Pinnacles Peaks (82 L/1), cuts across layering and F1 and F2 folds at high angle, elevation 6610', The Pinnacles, UTM 411850E-5563150N
SC951	coarse-grained mylonitic, biotite-sillimanite bearing leucocratic migmatite ~50 cm wide, hosted in semi-pelitic gneiss, west of Mount Symonds above the Monashee décollement (82 L/8), elevation 7900', UTM 417560E-5593920N
SC1028	medium-grained, biotite-garnet-sillimanite bearing, mylonitic granite in 30 cm wide boudinaged layer, hosted in pelitic paragneiss (82 L/8); elevation 6900', UTM 415950E-5590850N
SC1122	sillimanite bearing 30-80 cm thick concordant pegmatite folded by F2 in immediate hanging wall of the Monashee décollement on Cariboo Alp (82 L/9), sillimanite lies in axial surface of F2., elevation 6800', UTM 414850E-5596250N

TABLE 1.5: SUMMARY OF U-Pb ZIRCON VERSUS MONAZITE AGES

Sample Number	Interpreted U-Pb zircon age (Ma)	$^{207}\text{Pb}/^{235}\text{U}$ U-Pb monazite age (Ma)
SC530	60.5 $\pm$ 0.3	*56.2 $\pm$ 0.3 *56.3 $\pm$ 0.4 59.2 $\pm$ 1.4
SC534	55.5 $\pm$ 0.3	*55.4 $\pm$ 1.8 *55.4 $\pm$ 0.6 56.6 $\pm$ 0.7
SC570	58.0 $\pm$ 0.3	56.1 $\pm$ 0.9 *61.1 $\pm$ 0.2 *61.2 $\pm$ 0.5 62.0 $\pm$ 0.4
SC951	59.0 $\pm$ 0.3	56.0 $\pm$ 0.4 56.0 $\pm$ 0.4
SC1028	62.0 $\pm$ 0.3	55.1 $\pm$ 0.3 57.0 $\pm$ 0.3
SC1122	uncertain > 58 Ma	*51.0 $\pm$ 0.6 *51.2 $\pm$ 0.6 *51.4 $\pm$ 0.5 *51.5 $\pm$ 0.8

* $^{207}\text{Pb}/^{235}\text{U}$ monazite ages in agreement.

Figure 1.1 Tectonic map of southern Omineca Belt, modified from Parrish et al. (1988). Insets locate the geologic belts of the Cordillera and the Intermontane (IM) and Insular (IS) superterrane. The Omineca Belt lies between the southern Rocky Mountain Trench (SRMT) in the northeast and the Fraser-Straight Creek (FSF), Yalakom (YF), Hozameen (HF), and Pasayten (PF) strike slip faults in the southwest. The unpatterned area in the Omineca Belt represents the Upper Crustal Zone (see text). Rocks of North American affinity (NA) are separated from the Intermontane Superterrane (IM) by the Terrane Accretion Boundary (TAB). Features shown with patterns form the Shuswap metamorphic complex. The Middle Crustal Zone (diagonal stripes) consists of metamorphic rocks characterized by 45-60 Ma K-Ar mica dates. Basement rocks of the Basement Zone (dark grey) are exposed in Frenchman Cap (FC) and Thor-Odin (TO) culminations in the Monashee complex and the Malton complex (M). High-grade culminations of the Shuswap metamorphic complex also include the Kettle-Grand Forks (K), Okanagan (OC), Priest River (PR), and Valhalla (V) complexes. Mesozoic-Paleocene thrust faults are the Monashee décollement (MD) and Gwillim Creek shear zones (GCS). Eocene normal faults are the Columbia River fault (CF), Granby fault (GF), Greenwood fault system (GWF), Kettle fault (KF), Newport fault (NF), Okanagan Valley - Eagle River fault system (OF), Purcell Trench fault (PTF), Slokan Lake fault (SLF) and Valkyr shear zone (VS).

FIGURE 1.2 Geology of the Thor-Odin - Pinnacles area and surrounding area

LEGEND

UPPER CRUSTAL ZONE

MIDDLE JURASSIC NELSON INTRUSIVE SUITE: predominantly granodiorite

PALEOZOIC - LOWER JURASSIC STRATIFIED ROCKS:

MIDDLE CRUSTAL ZONE

LATE PALEOCENE - EARLY EOCENE LADYBIRD GRANITE SUITE: biotite granite, quartz monzonite, leucocratic pegmatite (also includes areas with pegmatite with <50% metamorphic rocks)

LATE CRETACEOUS WHATSHAN BATHOLITH (includes Cariboo Creek stock): hornblende biotite bearing K-feldspar megacrystic quartz monzonite, mafic hornblende biotite diorite

LATE PROTEROZOIC - MESOZOIC AMPHIBOLITE FACIES METAMORPHIC ROCKS: FA = Fawn Lake assemblage; GA = Gold Range assemblage

BASEMENT ZONE

PROTEROZOIC CRYSTALLINE BASEMENT AND LATE PROTEROZOIC - (?) CAMBRIAN COVER GNEISSES

GEOLOGIC CONTACT; MAPPED, COMPILED FROM PUBLISHED MAPS, ASSUMED

LOW - MODERATE ANGLE EOCENE NORMAL FAULT (PEGS ON HANGING WALL)

STEEP EOCENE NORMAL FAULT (PEGS ON HANGING WALL)

STEEP EOCENE NORMAL FAULT; SENSE OF DISPLACEMENT UNCERTAIN

LITHOPROBE LINE

BF	BEAVEN FAULT
CF	CHERRYVILLE FAULT
CRF	COLUMBIA RIVER FAULT
GCSZ	GWILLIM CREEK SHEAR ZONES
MD	MONASHEE DECOLLEMENT
OF	OKANAGAN VALLEY - EAGLE RIVER FAULT SYSTEM
SLFZ	SIOCAN LAKE FAULT ZONE
SSZ	SLATE MOUNTAIN SHEAR ZONE
VSZ	VALKYR SHEAR ZONE

Figure 1.3 Distribution of metamorphic assemblages and minerals in pelitic rocks in the Thor-Odin - Pinnacles area

FIGURE 1.4. STRAIN VARIATION IN THE PALEOCENE - EOCENE LADYBIRD GRANITE SUITE IN THE THOR-ODIN - PINNACLES AREA

UPPER CRUSTAL ZONE

- **PALEOZOIC - EARLY JURASSIC LOW- TO MEDIUM-GRADE METAMORPHIC ROCKS AND MIDDLE JURASSIC GRANITOID ROCKS (NELSON SUITE)**

MIDDLE CRUSTAL ZONE

- **LATE PALEOCENE - EARLY EOCENE LADYBIRD GRANITE**
- **LATE PALEOCENE - EARLY EOCENE PEGMATITE WITH 5-50% AMPHIBOLITE FACIES METAMORPHIC ROCKS**
- **LATE CRETACEOUS WHATSHAN BATHOLITH**
- **LATE PROTEROZOIC - MESOZOIC AMPHIBOLITE FACIES METAMORPHIC ROCKS INTRUDED BY <40% LATE PALEOCENE - EOCENE LADYBIRD GRANITE AND PEGMATITE**

BASEMENT ZONE

- **PROTEROZOIC CRYSTALLINE BASEMENT AND LATE PROTEROZOIC - (?) CAMBRIAN COVER GNEISSES**

- **GEOLOGIC CONTACT; MAPPED, COMPILED FROM PUBLISHED MAPS, ASSUMED**
- **LOW - MODERATE ANGLE EOCENE NORMAL FAULT (PEGS ON HANGING WALL); MAPPED, ASSUMED, INFERRED**
- **STEEP EOCENE NORMAL FAULT (PEGS ON HANGING WALL)**
- **STEEP EOCENE NORMAL FAULT; SENSE OF DISPLACEMENT UNCERTAIN**
- **FOLIATION AND LINEATION IN LADYBIRD GRANITE OR PEGMATITE**
- **PENETRATIVE MYLONITIC FOLIATION AND LINEATION IN LADYBIRD GRANITE OR PEGMATITE; ARROW INDICATES DIRECTION OF MOVEMENT OF UPPER MEMBER OF THE SHEAR COUPLE**
- **MYLONITIC FOLIATION AND LINEATION IN DISCRETE SHEARS WITHIN LADYBIRD GRANITE OR PEGMATITE; ARROW INDICATES DIRECTION OF MOVEMENT OF UPPER MEMBER OF THE SHEAR COUPLE**
- **LITHOPROBE LINE**

FABRICS IN LADYBIRD GRANITE SUITE

- **ZONE A: ANNEALED SILLIMANITE BEARING MYLONITES**
- **ZONE B: UNANNEALED LOWER AMPHIBOLITE - GREENSCHIST FACIES MYLONITES**
- **ZONE C: WEAK - MODERATE FOLIATION AND/OR PROTOMYLONITIC FABRICS**
- **ZONE D: UNDEFORMED IGNEOUS TEXTURES**

- BF** **BEAVEN FAULT**
- CF** **CHERRYVILLE FAULT**
- CRF** **COLUMBIA RIVER FAULT**
- MD** **MONASHEE DECOLLEMENT**
- OF** **OKANAGAN VALLEY FAULT**
- SSZ** **SLATE MOUNTAIN SHEAR ZONE**

MAPPING BY S. CARR (1986, 1987, 1988, 1989). CONTACT OF PLUTON NORTH OF SUGAR LAKE COMPILED FROM JONES (1957); TRACE OF COLUMBIA RIVER FAULT FROM HYNDMAN (1977), READ AND WHEELER (1976) AND READ (1979); TRACE OF THE MONASHEE DECOLLEMENT FROM COLEMAN (1990).

Figure 1.5. Generalized east-west schematic cross section showing strain distribution within the Ladybird suite in the Thor-Odin - Pinnacles area. A, B, C and D refer to fabric Zones A to D (see text). Horizontal = vertical scale.

LEGEND	
gn	UNDIVIDED METAMORPHIC ROCKS
BF	BEAVER FAULT
CF	CHERRYVILLE FAULT
CRF	COLUMBIA RIVER FAULT
MD	MONASHEE DECOLLEMENT
OF	OKANAGAN VALLEY - EAGLE RIVER FAULT SYSTEM
P _{ls}	PALEOZOIC - LOWER JURASSIC STRATIFIED ROCKS

FIGURE 1.6. U-Pb SAMPLE LOCATION MAP

UPPER CRUSTAL ZONE

MIDDLE JURASSIC NELSON INTRUSIVE SUITE: predominantly granodiorite

PALEOZOIC - LOWER JURASSIC STRATIFIED ROCKS:

MIDDLE CRUSTAL ZONE

LATE PALEOCENE - EARLY EOCENE LADYBIRD GRANITE SUITE: biotite granite, quartz monzonite, leucocratic pegmatite

LATE PALEOCENE - EARLY EOCENE LADYBIRD PEGMATITE WITH 5-50% PALEOZOIC - LOWER JURASSIC METAMORPHIC ROCKS:

LATE CRETACEOUS WHATSHAN BATHOLITH (includes Cariboo Creek stock): hornblende biotite bearing K-feldspar megacrystic quartz monzonite, mafic hornblende biotite diorite

LATE PROTEROZOIC - MESOZOIC AMPHIBOLITE FACIES METAMORPHIC ROCKS:

BASEMENT ZONE

PROTEROZOIC CRYSTALLINE BASEMENT AND LATE PROTEROZOIC - (?) CAMBRIAN COVER GNEISSES

GEOLOGIC CONTACT; MAPPED, COMPILED FROM PUBLISHED MAPS, ASSUMED

LOW - MODERATED ANGLE EOCENE NORMAL FAULT (PEGS ON HANGING WALL); MAPPED, ASSUMED, INFERRED

STEEP EOCENE NORMAL FAULT (PEGS ON HANGING WALL)

STEEP EOCENE NORMAL FAULT; SENSE OF DISPLACEMENT UNCERTAIN

**BF BEAVEN FAULT
CF CHERRYVILLE FAULT
CRF COLUMBIA RIVER FAULT
MD MONASHEE DECOLLEMENT
SSZ SLATE MOUNTAIN SHEAR ZONE**

Figure 1.7. Concordia diagram of SC1028 U-Pb zircon and monazite analyses (see text for interpretation).

Figure 1.8. Concordia diagram of SC855 U-Pb zircon analyses (see text for interpretation).

Figure 1.9. Concordia diagram of SC534 U-Pb zircon and monazite analyses (see text for interpretation).

Figure 1.10. Detail of SC534 concordia curve.

Figure 1.11. Concordia diagram of SC570 U-Pb zircon and monazite analyses (see text for interpretation).

Figure 1.12. Concordia diagram of SC951 U-Pb zircon and monazite analyses (see text for interpretation).

Figure 1.13. Concordia diagram of SC530 U-Pb zircon and monazite analyses (see text for interpretation).

Figure 1.14. Detail of SC530 concordia curve.

Figure 1.15. Concordia diagram of SC1122 U-Pb zircon and monazite analyses (see text for interpretation).

Plate 1.1. (a) Eastward view of the Empress marble on Mount Symonds. (b) Sillimanite porphyroblasts lie in the S2 foliation in Snow Mountain schist. (c) Westward view of F3 refolded by F2 in calc-silicate gneiss (Mcunt Fosthall). (d) Westward view of F3 hinge outlined by folded quartzo-feldspathic layers and sillimanite mats in pelitic schist.

Plate 1.2. Highly strained sillimanite bearing leucogranites (Zone A, Figure 4) within the hanging wall of the Monashee décollement. (a) Three generations of leucocratic intrusives with various degrees of strain postdate foliation and F1 fold in semi-pelitic paragneiss. The upper sill is mylonitic, the lower sill is a foliated and lineated protomylonite and dyke is undeformed (Slate Mountain). (b) Boudins of mylonitic leucogranite in semi-pelitic paragneiss (Mount Margie). (c) Leucogranite (SC1028) which occurs as stringers, porphyroclasts, pods and boudinaged sills is involved in sillimanite bearing mylonitic fabric (Mount Fosthall). Zircons from the sill are 62.1 ± 0.3 Ma. (d) Mylonitic migmatite (SC951) within interlayered psammite and semipelite of the Fawn Lake assemblage (Mount Margie). Zircons from the leucosome are 59.0 ± 0.3 Ma.

Plate 1.3. (a) Sillimanite bearing pegmatite (SC1122) folded by F2 fold in the immediate hanging wall of the Monashee décollement (Cariboo Alp). (b) 58.0 +/- 0.3 Ma undeformed pegmatite dyke crosscuts annealed mylonitic fabric of the Monashee décollement in Cariboo Alp. (c) Unannealed mylonitic fabric (Zone B) in deformed leucogranite is axial planar to folds in late-kinematic vein in the footwall of the Columbia River fault (Plant Creek). C- and S-fabrics and fold vergence indicate a sinistral or easterly directed shear sense. (d) Zone B fabric in unannealed mylonitic pegmatite in the footwall of the Columbia River fault (Plant Creek). C- and S-fabrics indicate a sinistral or easterly directed shear sense.

Plate 1.4. (a) Leucogranite sill has strongly developed lineation on the foliation surface typical of Zone C fabrics (Vidler Ridge). (b) Leucogranite cross-cuts foliation in the country rock but is itself foliated (Slate Mountain). (c) Undeformed post-tectonic coarse grained pegmatite with Zone D fabrics (Snow Mountain). (d) Westward view of weakly foliated sill of 54.3 +/- 0.5 Ma hornblende bearing granite (SC855) that crosscuts interlayered calcareous quartzite and thin marble of the Vidler calc-silicate gneiss (Pinnacles Peaks). North-verging asymmetric F2 folds are superimposed on F1 Z folds.

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CHAPTER 2

Geology of the Thor-Odin - Pinnacles area, southern Omineca Belt, British Columbia

Abstract

The present crustal architecture of the southern Omineca belt in the Canadian Cordillera is a product of Eocene extension and crustal thinning superimposed on a crust that was thickened and deformed during Paleozoic and Jurassic to Late Paleocene compression. Amphibolite-facies rocks exposed as gneiss complexes within the Shuswap metamorphic complex, in the southern Omineca belt, were buried during compression and were exhumed in the lower plates of low- to moderate-angle plastic-brittle Eocene extensional faults.

Polydeformed gneisses of the Thor-Odin - Pinnacles area, within the Shuswap complex, are bounded at the base by the Monashee décollement, a north-easterly directed Mesozoic - Paleocene thrust fault and are bounded at the top by crustal-scale Eocene normal faults; the Columbia River fault on the east and the Okanagan Valley - Eagle River normal fault system on the west. The metamorphic rocks host extensive plutons, stocks and sheets of the syn- and post-tectonic Late Paleocene - Early Eocene Ladybird granite suite. K-Ar hornblende and U-Pb zircon and titanite ages indicate that both metamorphic and igneous rocks were hot in the Paleocene and cooled rapidly in the early Tertiary; rapid cooling resulted from extensional denudation.

The metamorphic rocks within the Thor-Odin - Pinnacles area are divided into two tectonostratigraphic packages; the Fawn Lake assemblage which forms a 0-3 km wide belt in the immediate hanging wall of the Monashee décollement, and the Gold Range assemblage which extends over a >1200 km² area between the Fawn Lake assemblage and the Whatshan Batholith. The Fawn Lake assemblage is thought to be correlative with the semipelite - amphibolite division of the Horsethief Creek Group of the Upper Proterozoic Windermere Supergroup. It is bounded at the top by an unannealed Late

Paleocene or Early Eocene shear zone, the Slate Mountain shear zone, which cuts down section in the Fawn Lake assemblage from west to east and may be an extensional transfer zone related to the Columbia River normal fault.

The Gold Range assemblage is correlated with Cambrian to Jurassic stratigraphy of the Hamill Group, Badshot Formation, Lardeau Group, Milford Group, Kaslo Group, Marten conglomerate and Slocan Group. The southern part of the Gold Range assemblage is intruded by the potassium feldspar megacrystic hornblende bearing leucocratic Whatshan batholith. It is 77 Ma based on U-Pb zircon geochronology and is variably deformed; a well developed foliation and superposed folds in exposures near Lower Arrow Lake indicate that amphibolite-facies metamorphism and at least two phases of deformation must be Late Cretaceous or younger.

The predominant foliation (S2), northerly verging tight to isoclinal F2 folds and the northeasterly directed Monashee décollement formed progressively during D2 and are generally synchronous with the peak of metamorphism. Open to tight, westerly plunging F3 folds formed as metamorphic conditions were waning. A vergence reversal in F3 folds, that is coincident with the axis of a structural depression between Thor-Odin and Pinnacles culminations, is attributed to the wedge-like effect of underthrusting of blind thrust sheets imaged in LITHOPROBE seismic reflection data. The timing of the onset of compressional deformation is uncertain; however, U-Pb ages of deformed granitic rocks indicate that thrusting on the Monashee décollement and F3 folding were ongoing in the Late Cretaceous - Paleocene.

D2 and D3 structures are overprinted by a post-metamorphic D4 crenulation cleavage and by D5 broad open folds or warps. These structures may be coeval with crustal-scale plastic-brittle Eocene extensional faults. The Beaven fault, a normal fault on the west side of the Pinnacles culmination is a brittle +/- plastic structure that is interpreted to be the eastern continuation of the west-dipping and westerly directed

Okanagan Valley - Eagle River fault system and has been down-dropped by younger normal faults such as the Cherryville fault.

Introduction

The Mesozoic and early Tertiary tectonic history of the southern Canadian Cordillera includes accretion of outboard terranes to the western margin of ancient North America, protracted compression and crustal thickening, strike slip faulting and crustal extension (Monger et al. 1982; Gabrielse 1985; Brown et al. 1986; Parrish et al. 1988). The Omineca Belt, the metamorphic hinterland that lies west of the Foreland Belt (inset, Figure 2.1), consists predominantly of Late Proterozoic - Paleozoic rocks deposited on the North American margin and allochthonous Paleozoic-Mesozoic strata of the Intermontane Superterrane, the most inboard of the accreted superterranes, that were overthrust onto and imbricated with the North American rocks. These rocks were polydeformed and metamorphosed in the Middle Jurassic and Late Cretaceous - Paleocene and were intruded by Middle Jurassic, Late Cretaceous and early Tertiary plutonic suites.

The Shuswap metamorphic complex, in the southern Omineca Belt, was loosely defined as a complex of metamorphic rocks generally bounded by the sillimanite isograd (McMillan 1970; Reesor 1970) including rocks that had been referred to by earlier workers as the Shuswap series (Brock 1903, 1934; Daly 1915; Cairnes 1939; Jones 1959). Migmatites and gneisses within structural culminations of the Shuswap metamorphic complex, such as the Frenchman Cap, Thor-Odin, Valhalla and Pinnacles culminations, were referred to as core gneisses within gneiss domes, and were interpreted as mantled gneiss domes related to the upwelling of mobile cores (Reesor 1965; Wheeler 1965; Fyles 1970; Reesor and Moore 1971).

The high-grade culminations in the Shuswap metamorphic complex were reinterpreted as Cordilleran metamorphic core complexes by Coney (1980) and

Armstrong (1982) and the controversy arose as to whether these culminations were primarily compressional (Brown and Read 1983) or extensional structures (Davis and Coney 1979; Coney 1980). The idea that the obduction of accreted terranes and polyphase compressional deformation in the hinterland were *linked* with the progressive development of the Rocky Mountain Foreland Belt was key to our understanding of the tectonic evolution of the Omineca Belt and the southern Cordillera (Price and Mountjoy 1970; Price 1973; Brown and Read 1983). Compression and crustal thickening were initiated in the Middle Jurassic and continued into the Cretaceous and Early Tertiary resulting in an elevated crustal welt ~60 km thick in the hinterland (Price et al. 1985; Brown et al. 1986; and references therein). The importance of crustal-scale extensional tectonics in the southern Omineca and Intermontane belts was recognized (Parrish et al. 1988) following the identification of plastic-brittle shear zones that bounded the high-grade gneiss complexes and the documentation of their timing (Harms 1982; Parrish 1984; Parkinson 1985; Bardoux 1985; Price 1979, 1985; Carr 1986; Journeay and Brown 1986; Carr et al. 1987; Johnson 1988). It is now recognized that the structural culminations or gneiss complexes within the Shuswap complex were exhumed on low- to moderate-angle, plastic and/or brittle normal faults during Eocene crustal extension (Carr et al. 1987; Journeay and Brown 1986; Parrish et al. 1988), and that the present crustal geometry of the southern Omineca Belt and the map-view exposures of high-grade gneiss culminations within the Shuswap complex are a result of crustal-scale Eocene extension superimposed on a crust that was deformed and thickened during Jurassic to Paleocene compression (Figure 2.1; Coney and Harms 1984; Brown and Journeay 1987; Sonder et al. 1987; Parrish et al. 1988).

The present geology of the southern Omineca Belt at the latitude of the Thor-Odin - Pinnacles area can be described in terms of three crustal zones, herein called the Basement, Middle Crustal and Upper Crustal zones (Figure 2.1). The three zones experienced different deformation and thermal histories and were later juxtaposed by

crustal-scale shear zones. The Basement Zone, the deepest exposed structural level, is exposed as a tectonic window beneath the Middle Crustal Zone. The high-grade rocks of the Shuswap metamorphic complex form the Basement and Middle Crustal Zones, whereas surrounding rocks which are either unmetamorphosed or were metamorphosed in the Jurassic are part of the Upper Crustal Zone (Figure 2.1).

The Basement Zone is exposed in the Monashee complex and is bounded on the top by the Monashee décollement, a Mesozoic-Paleocene ductile thrust fault exposed on the flanks of the Monashee complex (Figures 2.1 and 2.2). In the Monashee complex, Basement Zone rocks consist of Proterozoic crystalline basement (Wanless and Reesor 1975; Parrish and Armstrong 1983), thought to be part of the North American craton (Armstrong 1988; Parrish and Ross 1989, 1990; Armstrong and van der Heyden 1989), overlain by Proterozoic- Cambrian (?) cover gneisses (Read 1980; Höy and Goodwin 1988; Parrish and Scammell 1988; Scammell and Brown 1990, and references therein) . The age of three phases of deformation that postdates the deposition of cover gneisses is uncertain; however, there is little evidence of penetrative Eocene extensional deformation within the Basement Zone.

The Middle Crustal Zone structurally overlies the Basement Zone in the hanging wall of the Monashee décollement and is exposed in structural culminations throughout the southern Omineca Belt (Kettle - Grand Forks, Okanagan, Priest River, Valhalla complexes; Figure 2.1). The Middle Crustal Zone comprises Proterozoic to Mesozoic amphibolite-facies rocks that were polydeformed during Mesozoic - early Tertiary compression, intruded by the Late Paleocene - Eocene Ladybird leucogranite suite and penetratively deformed by Eocene extensional strain. This zone is characterized by Late Cretaceous - early Tertiary ductile strain, plutonism and thermal quenching and is bounded at the top by crustal-scale normal faults (Columbia River - Standfast Creek, Granby, Greenwood, Kettle, Newport, Okanagan Valley - Eagle River, Purcell Trench, Slocan Lake - Valkyr fault systems).

The Upper Crustal Zone, in the hanging walls of the normal faults, preserves the Middle Jurassic compressional history of the orogen and has a Mesozoic plutonic and cooling history (Read and Wheeler 1976; Brown and Tippet 1978; Read 1979a; Okulitch 1979; Parrish and Wheeler 1983; R. L. Armstrong, unpublished data file, 1984; Archibald et al. 1983; Parrish et al. 1988, and references therein). During Eocene extension, rocks of the Upper Crustal Zone were either transported relatively passively on low- to moderate-angle normal faults or were dissected by brittle normal faults in domino style or listric arrays.

The Thor-Odin - Pinnacles area, in the Gold and Whatshan ranges between Arrow Lakes and the Okanagan Valley consists predominantly of Middle Crustal Zone rocks (Figure 2.1). The map area straddles the south flank of the Thor-Odin culmination, a second order domal structure within the Monashee complex (Reesor and Moore 1971), and encompasses the Pinnacles culmination, a smaller structural culmination in the southern part of the region (Reesor and Froese 1968, 1969; Read 1979a, 1979b), and the poorly exposed rocks of the structural depression between the two culminations. The Middle Crustal Zone rocks of the Thor-Odin - Pinnacles area lie in the hanging wall and are bounded at the base by the Monashee décollement. These rocks were exhumed and are bounded on the top by the outwardly-dipping Columbia River and Okanagan Valley - Eagle River fault systems (Figures 2.1 and 2.2). The focus of the study is the geology of the amphibolite-facies Middle Crustal Zone rocks in the Thor-Odin - Pinnacles area and the geometry, kinematics and timing of their internal and bounding structures. Problems that are addressed include the correlation of the metamorphic rocks in the region and the age of the deformation that occurred prior to Eocene extension.

Previous work includes the following (Figure 2.1). In the 1940's and 50's Jones (1959) mapped the Vernon 1:250,000 sheet and delineated high-grade gneisses of the Shuswap terrane, stratigraphy in low-grade and unmetamorphosed rocks, major boundaries, structural trends, faults and metamorphic breaks. Detailed mapping of

lithologic units and the concept of a mantled gneiss dome in Thor-Odin culmination was published by Reesor and Moore (1971), a fold in the Pinnacles area was described by Reesor and Froese (1968, 1969) and mapping was done on the eastern side of the area by Read and Wheeler (1976) as part of the Lardeau west-half map project. Basement and cover gneisses, the Columbia River fault, klippen of low-grade rocks and the southern part of the Beaven fault were mapped by Read (1979a, 1979b) and Read and Klepacki (1981). Duncan (1982, 1984) interpreted the evolution of Thor-Odin culmination in terms of fold interference. Parrish et al. (1988) presented geochronological and structural arguments that are consistent with exhumation of the complex in the Paleogene due to Eocene extension. Coleman (1979; 1990) documented the Monashee décollement on the western and southern flanks of Thor-Odin culmination.

Detailed mapping for this project was done along the major shear zones and faults that bound the area, on the southern flank of Thor-Odin and within a NE-SW trending corridor from Thor-Odin to Pinnacles (Map 1). Reconnaissance mapping was done in the Pinnacles area, west of Sugar Lake in the Buck Hills and Silver Hills and east of Vernon.

The purpose of this project is to study the geometry and timing of compressional and extensional structures and the relationships between them and to provide "ground truth" data to aid in the interpretation of the southern Canadian Cordilleran LITHOPROBE reflection seismic transect that crosses the area. The timing of compressional and extensional structures and their relative contributions to the uplift of the Monashee complex and the Middle Crustal Zone in the Thor-Odin - Pinnacles area are discussed in Chapters 1 and 3, respectively. This paper summarizes the results of 7 months of field work in the Thor-Odin - Pinnacles area that included mapping of lithology, structure, shear zones and granitic intrusions. Also presented in this paper are possible correlations of lithologic assemblages to strata recognized elsewhere, structural data and cross-sections of the region (Figure 2.3). The geological data are integrated with

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STANDARD REFERENCE MATERIAL 1010a
(ANSI and ISO TEST CHART No. 2)

LITHOPROBE seismic reflection data in a crustal-scale cross-section (Figure 2.4; see also Carr and Brown 1990; Brown et al. 1990).

General geology of the Thor-Odin - Pinnacles area and its bounding faults

Monashee complex (Basement Zone)

The Monashee complex, in the footwall of the Monashee décollement, contains the oldest exposed rocks in the southern Cordillera (Figure 2.1). Crystalline basement consists of paragneiss and granitoid orthogneiss (Plate 2.1a; Reesor and Moore 1971; Read 1979a, 1979b; Read and Klepacki 1981). The predominant paragneiss lithology is migmatitic biotite-quartz-feldspathic gneiss with minor pelitic schist, amphibolite and calcsilicate gneiss. Orthogneiss comprises biotite-hornblende-potassium feldspar augen granodiorite and biotite-quartz monzonite gneiss. Zircon data indicate an Early Proterozoic age for the basement rocks: ortho- and paragneiss in Frenchman Cap are 2061 ± 11 and 2007 ± 7 Ma (Parrish and Armstrong 1983), and the potassium feldspar orthogneiss from Thor-Odin is 1.96 Ga (Wanless and Reesor 1975). A paragneiss in Thor-Odin yields a seven-point Rb-Sr 2.8 ± 0.2 Ga "scatterchron" (Duncan 1978) and may reflect an Archean component. Some studies interpreted seismic refraction data to indicate that North American basement did not extend as far west as the Monashee complex, and they considered it a suspect terrane (Monger and Price 1979; Brown and Read 1983); however, comparative studies of U-Pb zircon ages of basement from subsurface drill core in Alberta and exposed basement in British Columbia (Parrish and Ross 1989; 1990) and deep crustal seismic reflection studies (Cook et al. 1987; Brown et al. 1990) support the view that basement rocks in the Monashee complex are part of the North American craton.

The basement rocks are unconformably overlain (Höy 1987, and references therein) by cover rocks, a sequence of predominantly stratified metamorphic rocks, that are

interpreted to have shallow water clastic and carbonate protoliths, and mafic volcanic rocks (Scammell and Brown 1990, and references therein). The cover rocks were thought to be Precambrian and/or Cambrian (Wheeler 1965; Höy and McMillan 1979; Brown and Psutka 1979; Read and Brown 1983). The ca. 740 Ma age of the Mount Copeland syenite, which intrudes the lower part of the sequence, is consistent with a Late Proterozoic age for part of the sequence (Parrish and Scammell 1988); however, a model Pb-isotope age on the stratiform Cottonbelt Pb-Zn deposit indicates that the cover rocks may be, in part, Cambrian (Höy and Goodwin 1988). Detrital zircon studies from cover gneisses predominantly indicate an Early Proterozoic source terrane (Parrish et al. 1987; Coleman 1990).

At least three phases of deformation postdate the deposition of cover on basement rocks (Wheeler 1965; Reesor and Moore 1971; Höy 1979; Read 1979a, 1979b; Brown and Psutka 1979; Read and Klepacki 1981; Duncan 1982, 1984; Journeay 1986). Nappes and low-angle thrusts (D1), which infold and imbricate cover and basement rocks at the map scale (Figure 2.1), are deformed by D2 pre- to syn-metamorphic folds and D3 post-metamorphic folds. In the Thor-Odin culmination, sillimanite-kyanite-melt bearing metamorphic mineral assemblages are in part synchronous with F2 folds and shearing on the Monashee décollement (Figure 2.5; Reesor and Moore 1971; Duncan 1982, 1984; Coleman 1990) and are interpreted as a relatively high-pressure (i.e. kyanite bearing) assemblage (Reesor and Moore 1971; Coleman 1990). The kyanite-sillimanite-melt assemblage is interpreted to have equilibrated at conditions in excess of 6.4 kb (bathozone 6, Carmichael 1978).

A Middle Jurassic age of early deformation and metamorphism of the Monashee complex has been proposed on the basis of correlation with timing of the deformation in the Selkirk allochthon and Kootenay Arc to the east (Brown 1980; Brown and Read 1983; Monger et al. 1986), although there is no direct evidence of this timing from within the Basement Zone itself. Middle Jurassic and Cretaceous - early Tertiary

orogenic phases were proposed by Journeay (1986) and Brown and Journeay (1987) to explain structural and metamorphic relationships in Frenchman Cap. Addressing this problem, hornblende $^{40}\text{Ar}/^{39}\text{Ar}$ data and U-Pb dating of metamorphic zircons have resulted in Late Cretaceous and Paleocene ages (Journeay and Archibald, unpublished data 1985 cited in Journeay, 1986; Parrish and Scammell 1988; Journeay and Parrish 1989).

Monashee décollement

The Monashee décollement, exposed on the margins of the Monashee complex, is a westerly-rooting deep-seated ductile shear zone with northeasterly directed thrust motion and ~100 km of proposed displacement (Brown 1980; Read and Brown 1981; Duncan 1984; Journeay 1986; Scammell 1986; Journeay and Brown 1986; Coleman 1989; Johnson 1990; Brown et al. 1990). It is arched over the Monashee complex and truncated on the eastern margin by the Columbia River normal fault (Wheeler 1965; Read 1979a, 1979b; Read and Brown 1981; Lane 1984, Lane et al. 1989). The Cariboo duplex is a lozenge of fault-bounded slices of basement and supracrustal gneisses on the southwest flank of Thor-Odin culmination (Map 1; Plate 2.1b; Coleman 1989, 1990).

There is evidence from the northwestern flank of Frenchman Cap that the shear zone had a protracted movement history that included a two-stage syn-metamorphic movement history; syn-kinematic low-pressure metamorphic assemblages overprint high-pressure syn-kinematic peak assemblages (Brown 1980; Journeay 1986; Scammell 1986; Journeay and Brown 1986). On the basis of regional arguments, it is likely that there was displacement prior to the metamorphic peak. In contrast to Frenchman Cap, in Thor-Odin culmination there is evidence of shearing during the culmination of regional deformation and metamorphism; however, there is no clear evidence of either a pre-metamorphic movement history or of a low-pressure reactivation of the Monashee décollement (Coleman 1989, 1990). Sillimanite - potassium feldspar - melt equilibrium

assemblages in the hangingwall (Middle Crustal Zone) are juxtaposed against peak sillimanite-kyanite-melt bearing assemblages in the footwall Basement Zone (Figure 2.5). There is no pressure or temperature data from the hanging wall; however, the hanging wall was apparently at higher temperatures than the footwall (Coleman 1990).

Middle Crustal Zone

Metamorphic rocks in the Middle Crustal Zone were polydeformed at generally high grade. The sillimanite - potassium feldspar isograd was mapped within the area (Reesor and Moore 1971; this study, Figure 2.5), and granite melt was found to be in equilibrium with the sillimanite - potassium feldspar bearing mineral assemblage within this zone. This zone is coincident with extensive leucogranite plutons, stocks, sheets and pegmatite stockwork, known to be part of the Late Paleocene - Eocene Ladybird suite (Carr, Chapter 1).

Two fault bounded tectonostratigraphic packages were identified in this study, the Fawn Lake and Gold Range assemblages (Figures 2.2 and Table 2.1). They lie in the hanging wall of the Monashee décollement, in the Middle Crustal Zone. The Fawn Lake assemblage consists of migmatitic semipelitic and psammitic paragneiss and amphibolite gneiss with concordant and cross-cutting early Tertiary Ladybird pegmatite. It is exposed in a narrow belt on the southern flank of Thor-Odin (Figure 2.1 and Map 1). The top of the Fawn Lake assemblage is an unannealed strain zone, herein named the Slate Mountain shear zone, which is apparently responsible for structural thinning and stratigraphic omission (Map 1). The nature and westward extent of the shear zone is uncertain and is discussed further on page 117. The Fawn Lake assemblage is probably correlative with the semipelite-amphibolite division of the Horseshoe Creek Group (see page 94 for details of correlation).

The Gold Range assemblage, in the hanging wall of the Slate Mountain shear zone, is exposed from Mt. Symonds and Mount Fosthall in the north to the Whatshan batholith

and Scalping Knife Mountain in the south (Figure 2.1). The map units within the Gold Range assemblage are repeated by a series of map-scale F3 folds (Figure 2.3). The Gold Range assemblage is a minimum of 7 km thick (excluding Ladybird granite) and is probably correlative with early Paleozoic to Early Jurassic stratigraphy (Table 2.1). The metamorphic rocks of the Gold Range assemblage are intruded by a substantial volume of Late Paleocene - Eocene Ladybird leucogranite plutons, sheets, stocks and pegmatite, including the South Fosthall pluton (Figure 2.1; Map 1).

Upper Crustal Zone

Rocks of the Upper Crustal Zone are exposed in the southern Omineca and Intermontane belts (inset, Figure 2.1) east of the trace of the Columbia River fault in the Selkirk Mountains and Kootenay Arc, in irregular shaped klippen and salients between the Columbia and Okanagan Valleys, and west of the trace of Okanagan Valley - Eagle River fault system (Figure 2.1). The Upper Crustal Zone comprises Proterozoic-Paleozoic rocks that were tectonically emplaced on the western margin of North America and Paleozoic - Upper Triassic strata that were deposited on attenuated continental crust or in basinal and/or arc settings, and were obducted on and imbricated with North American strata in the Middle Jurassic.

Early Proterozoic to Cambrian clastic strata of Belt-Purcell and Windermere supergroups and shallow water Cambrian clastic and carbonate strata of the Hamill Group and Badshot Formation were deposited on the western margin of ancient North America (Price 1981, and references therein). In the Selkirk Mountains, the Cambrian-Ordovician Lardeau Group overlies, in part conformably, the Badshot Formation, and consists of clastic and carbonate strata and volcanic rocks. A talc bearing schist in association with disrupted and sheared rocks in the lower Lardeau Group (Zwanzig 1973; Sears 1979) has been interpreted as a Paleozoic tectonic boundary (Gehrels and Smith 1987). The Lardeau Group is unconformably overlain by and stratigraphically linked to

the Upper Mississippian - Pennsylvanian Milford Group (Read and Wheeler 1976; Klepacki 1985). The Milford Group comprises three assemblages, the Davis, Keen Creek and McHardy assemblages (Figure 2.6). During the Permian event, the McHardy assemblage was juxtaposed with Permian volcanics, chert and ultramafics of the Kaslo Group. These rocks were overlain by Triassic clastic rocks of the Slocan Group and the Milford and younger rocks were collapsed and shortened during Middle Jurassic thrusting (Klepacki 1985).

The Lardeau Group, Davis assemblage and Keen Creek assemblage comprise the Kootenay terrane and are thought to have been deposited on attenuated continental crust (Klepacki 1985). The McHardy assemblage and Kaslo Group are part of the Slide Mountain assemblage deposited in a marginal basin. The Slocan Group is part of Quesnellia thought to have been deposited on the Slide Mountain terrane (Price et al. 1985).

Within the study area, Paleozoic and early Mesozoic strata are intruded by a Jurassic igneous suite which includes the Nelson and Kuskanax batholiths in the Kootenay Arc (Little 1959, 1960, 1961; Nguyen et al. 1968; Duncan et al. 1979; Parrish and Wheeler 1983; Parrish and Armstrong 1987; Parrish et al. 1988) and the Spruce Grove batholith on the Monashee Highway (Appendix 2.1). The timing of obduction and associated compressional deformation is bracketed by the youngest allochthonous strata, which are Toarcian (Tipper 1984), and ca. 170 Ma Middle Jurassic plutons which cut across structures and isograds (Read and Wheeler 1976; Parrish and Armstrong 1983).

West of the Okanagan Valley - Eagle River fault system the Upper Crustal Zone mainly comprises the Early Cambrian - Mississippian Eagle Bay assemblage and Fennel Formation (Schiarizza and Preto 1987;) and (?) Paleozoic Mount Ida Group. These stratified rocks are intruded, in part, by Devonian and Cretaceous plutons. Mainly Mesozoic strata of the Upper Triassic Nicola and Slocan groups and Upper Triassic -

Lower Jurassic Nicola and Rossland groups (Okulitch 1979) outcrop in the klippe and salients between Pinnacles and the Okanagan Valley.

Contrasting timing of deformation and cooling histories of the Upper and Middle Crustal zones

The timing of peak metamorphism, compressional deformation and regional cooling of the Middle and Upper Crustal zones, which are separated by normal faults, is very different. Metamorphism and contractional polydeformation in the Upper Crustal Zone is primarily Middle Jurassic whereas high-grade Late Cretaceous - Paleocene compressional structures in the Middle Crustal Zone transposed and overprinted older structures. The ca. 163 Ma Galena Bay stock (Parrish and Armstrong 1987) and the ca. 173 Ma Kuskanax batholith crosscut isograds in the hanging wall of the Columbia River fault placing a minimum age of Middle Jurassic on the metamorphism in the Upper Crustal Zone (Read and Wheeler 1976; Read and Brown 1981; Parrish and Wheeler 1983; Parrish et al. 1988). This is consistent with observations further north in the Selkirk Mountains (Brown and Tippet 1978) and further east in the Kootenay Arc (Archibald et al. 1983). In contrast, the Middle Crustal Zone was hot in the early Tertiary. This is evident because Late Paleocene Ladybird intrusives were deformed in shear zones and were folded at sillimanite grade (Carr, Chapter 1), metamorphic zircon and titanite U-Pb dates from the region are Late Paleocene - Eocene (Figure 2.7 and Appendix 2.2) and 62-55 Ma intrusions and pegmatites (Carr, Chapter 1) are variably deformed and do not impose contact metamorphism on country rocks.

A compilation of K-Ar and Rb-Sr mineral dates and limited $^{40}\text{Ar}/^{39}\text{Ar}$ analyses reveal that the Upper Crustal Zone and Middle Crustal Zone have different cooling histories (Figure 2.7, Tables 2.2 and 2.3; Baadsgaard et al. 1961; Mathews 1981; Parrish et al. 1988). Except for very localized areas, mainly related to Eocene intrusions, the Upper Crustal zone cooled during the Mesozoic whereas the Middle Crustal Zone cooled during the early Tertiary.

Columbia River fault system

The trace of the east-dipping Columbia River normal fault extends north-south for about 200 km and bounds the eastern margin of the Monashee complex and the Thor-Odin - Pinnacles area (Figures 2.1 and 2.2; Jones 1959; Campbell 1971; Read and Wheeler 1976; Read 1979a; Brown and Murphy 1981; Lane 1984; Parrish and Armstrong 1987). The fault appears to die out north of Frenchman Cap (Figure 2.1). Adjacent to the Thor-Odin - Pinnacles area, the fault is a plastic-brittle shear zone (Parrish et al. 1988); in the footwall, biotite +/- chlorite grade mylonites (Plate 2.1c) are overprinted by brittle fabrics and are juxtaposed against rocks with brittle fabrics in the hanging wall. The fault is a corrugated surface with irregular grooves, flats and ramps; however, regionally the fault dips 30° to the east. Displacement is estimated on the order of 20-30 km (Read 1979b; Parrish et al. 1988). In the vicinity of Revelstoke, the fault is predominantly brittle (Lane 1984; Lane et al. 1989) and it has been suggested that at this latitude plastic displacement was accommodated by structures further east (Parrish et al. 1988; Figure 2.1). The south end of the Columbia River fault has not been mapped south of Scalping Knife Mountain. It was originally shown to be cut by the Cariboo Creek stock (Hyndman 1968), which is now known to be older than the fault. Parrish et al. (1988) inferred that it died out on the northwest flank of the Valhalla complex within the Cariboo Creek stock (Figure 2.1); however, mapping and structural data from this study (Map 1) suggest that it may continue further south, either as one fault or as a number of splays, allowing reconstructions of known geological relationships between the west flank of Valhalla complex and Arrow Lake.

The Eocene age of the Columbia River fault is constrained by fabric relationships and geochronology of the South Fosthall pluton (Figure 2.1). The pluton, which has an igneous fabric on the west side of the region, is transposed into a mylonitic sheet in the footwall of the Columbia River fault (Plate 2.1c). The U/Pb dates (55 +/- 1.5 and 55 +/-

1.0 Ma) and Rb-Sr dates of syn-kinematic muscovite (53.0 $\pm$ 0.8, 56.0 $\pm$ 0.9 and 59.7 $\pm$ 1.2 Ma) indicate that the fault was active in the Early Eocene (Parrish et al. 1988).

Okanagan Valley - Eagle River fault system

The Okanagan Valley - Eagle River fault system (Parkinson 1985; Bardoux 1985; Parrish et al. 1985; Journeay and Brown 1986; Johnson 1988) is a low-angle, west-dipping, plastic-brittle shear zone with a strike length of ~ 300 km (Figures 2.1 and 2.2). In the Vernon area, high-grade footwall mylonites are well exposed on the highway near Swan Lake. Structure contouring of the fault surface in the Vernon area indicates that the fault is locally an irregular surface which regionally dips 8-25° to the west (this study, Map 1; Figure 2.1). A penetratively deformed 52 Ma rhomb porphyry dyke (Parkinson 1985) and a penetratively deformed 47 Ma leucocratic sill (Parrish et al. 1985) in the footwall of the fault, in the southern Okanagan valley, indicate that a substantial amount of ductile motion on the fault is Middle Eocene or younger (Parrish et al. 1988). This is in contrast to the easterly-directed fault systems (Valkyr - Slocan Lake, Kettle, Columbia River fault systems) which are primarily Early Eocene (Parrish et al. 1988).

The Beaven - Cherryville fault system

The Beaven fault is a northwest-trending normal fault that dips ~45° to the west and bounds the western side of Pinnacles culmination (Figure 2.1). It is interpreted as the most easterly exposed continuation of the Okanagan Valley fault system. It was initially identified and mapped, in part, by Jones (1959) and Read (1979a, 1979b). Reesor (1970) interpreted it as a sharp metamorphic transition. The Beaven fault, as mapped in this study, is a predominantly brittle structure and is exposed on the ridges west of the Pinnacles culmination, on the Outlet and Cherry Creek logging roads and on Vidler Ridge (Plate 2.1d). On Vidler Ridge the cataclastic zone is ~60 m wide. Twenty kilometres to the south, on the west side of Pinnacles Peaks near Railroad Creek (Map 1),

a horse of plastically deformed mylonitized footwall-rocks within the fault zone are juxtaposed against the highest-grade (garnet-staurolite-kyanite) rocks found in the hanging wall (Figure 2.5), indicating that deeper levels of the fault are exhumed in the south. The Beaven fault has been mapped for ~ 30 km and further mapping southwest of Pinnacles is required to delineate the southern extent of the fault. It probably continues southward and separates adjacent belts of rocks with contrasting thermal histories (Figures 2.2 and 2.5). The Late Cretaceous Whatshan batholith and Eocene Ladybird granite plutons, with Late Cretaceous and Early Tertiary mineral cooling ages, respectively, are inferred to be in fault contact with the Middle Jurassic Spruce Grove batholith (part of the Nelson suite) which has a Middle Jurassic cooling history (Figure 2.7 and Appendix 2.1).

The Cherryville fault, first mapped by Jones (1959) extends along the Shuswap River valley for ~ 20 km and is unexposed. It is inferred on the basis of the juxtaposition of sillimanite and Ladybird granite bearing rocks against chlorite-grade rocks near the river valley and on the west flank of Vidler Ridge (Figure 2.5). Jones (1959) continued the trace of the fault northward along Sugar Lake; however, mapping both shorelines at low water precludes this interpretation because east-west trending map units and structures match on both sides of the lake (Maps 1). The magnitude of the dip of the Cherryville fault is not certain but is inferred to be steep.

The Beaven and Cherryville faults dip towards each other and intersect at their northern ends on Vidler Ridge, resulting in a salient of greenschist-facies rocks surrounded on three sides by amphibolite-facies gneiss and schist (Figure 2.1). Footwall rocks consist of sillimanite +/- staurolite +/- muscovite bearing gneiss and schist intruded by Ladybird leucogranite and pegmatite. The hanging wall is primarily composed of cleaved and folded shale, chlorite +/- biotite bearing fine-grained schist, minor limestone and sandstone, intermediate to mafic volcanic rocks and augite porphyry (Plate 2.1e). These rocks are correlated with the Upper Triassic Slocan Group (Jones 1959; Read

1979a; Okulitch 1979) and possibly the Lower Jurassic Rossland Group. The metamorphic grade is generally low; however, garnet, staurolite and kyanite occur in fine-grained medium-grade schists in the immediate hanging wall of the Beaven fault, west of Pinnacles (Figure 2.5).

The Cherryville fault is interpreted as a steep fault that cuts the Beaven fault and the spoon-shaped, low-grade hanging wall salient is a shallow feature (Carr and Brown 1989). This is consistent with relationships further to the west (Figure 2.1) and implies that the Beaven fault is part of the westerly directed Okanagan valley fault system. This interpretation is also consistent with LITHOPROBE seismic reflection data since no surface features in this vicinity can be traced to depth in lines 9 and 10 (Carr and Brown 1990; Cook et al. 1990).

Normal faults between Pinnacles and Vernon

Unmetamorphosed rocks and low- to medium-grade rocks are exposed as irregular shaped klippen between the Pinnacles culmination and the Okanagan valley (Carr and Brown 1989; Plate 2.1e, Figure 2.1). This includes rocks in the hanging walls of the Beaven-Cherryville faults. The klippen comprise upper Paleozoic to Early Jurassic strata, Middle Jurassic granodiorite and Tertiary volcanic and sedimentary rocks of the Upper Crustal Zone (Okulitch 1979). They are juxtaposed against underlying medium- and high-grade rocks along generally flat lying plastic-brittle and brittle detachment faults (Carr and Brown 1989). These flat lying faults, which are dissected and disrupted by younger steep normal faults, are thought to be part of the Okanagan Valley fault which has been down dropped and dissected by younger steep normal faults (Figure 2.1). This interpretation is based on reconnaissance observations of the flat lying detachment in the Trinity Hills and in the Buck Hills southeast of Vernon, the contrast between metamorphic assemblages and stratigraphy of Middle Crustal Zone footwall and Upper Crustal Zone hanging-wall rocks and the recognition of Ladybird granite with westerly-

directed mylonitic fabrics in the footwall. This interpretation is consistent with mapping and stratigraphic designations made by Jones (1959) and Okulitch (1979). Structure contours of the detachment surface indicates that it is generally flat lying with shallow dips and greatly variable strike.

Unfortunately the area between Pinnacles and the Okanagan valley is in part very poorly exposed; however, the interpretation of a flat lying detachment (Okanagan fault) can be tested by further mapping and by K-Ar and Rb-Sr mineral dating. Hanging-wall rocks should record a Mesozoic cooling history, whereas footwall rocks should record an Early Tertiary cooling history.

Although the palaeogeographic reconstruction of the active Okanagan valley fault is uncertain, the magnitude of displacement appears to be bracketed between 30 and 65 km and is less than the 90 km proposed by Tempelman-Kluit and Parkinson (1986). Near the Okanagan valley, unmetamorphosed and low-grade rocks in the hanging wall are juxtaposed against sillimanite-muscovite and hornblende bearing mylonitic gneisses in the footwall. Further to the east near Sugar Lake, the footwall is predominantly brittle and comprises medium-grade staurolite +/- sillimanite bearing rocks. These associations can be used to infer that the Okanagan fault is cutting "upgrade" and thus possibly "upsection" from west to the east.

Stratigraphy and igneous rocks of the Thor-Odin - Pinnacles area

The rocks of the Thor-Odin - Pinnacles area consist of a diverse variety of lithologies. The Fawn Lake assemblage is the lowest exposed package above the Monashee décollement, and is separated from the Gold Range assemblage by the Slate Mountain shear zone. Within the Gold Range assemblage, eight lithological subdivisions have been recognized, along with a variety of igneous lithologies which range in age from Jurassic to Eocene. All of these rocks are described below. Their proposed

stratigraphic correlations are summarized in Table 2.1 and their distribution is shown on Map 1.

The Fawn Lake assemblage

A well exposed panel of rusty-coloured, flaggy-weathering migmatitic sillimanite-garnet-biotite - quartzo-feldspathic paragneiss and amphibolite gneiss (Plates 2.2a and 2.2b) is a minimum of 1700 m thick and is generally equivalent to units M1 and M2 of Reesor and Moore (1971). The paragneiss has interlayers of quartzite, calcsilicate gneiss and pelitic schist, and an olivine-orthopyroxene-clinopyroxene bearing ultramafic pod was mapped within the unit on Slate Mountain. Relative to similar lithologies in the Gold Range assemblage, these paragneisses are Al-poor, particularly in the upper part of the unit. Approximately 15-30% leucocratic pegmatite of the Ladybird suite is present as concordant layers, boudins and cross-cutting dykes on the southern flank of Thor-Odin culmination. On the west flank, west of Slate Mountain, pegmatite is the predominant rock type.

A striking characteristic of the Fawn Lake assemblage is that all layers are concordant (Plates 2.2a and 2.2b), the limbs of folds are transposed into near parallelism with the axial planar foliation. This is interpreted as a high strain zone that formed during movement on the Monashee décollement (see section on deformation, page 109). Minerals are annealed but the stretching lineation is well preserved. The Fawn Lake assemblage is structurally thinned and, in part, completely omitted on the southeast flank of Thor-Odin, probably due to Eocene extensional shearing (Map 1).

The Fawn Lake assemblage is lithologically similar to the semipelite-amphibolite (SPA) division of the Proterozoic Horsethief Creek Group north of the Monashee complex (Poulton and Sinony 1980; Raeside and Simony 1983; Pell and Simony 1987). The assemblage is generally on strike with migmatitic paragneisses of the Shuswap assemblage in the Hunters Range (Johnson 1988, 1990) which have also been correlated with the SPA division and it is at the same structural level, in the immediate hanging wall

of the Monashee décollement, as rocks further north that are correlated with Windermere stratigraphy (Harrap 1990; Journeay 1986; Scammell 1986, 1990). If the Fawn Lake assemblage is the SPA division, then there is substantial structural and/or depositional stratigraphic omission above and below the section. The implications of this are discussed on page 118.

The Gold Range assemblage

The Gold Range assemblage corresponds to map units M3-M8 of Reesor and Moore (1971) who mapped out units such as quartzites, marbles, calcsilicate schists and amphibolite gneisses (M3 and M6-M8) within a heterogeneous schist and gneiss package (M5). Correlations by Reesor and Moore (1971, p. 113) were made prior to the recognition of the Columbia River fault and were in part based on rocks now known to be in the hanging wall of this structure. They interpreted the Basement Zone (Monashee complex) as Windermere Supergroup, the Fawn Lake assemblage as Cambrian Hamill - Badshot and the Gold Range assemblage as Lardeau Group.

In this study, map units within the Gold Range assemblage consist of eight regionally persistent lithologic packages or marker units (Table 2.1, Map 1 and Figure 2.3) which are recognized throughout the Thor-Odin area. There is continuous exposure of all units in the alpine along a NE-SW corridor from Thor-Odin culmination to the northwest part of Pinnacles culmination except for the central part of the Mount Fosthall composite unit designated as unit 7 on Map 1. The lower and upper sections, units 7a and 7b respectively, are isolated by areas with no exposure in glacial till and tree covered valleys (Map 1). Therefore the division between members 7a and 7b of the Mount Fosthall unit, as shown on Map 1 and Figure 2.3, was assigned arbitrarily.

Some areas below treeline, particularly along the east side of the area, are very poorly exposed. The most resistant lithologies such as amphibolite gneiss, quartzofeldspathic gneiss and pegmatite outcrop almost exclusively and are generally not representative or diagnostic of the section; however, rocks in these areas are assigned to

map units wherever possible. Areas which could not be assigned to map units or that were not mapped in this study are designated as unit 12, are labelled according to the lithology (this study; Read 1979a) and are not assigned to the map units described below.

Most of the rocks of the Gold Range assemblage are migmatitic with pods and layers of leucocratic quartzo-feldspathic material, granite and pegmatite and are intruded by Ladybird granite and pegmatite, particularly in areas within the sillimanite - potassium feldspar zone (Figures 2.2 and 2.5). The notable exceptions to this include rocks on Vidler Ridge and Snow Mountain on the west side of the area and Whatshan Peak, and Scalping Knife Mountain in the south; however, these regions are intruded by dykes and stocks of Ladybird granite.

The Gold Range assemblage is tentatively correlated with Paleozoic to Mesozoic strata of the Kootenay Arc (Table 2.1). One should bear in mind that the rocks are now at generally high metamorphic grade and early folds and structures which may duplicate or omit stratigraphy are overprinted by younger structures and there has been structural thinning and thickening of units. The question of detailed correlation needs to be further addressed by characterizing the geochemistry, isotopic signatures and provenance of the units. The apparent thickness of the units are shown on Figure 2.3. However, the distinctiveness of the overall section, including conglomerate, marbles and ultramafic rocks, is sufficiently similar to units within the Kootenay Arc that the overall correlation of the *package* is nearly certain.

Symonds quartzite bearing unit

The basal map unit of the Gold Range assemblage is a heterogeneous package of interlayered quartzite, rusty weathering semipelitic to psammitic gneiss and amphibolite gneiss with minor pelitic schist, calcsilicate schist and marble (Plates 2.2c, 2.2d and 2.3a). It is well exposed as an east-west trending belt on the south flank of the Thor-Odin culmination on Slate Mountain (Map 1). It is recognized by its heterogeneity and because of its position between the distinctive Fawn Lake assemblage and the Empress marble.

In the central part of the area on the north flank of Mount Fosthall, the layers are repeated by tight F2 folds similar to the Ledge antiform described by Höy (1977a) on Mount Symonds (Figure 2.3). A large unmapped closure is visible on the northwest flank of Mount Fosthall (Map 1 and Figure 2.3). In the eastern part of the area, on Mount Symonds, the stratigraphy is highly attenuated and thinned; this probably occurred during Eocene extension related to motion on the Columbia River fault.

The pyrrhotite, pyrite and sphalerite bearing Big Ledge deposit is hosted in a graphitic calcareous schist in the upper part of the unit on Mount Symonds, and was traced for ~10 km along strike (Abraham 1967; Höy 1977b). Duncan (1982) analysed Pb isotopes and assigned a Cambrian age on the basis of model Pb ages and an interpretation that the mineralization is stratabound and syndepositional. Höy (1977a) correlated strata of the Symonds quartzite bearing unit with the Lower Cambrian Mohican Formation on the basis of lithologic similarity and the presence of Pb-Zn deposits, which are commonly found in Cambrian carbonate rocks in the Omineca Belt.

Empress marble

The Empress marble is a 30-80 m thick marble marker that extends from Mount Symonds westward across the north flank of Mount Fosthall (Map 1, Figure 2.3 and Plate 2.3b). In places, the marble bifurcates into two layers with intervening calcsilicate schist. The predominant lithology is a coarse-grained phlogophite graphite calcite marble which may also contain titanite, apatite, diopside, tremolite and/or dolomite. Thin quartzofeldspathic lenses are common. The marble is generally coarse-grained; however, on Mount Fosthall fine-grained unannealed fabrics are preserved (Plate 2.3b). Marble markers on the east side of the area near Arrow Park lakes and north of Saddle Mountain (Map 1) are tentatively correlated with the Empress marble on the basis of structural interpretations (Figure 2.3) and similarities of overlying strata.

Höy (1977a) correlated the Empress marble with the Lower Cambrian Badshot Formation of the Kootenay Arc on the basis of its lithologic similarity.

Mount Fosthall composite unit

This map unit is the most widespread unit in the Mount Fosthall 1:50,000 map area (82 L/8) and is well exposed in the vicinity of Mount Fosthall. It is divided into two members although the division between the two members is arbitrarily assigned because the units are gradational and the central part of the map unit is poorly exposed.

Calcsilicate-pelite-amphibolite-ultramafic member. The Empress marble is overlain by a sequence of migmatitic calcsilicate schists and gneisses interlayered with amphibolite gneiss and migmatitic pelitic schist (Plates 2.3c and 2.3d). Minor marble, quartzite and rusty psammitic gneiss interlayers from 0.5-5 m thick occur throughout the section and there is one ultramafic marker horizon (Plate 2.4a). The calcsilicates are green and purple weathering, with graphite, biotite, and diopside. Marbles are brown weathering and have the same variety of mineralogy as the Empress marble. The phlogophite-orthopyroxene-clinopyroxene-tremolite-olivine-calcite bearing ultramafic gneiss occurs as boudinaged layers, blocks and pods at a particular stratigraphic level near Mount Fosthall, Mount Symonds, Twin Peaks, Goat Mountain, Sitkum Plateau, Plant Creek and east of Mabel Lake (Map 1). The primary nature of the ultramafic is not certain as the S2 foliation, F2 and F3 folds and the intrusion of granite and pegmatite obscure primary contact relationships (Plate 2.4a); however, on Mount Symonds the ultramafic appears to be a block in a tectonic melange. This map unit apparently trends westward and is probably correlative with metamorphic rocks and ultramafic pods that were mapped on the east side of the Okanagan Valley, north of Vernon (Okulitch 1979).

Duncan (1982 pp. 15, 200; 1984 pp. 92, 103, 116) shows post-metamorphic faults that postdate folding, truncate layering and coincide with the horizon which bears the ultramafic pods, although he does not present evidence for these post D2 faults. Detailed mapping in the vicinity of the ultramafic pods failed to reveal any evidence for post D2 faults. A band of calcsilicate, amphibolite and pelitic schist with ultramafic pods was

mapped for ~8 km along strike from the north flank of Mount Fosthall and to the south flank of Mount Symonds and a fault was not observed (Map 1). The ultramafic pods on the south flank of Mount Symonds are associated with amphibolite gneiss and occur in the hinge of a km-scale F3 second order fold closure; all layers are folded and no evidence of a post-metamorphic discordant fault was found at this locale. On this basis the faults on Duncan's map that were subsequently compiled by Read (1979a) have been deleted from Map 1. The presence of the ultramafics and their boudinaged nature supports the view that this horizon could represent a suture; however, any shearing along this zone must be pre-metamorphic. A structure, assumed to be a thrust, is interpreted as being parallel to the ultramafics and folded with the enclosing layering.

The lower member of the Mount Fosthall composite unit is correlated with the Cambrian and Ordovician Lardeau Group on the basis of lithologic similarity, as suggested by Höy (1977a), since there are many similarities with the Lardeau Group as described by Fyles and Eastwood (1962), Fyles (1964) and Read (1973). The ultramafic boudins within the South Fosthall unit could be the high-grade equivalent of talc schists described by Sears (1979) and Zwanzig (1973) in the Selkirk mountains which occur in association with sheared calcareous graphitic phyllites, discontinuous marbles and quartzites in the Lardeau Group. The sheared rocks, which in places occur in association with talc bearing schists, are evident on a regional scale and have been interpreted as part of a Paleozoic thrust system (Gehrels and Smith 1987).

Psammite - semipelite member. The upper member of the Mount Fosthall composite unit comprises semipelitic and psammitic paragneiss, siliceous quartzo-feldspathic gneiss with calcsilicate pods (strained interlayered sandstone and carbonate or conglomerate), hornblende bearing quartzo-feldspathic gneiss (metamorphosed greywackes) and calcsilicate gneiss, with marble, quartzite and amphibolite gneiss interlayers. This member is distinguished from underlying rocks by the large proportion of semipelitic and

psammitic gneisses and lack of pelitic schists. No ultramafic rocks have been recognized in this subdivision.

Rusty weathering quartzo-feldspathic gneisses with amphibolite gneiss interlayers underlie the Vidler calcsilicate gneiss on Sugar, Scalping Knife and Saddle mountains and in the headwaters of Plant Creek, and they are thought to be part of this unit (Map 1).

The Mount Fosthall composite gneiss unit is probably correlative with part of the Cambrian and Ordovician Lardeau Group and the overlying Upper Mississippian to Lower Pennsylvanian Milford Group which consists of siliceous argillite, sandstone, limestone and volcanic rocks (Figure 2.6; Read and Wheeler 1976; Read 1973; Reesor 1973; Klepacki 1983, 1985; Klepacki and Wheeler 1985).

Vidler calcsilicate gneiss

The calcsilicate gneiss is well exposed on Vidler Ridge, Scalping Knife Mountain, Saddle Mountain and in Pinnacles peaks (Plate 2.4b and Figure 2.2). It is a white- to buff-weathering quartzite with varying amounts of calcite and diopside and marble interlayers at all scales. The calcite weathers out giving it a distinctive texture; it was described by Jones (1959) as "the pitted quartzite". The Vidler calcsilicate has rare amphibolite and semipelitic schist interlayers. One 2-10 m wide psammitic cobble conglomerate within a calcareous quartzite horizon was observed near the top of the section on Vidler Ridge. This unit may be equivalent to the conglomerate bearing siliceous argillite member of the McHardy assemblage of the Milford Group (Figure 2.6) as described by Klepacki (1985).

Outlet Creek ultramafic bearing unit

A sequence of interlayered amphibolite gneiss, rusty weathering hornblende bearing semipelitic schist, psammitic schist and pelitic sillimanite +/- staurolite schist hosts pods and layers of phlogophite-tremolite-pyroxene-olivine-calcite bearing ultramafic rocks. The ultramafic rocks occur as a 40 x 100 m pod southeast of Vidler Ridge (Plate 2.4c)

and as a 15-20 m wide layer on Scalping Knife Mountain, which can be traced for hundreds of metres and appears to stay at the same stratigraphic position relative to enclosing rocks (Map 1). Major phases include olivine, anthophyllite and enstatite.

This unit is probably correlative with the ultramafic bearing succession at Nemo Lakes ~30 km east of Scalping Knife Mountain and north of the Valhalla complex (Parrish 1981) and may be part of the Lower Permian Kaslo Group (Figure 2.6; Klepacki 1985). The ultramafics probably represent bodies of metamorphosed serpentinite. If they represent the tectonic base of the thrust Quesnellia terrane (Figure 2.6; Klepacki 1985), any structural evidence for such a Jurassic and pre-metamorphic boundary has been obliterated by younger deformation.

Mount Mafic amphibolite gneiss

A hornblende amphibolite gneiss pod was mapped for a strike length of 6 km near the headwaters of Cherry and Cusson creeks (Map 1). The discontinuous nature of the unit may be primary or structural. It is predominantly a foliated and lineated hornblende +/- biotite gneiss, and some horizons contain pancake shaped clasts and may have a breccia or conglomerate protolith (Plate 2.4d). Clasts within a hornblende-pyroxene-plagioclase +/- biotite matrix range from crystal size to 20 cm x 10 cm and consist of hornblende clots, felsic clasts (+/- hornblende), rare diorite, ultramafic rock and psammitic and semipelitic clasts.

This unit may be correlative with the Marten conglomerate in the Goat Range, which lies unconformably on the Kaslo Group and is overlain unconformably by the Slocan Group (Klepacki 1985). The Marten conglomerate is a greenstone conglomerate that has diorite, greenstone, limestone and serpentinite clasts. No other conglomerate in the Paleozoic-Mesozoic succession has ultramafic clasts. This distinctive lithology makes the correlation of the Mount Mafic amphibolite with the Marten conglomerate a strong one.

The Snow Mountain schist

This > 1.5 km thick Snow Mountain aluminous schist is predominantly a coarse, black-weathering, sillimanite +/- muscovite +/- staurolite-biotite schist with quartzite (Plate 2.5a), clean marble, semipelitic schist and minor felsic (? tuffaceous) interlayers. In the footwall of the Beaven fault and on the shores of Sugar Lake, the schist is orange weathering and contains staurolite crystals up to 15 cm long and, in some locations, post-tectonic kyanite blades which grow across the S2 foliation (Figure 2.5).

The Slocan Group comprises a succession of carbonaceous and/or pelitic shale and/or slate with intercalations of limestone quartzite, sandstone and volcanic rocks. The thickness of the group is uncertain, but 3000 m thick sections, that may have been structurally thickened, have been reported northeast of Slocan (Cairnes 1934; Hedley 1952). The Snow Mountain schist is probably correlative with the Upper Triassic Slocan Group on the basis of lithology. There is no other thick pelite that is a possible correlative, and the association with the Mount Mafic amphibolite - Marten conglomerate strengthens the correlation.

Igneous rocks

Jurassic igneous rocks. Two Jurassic granitoid stocks were discovered within the Thor-Odin - Pinnacles area, and both are at the highest structural level in the entire Middle Crustal Zone, in the immediate footwalls of normal faults. A foliated leucocratic pyroxene and amphibole bearing granodiorite stock which contains mafic xenoliths of amphibole and pyroxene bearing amphibolite gneiss occurs in the footwall of the Beaven Fault southeast of Mount Beaven (Map 1). In thin section, it contains albite and aegirine-augite. This lithology is unusual in southern British Columbia and is characteristic of the ca. 170 Ma Jurassic Kuskanax batholith (Read and Wheeler 1976; Read 1973; Parrish and Wheeler 1983). Because of this characteristic the stock is interpreted as part of the same suite.

A concordant sheet of foliated leucocratic granite on the west flank of Scalping Knife Mountain, in the footwall of the Columbia River fault, is hornblende, pyroxene and allanite bearing and is thus distinguished from the biotite bearing Ladybird suite. The U-Pb zircon data are not concordant due to substantial Pb loss (Appendix 2.1); however a Jurassic age is indicated.

The South Fosthall pluton. Okulitch (1985) presented zircon data from a leucogranite collected on the roadside near Vanstone Creek on the east flank of Thor-Odin culmination. This sample was thought to be representative of the South Fosthall pluton, and he interpreted the U-Pb data as indicating an Ordovician age. He interpreted the upper intercept ($486 \pm 157/-98$ Ma) of a chord of four fractions as representing the crystallization age. Alternatively, these data could be interpreted as Jurassic zircons based on the lower intercept of $172 \pm 47/-96$ Ma, with an inherited Pb component. Okulitch describes the zircons as brown or inclusion-rich light-yellow crystals. This is in contrast to 11 Ladybird zircon samples analysed from the Thor-Odin - Pinnacles area which have colorless and inclusion free zircons (Chapter 1; Parrish et al. 1988). Differences in U-Pb systematics and zircon characteristics suggest that it is unlikely that the South Fosthall pluton was, in fact, sampled.

There are two lithologies at the sample site located at a bridge across Vanstone Creek; a fresh hornblende bearing leucogranite and a chloritized and fractured mylonitic muscovite-biotite Ladybird leucogranite that is typical of the South Fosthall pluton in the footwall of the Columbia River fault. Resampling of the Ladybird granite at this site and elsewhere in the South Fosthall pluton consistently yields Early Eocene ages (Parrish et al. 1988; Carr, Chapter 1); therefore, it is presumed that Okulitch (1985) must have sampled the hornblende bearing rock. Okulitch (1989) suggested that the rock that he dated may be a xenolith within the Eocene South Fosthall pluton; however, none of the hornblende bearing leucogranite rocks at the sample site are *in situ*.

A similar hornblende bearing leucogranite was found in outcrop at only one locale in the region, on the south side of Plant Creek (Map 1). It is an isolated roadside exposure and no contact relationships are exposed, but it occurs within a belt of poorly exposed calcsilicate and amphibolite gneisses with ultramafic boudins that is correlated with the Mount Fosthall calcsilicate unit (Map 1 and Table 2.1).

Late Cretaceous Whatshan batholith. The Whatshan batholith occurs in the southern part of the area and includes the Caribou Creek stock on the east side of Arrow Lake (Figure 2.1 and Map 1). LITHOPROBE line 6 crosses the Whatshan batholith and strongly layered, flat to very gently dipping near-surface reflections indicate that the batholith is sheetlike in nature (Figure 2.4). The Whatshan is predominantly a leucocratic potassium feldspar megacrystic hornblende bearing quartz monzonite but mafic hornblende diorite phases occur on Whatshan Mountain. A U-Pb zircon sample from the Monashee Highway west of Arrow Lake yields a 77 Ma age (Appendix 2.2) and is consistent with Late Cretaceous U-Pb zircon ages from two locations within the Caribou Creek stock (Parrish, unpublished data 1985-1987). The potassium feldspar megacrystic leucogranite phase of the Whatshan batholith is similar in lithology but is older than the Paleocene Airy Quartz Monzonite in Valhalla complex (Carr et al. 1987; Parrish et al. 1988).

The Whatshan batholith is variably deformed. Some exposures along the Monashee Highway, west of Lower Arrow Lake, exhibit pristine igneous textures. Cataclastic textures that are evident along north-south topographic lineaments (Plate 2.5b) are a result of a system of steeply dipping early Tertiary normal faults which postdate movement on the Columbia River fault (Map 1). In contrast to these textures, along both shores of Arrow Lake, the Whatshan batholith and amphibolite and quartzo-feldspathic gneiss screens are strongly foliated and penetratively deformed. The foliation, in which hornblende is stable, is folded by two phases of folds. The foliation in the Whatshan is folded by upright open F3 folds similar in geometry and orientation to F3 folds near

Whatshan Lake and Whatshan Peak (Figure 2.3) The northern contact of the batholith is generally concordant with the subvertical S2 foliation on the steep limb of a large F3 anticline (Figure 2.3). The fabrics in the Whatshan are cut by younger pegmatites thought to be part of the Ladybird suite, which are themselves mylonitized. The 77 Ma age (Appendix 2.2) places a maximum age on deformation in this region and indicates that at least two phases of folding are Late Cretaceous or younger.

Early Tertiary Ladybird suite. The Early Tertiary Ladybird leucogranite suite is prevalent throughout the southern Omineca Belt (Carr et al. 1987; Parrish et al. 1988) and was originally mapped as the "Valhalla series" by Little (1957, 1959, 1960) and the Silver Star suite by Jones (1957). It generally occurs at a particular crustal level, in the Middle Crustal Zone above thrust faults and below extensional faults (Carr 1989). Field relationships and presence of inherited Pb in zircons are consistent with a crustal anatexis origin (Chapter 1).

The Ladybird suite is abundant throughout the Thor-Odin - Pinnacles area. The Ladybird suite, which ranges from granite to quartz monzonite has less than 10% biotite and generally subequal amounts of plagioclase, potassium feldspar and quartz. Accessory muscovite, sillimanite and/or garnet may be present. The leucogranite occurs as syn-kinematic sheets, plutons, stocks and pegmatites, and post-kinematic batholiths, plutons, stocks and pegmatites (Figure 2.2 and Map 1). Emplacement was diachronous with respect to both Paleocene compressional and Eocene extensional deformation in the region. U-Pb zircon dating demonstrates that, in the Thor-Odin - Pinnacles area, the suite ranges from 62 Ma to 55 Ma (Carr, Chapter 1). These data combined with clearly documented field relationships constrain the age of final thrusting on the Monashee décollement to be latest Paleocene. Thrusting was finished by 58 Ma and was followed closely by the onset of extension on normal fault systems (Carr, Chapter 1).

Middle Eocene granite A hornblende and allanite bearing leucogranite was observed in two localities. A stock on the south flank of Slate Mountain is undeformed and

crosscuts fabrics in the predominantly calcsilicate country rock. A 54 Ma sill in Pinnacles cuts F1 and F3 folds in the Vidler calcsilicate gneiss and is itself foliated (U-Pb zircon, Carr, Chapter 1). This may be part of the Ladybird suite, which is hornblende bearing rather than biotite bearing as a result of the composition of the source rock or the calcsilicate host rock.

Metamorphism in the Fawn Lake and Gold Range assemblages

Mineral assemblages and their textures indicate that peak thermal conditions coincided with F2 folding and D2 shearing on the Monashee décollement. In the southern part of the area, peak assemblages and D2 structures are overprinted by lower-temperature and lower-pressure kyanite +/- andalusite assemblages that must have formed during waning stages of metamorphism as the area was being unroofed. In the footwall of the Columbia River fault, retrograde greenschist facies minerals occur within the fault zone and are probably a result of the introduction of hydrous fluids in the shear zone during final stages of motion under plastic conditions (Figure 2.5).

Peak mineral assemblages

Two isograds have been identified in the Thor-Odin - Pinnacles area in the Middle Crustal Zone; the staurolite-out isograd and the isograd separating the sillimanite-muscovite and sillimanite - potassium feldspar zones. Kyanite-staurolite-muscovite-garnet in the presence of quartz and plagioclase occurs on Whatshan peak. The regional distribution of metamorphic zones and isograds is summarized on Figure 2.5 and is generally consistent with previous work by Reesor and Moore (1971) and Moore (unpublished manuscript, 1970). The main difference is that the juxtaposition of greenschist- and amphibolite-facies rocks on the east and west sides of the area is now known to coincide with the Columbia River and Beaven normal faults and does not represent a metamorphic transition as suggested by Reesor (1970).

Peak mineral assemblages are coincident with the formation of the predominant S2 foliation and L2 lineation, shearing on the Monashee décollement, F2 folds and some of the F3 folds. The highest grade sillimanite - potassium feldspar bearing rocks occur at the deepest structural levels in the northern part of the area, in Pinnacles culmination and on Scalping Knife Mountain (Figure 2.5). Many of the gneisses in the sillimanite - potassium feldspar zone are migmatitic with leucocratic feldspar-quartz layers and pods. These leucosomes probably represent *in situ* melt and are part of the high-grade equilibrium assemblage (Reesor and Moore 1971; Coleman 1990; this study). Sillimanite-muscovite assemblages, which predominate in the central part of the area and in the footwall of the Columbia River fault, also coincide with the area of the largest volume of Ladybird granite and pegmatite intrusion. Staurolite-muscovite +/- sillimanite bearing assemblages occur in the footwall of the Columbia River fault near Arrow Park Lake and Plant Creek, on the west side of the Pinnacles culmination between Sugar Lake and Snow Mountain and south of Pinnacles on Whatshan Mountain. Kyanite-garnet-biotite-muscovite assemblages were observed in fine-grained schists and semipelitic schists on Whatshan Peak.

The peak metamorphic assemblages were stable during the Paleocene and probably during the Late Cretaceous; peak thermal conditions of metamorphism may have been diachronous throughout the region; there is little data on peak pressure conditions. Hornblende bearing amphibolite-facies fabrics in the 77 Ma Whatshan batholith along the shore of Arrow Lake indicate that at least part of the metamorphism is Late Cretaceous or younger.

Sillimanite is present in the stretching lineation and axial planes of folded sheets of Late Paleocene leucogranites in the northern part of the area (Carr, Chapter 1) indicating that the high-temperature sillimanite bearing assemblage was stable in the early Tertiary.

Minerals which overgrow peak assemblages

Kyanite and staurolite crystals grew across fabrics and folds in the Snow Mountain schist on Snow mountain and near Outlet and Severide Creeks (Figure 2.5 and Map 1). Reesor and Moore (1971) report kyanite and andalusite that overprint the sillimanite-muscovite assemblage from the same unit near Outlet Creek. These late aluminosilicates are restricted to the aluminous Snow Mountain schist, occur in the immediate footwall of the Beaven fault and may be a result of mineral growth at lower pressure than peak conditions, during uplift and unroofing, perhaps due to extensional faulting (Carr, Chapter 3).

Retrograde greenschist facies metamorphism

On the east flank of Thor-Odin culmination, retrograde muscovite, sericite and chlorite are common on foliation and joint surfaces. Chlorite stretching lineations occur in the footwall of the Columbia River fault, as slickensides on joint planes and in cataclastic fault zones. Chlorite and epidote predominate in calcsilicates on the east slope of Mount Symonds. These retrograde minerals occur in a belt which parallels the Columbia River fault. They are interpreted to have formed during final motion on the fault in the Eocene and may be a result of the introduction of hydrous fluids along the shear zone during greenschist conditions.

Deformation

The following discussion of deformation is restricted to the Middle Crustal Zone Fawn Lake and Gold Ranges assemblages in the Thor-Odin - Pinnacles area. These rocks have undergone protracted Mesozoic-Paleocene compressional deformation including thrusting on high-grade shear zones and polyphase folding followed by denudation on outwardly dipping Eocene normal faults (Map 1, Figures 2.2 and 2.3). In Thor-Odin the regional foliations dip outward from the basement cored culmination; however, the dips are generally to the southwest on the southern flank. There is a regional east-west trending synformal structure between Thor-Odin and Pinnacles;

foliations generally dip southwest on the north limb and northwest on the south limb. The Pinnacles culmination between the Whatshan river valley and the Beaven fault is a westerly plunging F3 antiform.

Five phases of superposed folds were identified on the basis of refolded folds, interference patterns, crosscutting cleavages and the relationship of fabrics to metamorphic minerals. Thrusting on ductile shear zones such as the Monashee décollement and the Divide shear zone in Pinnacles culmination (Map 1) are synchronous in part with the peak of metamorphism and the formation of the main foliation (S2).

Reesor and Moore (1971) identified three phases of folds and interpreted the folds as having different geometries at different structural levels, consistent with the interpretation of the culminations as mantled gneiss domes. Post-metamorphic open folds which they designated F2 and F3 were interpreted as being equivalent to tight syn-metamorphic folds at lower structural levels; however, these post-metamorphic open folds are in fact superimposed on earlier F2 and F3 folds and are designated F4 and F5 in this study. F1 folds and S1 planar fabrics described by Duncan (1982, 1984) contain peak mineral assemblages. Pre-peak structures have been identified in this study and are designated D1; therefore, D2 in this study is equivalent to Duncan's D1.

D1

There is both direct and indirect evidence that a substantial deformation history predated the development of the main metamorphic foliation and growth of peak metamorphic minerals. The direct evidence is the rare occurrence of outcrop-scale F1 folds; no major closures have yet been identified within the study area. Biotite +/- garnet and the lack of sillimanite in the S1 axial planar foliation indicates that F1 folds formed prior to the peak of metamorphism.

The indirect evidence of early deformation is based on the correlation the Gold Range stratigraphy with Paleozoic - Mesozoic strata known to contain Paleozoic deformation and thrust faults (Read and Wheeler 1976; Klepacki 1985; Gehrels and

Smith 1987) and the Early-Middle Jurassic Intermontane Superterrane - North American obduction boundary.

D2

The main metamorphic foliation is designated S2. Where primary features are preserved on Snow and Whatshan mountains (Figure 2.5), S2 is generally at a very low angle to primary bedding; whereas at high grade throughout the rest of the area, it is generally not possible to distinguish S2 from bedding or layering. S2 is generally parallel to compositional layering, which probably represents transposed bedding. The S2 foliation contains sillimanite mats, quartz and quartzo-feldspathic segregations and platy and flattened minerals (Plates 2.2c, 2.2d and 2.3d). In many lithologies, distinct segregations of leucocratic and melanocratic minerals define the foliation; these include hornblende-biotite and plagioclase rich layers in amphibolite gneiss and biotite-garnet and quartzo-feldspathic layers in pelitic and semipelitic schists. At the outcrop scale, chocolate-tablet boudins of leucogranite and amphibolite, calcsilicate and psammitic gneiss are commonly aligned subparallel to the foliation, although they may have an internal foliation at an angle to S2 (Plate 2.2b).

In most lithologies, S2 contains a well developed lineation, L2, which is predominantly a stretching lineation (Plate 2.2d). L2 is defined by elongate minerals such as sillimanite and hornblende, elongate aggregates of minerals, quartz ribbon grains and the long axes of augen and porphyroclasts. S2 and L2 contain the peak metamorphic assemblages, which are annealed. Within the high strain zone of the Monashee décollement, S2 is concordant with the mylonitic shear foliation (C-plane of Berthé et al. 1979) and the shear zone itself, and the lineation is a stretching lineation interpreted as the transport direction. The interpretation of mylonitic fabrics consistently yields a northeasterly shear sense for the Monashee décollement (this study; Coleman 1990).

The predominant S2 foliation is most likely a diachronous fabric and in part represents a composite fabric into which earlier formed fabrics have been transposed,

particularly near high-strain regions such the Monashee décollement. The fabric in Paleocene granitoids, which postdates much of the strain in the country rock, is concordant with S2 in a general way, indicating that the granitoids have a different finite strain than the country rock. This implies that a certain amount of strain preceded the emplacement of the Paleocene granitic rocks.

Northeast-verging steeply inclined and generally gently plunging tight to isoclinal asymmetric similar folds are termed F2 (Plate 2.5d, Figure 2.3). F2 parasitic folds are pervasive at the hand-sample and outcrop scale and intermediate-scale second-order folds such as the Ledge anticline on the southern flank of the Thor-Odin culmination (Map 1 and Figure 2.3), have been mapped on the basis of small scale minor-fold vergence changes or on the presence of closures; however, no regional scale major F2 closures are evident in the Thor-Odin Pinnacles region.

Mineral assemblages and melt pods associated with peak conditions of metamorphism are contained within F2 axial surfaces indicating that at least part of the folding occurred in close association with peak metamorphic conditions. The folds appear to have formed progressively as some are axial planar to S2 and others fold S2. In most structural domains, particularly those in the immediate hanging wall of the Monashee décollement, the fold hinges are parallel or sub-parallel to the mineral lineation (Reesor and Moore 1971; Coleman 1990). In areas of high strain, in the Cariboo duplex and the Fawn Lake assemblage, early F2 folds have been rotated and some have sheath fold geometries.

Divide shear zone. In Pinnacles Peaks, the Vidler calcsilicate gneiss cores the Pinnacles culmination. The map pattern of the calcsilicate shown on Map 1 follows the interpretation of Read (1979a) and is apparently based on work by Reesor and Froese (1968, 1969). In Read's interpretation, the Pinnacles culmination is a large-scale northerly verging isoclinal fold that is refolded and domed by upright folds. The

northern limb of the early fold is apparently faulted out by an east striking fault (Map 1) which was apparently inferred on the basis of missing stratigraphy (Read 1979a).

A ductile shear zone, herein named the Divide shear zone, was discovered to the north of the calcsilicate gneiss in Pinnacles Peaks (Map 1). It was examined in detail at only one location, but is believed to be the westward continuation of the fault on Read's map. The ~ 25 m wide shear zone, in a pelitic schist layer that overlies the Vidler calcsilicate gneiss, strikes east-west and dips 25-30° to the north; the sillimanite bearing stretching lineation plunges north-northeast. A penetrative C fabric dips more steeply to the north than the S fabrics implying a northeasterly-directed shear sense. Muscovite is not present within the mylonitic fabric elements, although it grows across them. The mylonitic fabrics are annealed, stable sillimanite occurs in the stretching lineation in pressure shadows and in pulled apart garnets, and therefore the shear fabric is syn-metamorphic with respect to the peak of metamorphism. The mylonitic shear fabric (C plane) is axial planar to a set of syn-metamorphic rootless F2 folds defined by folded quartz veins. Both the mylonitic fabrics and F2 folds are folded by F3 folds. Therefore, the Divide shear zone is a D2 structure. The mylonitic fabrics and both phases of folds are crosscut by tourmaline and muscovite bearing pegmatites.

The Vidler calcsilicate gneiss occurs in the footwall of the Divide shear zone. The hanging wall comprises a ~2 km thick sequence of predominantly thinly interlayered psammitic and rusty weathering semipelitic schist with minor marble and quartzite in the hanging wall. This map unit is of uncertain correlation; it shares lithologic similarities with the Windermere Supergroup, the Broadview Formation of the Lardeau Group and the Milford Group.

The regional extent, displacement and nature of the shear zone are uncertain and require further work. It is likely that the Divide shear zone is part of the regional Cretaceous Paleocene thrust system.

F3 folds are open to tight, upright to reclined and are coaxial with F2 folds (Plates 2.3b, 2.3c, 2.6a and 2.6b). They plunge gently to the west (270° - 290°) throughout most of the region but are more steeply plunging (20° - 40°) on the west side of the area on Slate Mountain, Goat Mountain, in the Sugar Lake area and on Snow Mountain (Map 1). On Snow Mountain a steeply plunging stretching lineation defined by elongate biotite aggregates is parallel to the F3 fold hinges (Plate 2.6c). F3 folds deform the main S2 foliation containing peak metamorphic mineral assemblages and the L2 stretching lineation (Plates 2.4b and 2.6b). At deeper structural levels, in the hanging wall of the Monashee complex and in the core of the Pinnacles culmination, F3 axial planes contain peak metamorphic mineral assemblages and in pelitic schists can have a well developed penetrative axial planar foliation. On Mount Fosthall, a Late Paleocene leucogranite is deformed by F3 folds indicating that this phase of folding, is at least in part, Late Paleocene or younger.

F3 parasitic folds are well developed at the outcrop scale and larger closures were also identified. An anticline-syncline pair was mapped in the Mount Baldur - Twin Peaks - Goat Mountain area and km-scale second order parasitic folds are well exposed on Mount Fosthall. An F3 anticline is inferred to close on the treed and unexposed north flank of Whatshan Peak on the basis of minor folds, cleavage relationships to F2 folds and the dip reversal of regional foliations (Map 1). An F3 anticline is inferred in the Saddle Mountain - Scalping Knife Mountain area on the basis of stratigraphy and foliation data (compiled from Hyndman 1968; Read and Wheeler 1976), Hyndman's cross-section and limited reconnaissance mapping (Map 1).

Both major and minor F3 folds exhibit a vergence reversal at the latitude of Cusson Creek (Map 1 and Figure 2.3); they are north verging in the north, on the south flank of Thor-Odin, and verge to the south in the Pinnacles - Scalping Knife area. This may be related to blind structures imaged in LITHOPROBE seismic reflection data (Figure 2.4). The Monashee décollement projects into the north end of the seismic section at a depth

which corresponds to a broad band of reflections that have an apparent southward dip in line 6. An arched structure beneath the Pinnacles culmination is truncated at its base against the inferred trace of the Monashee décollement and is interpreted as a hanging wall anticline at the leading edge of a blind thrust (Carr and Brown 1990; Brown et al. 1990; Cook et al. 1990). The leading edge of the blind thrust coincides with the F3 vergence reversal. If the blind thrust was an "in sequence" thrust carried in the hanging wall of the Monashee décollement, then it would act as a wedge. The F3 vergence reversal could have occurred in response to south verging transport in the hanging wall of the roof thrust.

The northeast verging folds on the south flank of Thor-Odin have the opposite vergence to F3 folds elsewhere in exposures of Middle Crustal rocks reported by Johnson (1988, 1990) to the northwest in the Hunters Ranges and to the west in the Park and Silver Hills (Jones 1957). The interpretation that the vergence reversal is related to blind thrusts acting as wedges is consistent with subsurface geometries imaged on LITHOPROBE lines 7-10 between the Columbia River and the Okanagan fault and line 19 on the west flank of the Monashee complex north of the Trans-Canada Highway (Figure 2.4; Carr and Brown 1990; Brown et al. 1990; Johnson and Brown 1990; Cook et al., in preparation, 1990).

F4 crenulations

A penetrative crenulation cleavage (Plate 2.6a) and/or small 1 cm scale crenulations, most readily observed in pelitic schists (Plate 2.6d), fold all minerals and therefore postdate the metamorphic peak. The orientations of the axial surfaces are variable but crenulation fold hinges are generally shallowly plunging.

F5 open folds

The youngest folds are broad open warps observed on a scale of 1 to 30 m. They fold F4 crenulations and pegmatites. They postdate metamorphic mineral growth; there

is no foliation or lineation associated with F5 folds. There is no timing or geometric evidence to distinguish whether these folds are related to compressional or extensional structures.

D6 extensional structures

The Columbia River and Okanagan Valley - Eagle River fault systems (described on pages 89-93) are designated D6. This ranking depends upon the assumption that D4 and D5 folds formed prior to extensional shearing.

Westerly directed discrete shears

There is a regional divergence of Eocene transport directions along a north-south axis in the Thor-Odin - Pinnacles area. The Columbia River fault and mylonites on the east side of the region exhibit easterly directed shear fabrics. The Okanagan Valley fault and mylonitic fabrics on the west side of Pinnacles and Thor-Odin have westerly directed ductile shear fabrics. Discrete 10 cm - 50 m wide zones of shear occur in Ladybird granitoid rocks in the western part of the region, near Sugar Lake and in the Silver and Park Hills between the Shuswap River valley and Mabel Lake (Figure 1.4). Asymmetry of mylonitic fabrics indicates a westerly directed shear sense, and these shears are interpreted to represent distributed strain associated with the westerly directed Okanagan fault zone. It may be that these shears also occur throughout the metamorphic rocks, although they were easily recognized in granites. It may also be that the shears are concentrated in the granites, which are generally syn-kinematic with regional extension, because they were hotter and more ductile than surrounding country rocks.

Slate Mountain shear zone

A syn-metamorphic unannealed shear zone was mapped from the saddle north of Mount Symonds westward for ~4 km and on the south flank of Slate Mountain (Figure 2.2 and Map 1). The westward continuation of the trace of the shear zone is uncertain.

Sheared quartzites exhibit quartz ribbons and a strongly developed quartz stretching lineation, marbles and amphibolites are discontinuous pods and are mylonitized, and pelites are characterized by a well developed stretching lineation which contains sillimanite aggregates and mylonitic fabrics. In pelitic schists sillimanite occurs as needles and as mats that are wrapped around garnets, and the garnets are flattened and pulled apart (Plate 2.2c). The shear zone dips southward $\sim 40^\circ$ to the south and the stretching lineation trends east-west with a low-angle plunge.

Preliminary kinematic studies indicate an easterly directed shear sense. The unannealed nature of the fabrics is in striking contrast to mylonitic fabrics in the Monashee décollement, to the north, which are annealed. This suggests that final movement on the Slate Mountain shear zone may be younger than that on the Monashee décollement.

The Slate Mountain shear zone coincides with the lithologic division between the Fawn Lake assemblage and the Gold Range assemblage. If the stratigraphic correlations of the Fawn Lake assemblage and the basal Gold Ranges assemblage are correct, then the Slate Mountain shear zone appears to be cutting down-section in the footwall Windermere stratigraphy from west to east. Johnson (1988, 1989) correlates the Shuswap assemblage of the Hunters Range with the semipelitic-amphibolite division, middle marble and upper division so there is an apparent stratigraphic omission of the upper two divisions of the Horsethief Creek Group on the south flank of Thor-Odin.

Based on mapping in the poorly exposed area on the southeast flank of Thor-Odin near Ledge Creek, the Slate Mountain shear zone apparently cuts out all of the Fawn Lake assemblage; however, this could be an effect of the Columbia River fault.

It is uncertain whether the Slate Mountain shear zone is an extensional or compressional structure. Since the shear zone apparently cuts down section in the direction of transport it may be an extensional fault. The best model to explain the preliminary information about the Slate Mountain shear zone is that it is an extensional

transfer zone, kinematically linked to the easterly-directed Columbia River fault. It is likely that the shear zone breaks to the surface on the west flank of Thor-Odin culmination.

Steep normal faults

North-south trending normal faults have been identified in the Whatshan valley, near Vidler Ridge (Reesor and Moore 1971), on Mount Fosthall (Reesor and Moore 1971), in Pillar Pass (Jones 1957), east of Scalping Knife Mountain (Hyndman 1968) and on the west flank of Valhalla complex (Parrish et al. 1988). These faults are younger than the Columbia River fault and are brittle structures with ~0.1 - 4 km displacement on them.

Conclusions

The present crustal architecture of the southern Omineca belt in the Canadian Cordillera is a product of Eocene extension and crustal thinning superimposed on a crust that was thickened and deformed during Jurassic to Late Paleocene compression (and/or Late Paleozoic). High-grade rocks exposed as gneiss complexes within the Shuswap metamorphic complex, in the southern Omineca belt, were buried during compression and were exhumed in the lower plates of low- to moderate-angle plastic-brittle Eocene extensional faults. At the latitude of the Thor-Odin - Pinnacles area, three crustal zones and intervening shear zones are exposed at the surface and can be correlated with LITHOPROBE seismic reflection data. The Basement Zone, the deepest exposed crustal level, comprises Early Proterozoic crystalline basement infolded and imbricated with overlying cover gneisses and is bounded on the top by the Monashee décollement, a Mesozoic - Late Paleocene ductile thrust fault. The Basement Zone is overlain by the Middle Crustal Zone, which was carried in the hanging wall of the Monashee décollement. It is characterized by Late Cretaceous - Late Paleocene compressional deformation, penetrative plastic Eocene extensional strain and Early Tertiary plutonism and thermal quenching. High-grade rocks of the Middle Crustal Zone are bounded at the

top and were exhumed by regional scale Eocene normal faults. The Upper Crustal Zone, in the hanging walls of the normal faults, preserves a Middle Jurassic obduction and polydeformation history and was quenched in the Mesozoic. During Eocene extension these rocks were either transported relatively passively on low- to moderate-angle crustal scale shear zones or were dissected by brittle normal faults. Seismic reflection data indicate that both compressional and extensional shear zones are crustal-scale features that penetrate at least as deeply as the middle crust.

The three crustal zones and their bounding structures are exposed in the Thor-Odin - Pinnacles area. The Basement Zone is exposed in the Thor-Odin culmination, a second order dome within Monashee complex (Figure 2.2). The Monashee décollement is exposed on the flanks of the culmination and forms the lower boundary of Middle Crustal Zone high-grade metamorphic rocks intruded by the Late Paleocene to Early Eocene Ladybird leucogranite suite. The Middle Crustal zone rocks are bounded on the east by the east-dipping Columbia River normal fault and on the west by a hanging wall salient of the gently west-dipping Okanagan Valley - Eagle River normal fault system. Both of these fault systems carry Upper Crustal Zone rocks in their hanging walls. Timing constraints have been placed on the transition between compression and extension by U-Pb zircon and monazite dating of deformed and crosscutting Ladybird intrusives (Carr, Chapter 1). Compression was ongoing in the latest Paleocene, thrusting was over by 58 Ma, and compression was underway in the Early Eocene.

Lines 6-10 of the southern Canadian LITHOPROBE seismic reflection survey cross Middle and Upper Crustal Zone rocks in the Thor-Odin - Pinnacles area. Line 6 is north-south oriented and extends from near Edgewood in the Whatshan batholith to near Arrow Park Lakes on the southern flank of Thor-Odin (Figure 2.2). Line 6 is perpendicular to lines 7-10, which extend from the Columbia River valley to Vernon in the Okanagan Valley. The Monashee décollement is projected into the seismic lines and is coincident with a band of strong parallel reflections that have a gentle southwest true dip. Certain

reflection patterns in the middle crust are interpreted to represent blind thrust sheets in the hanging wall of the Monashee décollement (Figure 2.4). The correlation of these blind thrusts in lines 6 and 7-10 indicates that the tip-line of the thrust trends northwest. This coincides with the boundary between north and south verging F3 folds and the axis of a structural depression between Thor-Odin and Pinnacles culminations.

Amphibolite-facies Middle Crustal Zone gneisses of the Thor-Odin - Pinnacles area are divided into two tectonostratigraphic packages: the Fawn Lake assemblage, which forms a 0-3 km wide belt in the immediate hanging wall of the Monashee décollement, and the Gold Range assemblage, which extends over a >1200 km² area between the Fawn Lake assemblage and the Whatshan batholith (Figure 2.2 and Map 1). The Fawn Lake assemblage is thought to be correlative with the semipelite-amphibolite division of the Horsethief Creek Group of the Upper Proterozoic Windermere Supergroup. It is bounded at the top by an unannealed Late Paleocene or Early Eocene shear zone, the Slate Mountain shear zone, which cuts down section in the Fawn Lake assemblage from west to east and may be an extensional transfer zone related to the Columbia River fault.

The Gold Range assemblage is correlated with Cambrian to Jurassic stratigraphy of the Hamill Group, Badshot Formation, Lardeau Group, Milford Group, Kaslo Group, Marten conglomerate and Slocan Group. The southern part of the Gold Range assemblage is intruded by the potassium feldspar megacrystic hornblende bearing leucocratic Whatshan batholith. The Whatshan batholith is 77 Ma based on U-Pb zircon analyses, it is variably deformed and is considered to be part of the Middle Crustal Zone. Strong near-surface seismic reflection arrays on LITHOPROBE line 6 indicate that the Whatshan batholith is sheet-like. A well developed foliation and superposed folds in exposures of the Whatshan near Lower Arrow Lake indicate that high-grade metamorphism and at least two phases of deformation must be Late Cretaceous or younger.

There is some evidence of Paleozoic and perhaps Middle Jurassic deformation within Middle Crustal Zone rocks of the Thor-Odin - Pinnacles area; however, most of the deformation is Late Cretaceous - Eocene. In any case, these potential older events are certainly pre-thermal peak. Ultramafic bearing horizons within the Gold Range assemblage are correlated with the ultramafic bearing rocks in the Cambrian-Ordovician Lardeau Group and in the Lower Permian Kaslo Group, which are both associated with Paleozoic thrust faults (Klepacki 1985; Gehrels and Smith 1987). F1 minor folds are rarely observed, are biotite +/- garnet bearing and predate the peak of metamorphism. These may be correlative with either Paleozoic or Mesozoic structures reported elsewhere in the Selkirk and Monashee mountains.

The main foliation (S2), northerly verging F2 folds and the northeasterly directed fabrics of the Monashee décollement formed during D2 and are synchronous with the peak of metamorphism. F2 folds are tight to isoclinal with hinges that are generally sub-parallel to parallel to the L2 stretching lineation. F3 folds formed as peak metamorphic conditions were waning. They are open to tight gently westerly plunging folds which are co-axial with F2 folds. A vergence reversal in F3 folds coincides with the axis of a structural depression or broad east-west trending synformal structure between the southern flank of the Thor-Odin culmination and the southern part of the area. The vergence change in the F3 folds is attributed to the wedge-like effect of underthrusting of the blind thrust sheets imaged in the subsurface on LITHOPROBE lines 6 and 8.

The deformation of the 77 Ma Whatshan batholith and the Late Paleocene Ladybird leucogranites indicates that a considerable part of the compressional deformation, foliation development and F3 folding is latest Cretaceous - Paleocene.

D2 and D3 structures are overprinted by a post-metamorphic D4 crenulation cleavage and by D5 broad open folds or warps. These structures may be coeval with Eocene extensional faults. Rocks in the footwall of the east-dipping Columbia River fault are mylonitic in a zone of up to 5 km wide in map view. Biotite grade mylonites are

overprinted by chlorite grade plastic and brittle fabrics in the immediate footwall of the fault. The Beaven fault, a normal fault on the west side of the Pinnacles culmination is a brittle and/or plastic structure that is interpreted to be the eastern continuation of the west-dipping and westerly directed Okanagan Valley - Eagle River fault system which has been down-dropped by younger normal faults such as the Cherryville fault. Discrete westerly directed shear zones on the west side of the area in Ladybird granitoids are interpreted to represent distributed footwall strain associated with the Okanagan Valley fault system.

The youngest structures in the area are steep brittle normal faults that have minor displacements ranging from 0.1-4 km.

The data are consistent with a model of obduction of the Intermontane Superterrane, progressive crustal thickening and deformation in the Jurassic, followed by erosional unroofing and gradual cooling of rocks that would eventually be preserved in the upper plates of normal faults. Strain was partitioned during renewed thrusting: Middle Crustal Zone rocks were plastically deformed at deeper structural levels whereas the Upper Crustal Zone was transported eastward relatively passively on deep-seated thrust faults. Extensional faulting resulted in the denudation of the Middle Crustal Zone and its juxtaposition against the Upper Crustal Zone.

**TABLE 2.1 SUMMARY OF STRATIGRAPHIC CORRELATION OF METAMORPHIC
ROCKS IN THE THOR-ODIN - PINNACLES AREA**

Map unit	Tentative Correlation	References
<u>Gold Range assemblage</u>		
11 Snow Mountain schist	Slocan Group	Little 1960 Read and Wheeler 1976 Klepacki 1985
10 Mount Mafic amphibolite gneiss	Marten conglomerate	Read and Wheeler 1976 Klepacki 1895
9 Outlet Creek ultramafic-bearing unit	Kaslo Group	Klepacki 1985
8 Vidler calc-silicate gneiss	Milford Group	Read 1973 Read and Wheeler 1976 Klepacki 1985
Mount Fossil composite unit		
7b Calc-silicate - pelite - amphibolite - ultramafic member	Milford Group Lardeau Group	Fyles 1964 Read 1973 Read and Wheeler 1976 Klepacki 1985
7a Psammite - semi-pelite member	Lardeau Group (Index Formation)	Walker and Bancroft 1929 Fyles and Eastwood 1962 Fyles 1964 Read and Wheeler 1976 Zwanzig 1973 Höy 1977a, 1977b Sears 1979 Gehrels and Smith 1987

TABLE 2.1 (CONTINUED) SUMMARY OF STRATIGRAPHIC CORRELATION OF METAMORPHIC
ROCKS IN THE THOR-ODIN - PINNACLES AREA

Map unit	Tentative Correlation	References
6 Empress marble	Badshot Formation	Walker and Bancroft 1929 Fyles 1967 Höy 1977a, 1977b
5 Symonds quartzite bearing unit	Hamill Group	Fyles and Eastwood 1962 Fyles 1964 Reesor 1973 Read 1973 Höy 1977a, 1977b Read and Wheeler 1976
<u>Fawn Lake assemblage</u>	Semi-peletic amphibolite (SPA) division of the Horseshoe Creek Group	Poulton and Simony 1980 Raesside and Simony 1983 Pell and Simony 1987 Johnson 1989 Scammell 1990

TABLE 2.2 K-Ar ANALYSES (see Hunt and Roddick 1987 for analytical procedures)

Sample Number	Mineral	Age (Ma) (2 Sigma error)	Wt %. K (1 Sigma error)	Radiogenic Ar (cc/gm) (2 Sigma error)	Atmos. Ar
SC569	hornblende	58.2 +/- 1.2	0.846 +/- 0.7%	58.28×10^{-7} +/- 1.2%	23.0%
SC857	hornblende	64.7 +/- 1.1	0.754 +/- 0.6%	19.29×10^{-7} +/- 0.7%	14.15%
SC919	hornblende	174.3 +/- 4.3	0.82 +/- 1.1%	58.33×10^{-7} +/- 0.6%	11.0%
SC928	hornblende	57.3 +/- 1.1	0.431 +/- 0.5%	9.75×10^{-7} +/- 0.8%	17.0%

TABLE 2.3 K-Ar SAMPLE DESCRIPTIONS AND LOCATIONS

Sample number	Description
SC569	Folded, foliated hornblende-plagioclase bearing amphibolite gneiss, Cariboo Alp (82 L/8), elevation 7200', UTM 415150E- 559660N (lat. 50° 31'06"N long. 118°11'45"W)
SC857	Foliated, lineated biotite - hornblende bearing amphibolite schist, Pinnacles Peaks (82 L/1), elevation 7000', UTM 411440E-5563125N (lat. 50°13'05"N, long. 118°14'31"W)
SC919	Medium grained, hornblende - biotite granodiorite, ~ 2km west of Spruce Grove on the Monashee Highway (82 L/2), elevation 3900', UTM 389550E-5547350N (lat. 50°04'12"N, long. 118°32'30"W)
SC928	Foliated, lineated amphibolite gneiss, Saddle Mountain (82 K/4), elevation 7500', UTM 435810E-5557780N (lat. 50°10'14"N, long. 118°54'00"W)
SC1367	Foliated, lineated amphibolite gneiss, Goat Mountain (82 L/8), elevation 7220', UTM 407260E-5587120N (lat. 50°25'36", long. 118°18'26"W)

Figure 2.1 Tectonic map of southern Omineca Belt, modified from Parrish et al. (1988). Insets locate the geologic belts of the Cordillera and the Intermontane (IM) and Insular (IS) superterrane. The Omineca Belt lies between the southern Rocky Mountain Trench (SRMT) in the northeast and the Fraser-Straight Creek (FSF), Yalakom (YF), Hozameen (HF), and Pasayten (PF) strike slip faults in the southwest. The unpatterned area in the Omineca Belt represents the Upper Crustal Zone (see text). Rocks of North American affinity (NA) are separated from the Intermontane Superterrane (IM) by the Terrane Accretion Boundary (TAB). Features shown with patterns form the Shuswap metamorphic complex. The Middle Crustal Zone (diagonal stripes) consists of metamorphic rocks characterized by 45-60 Ma K-Ar mica dates. Basement rocks of the Basement Zone (dark grey) are exposed in Frenchman Cap (FC) and Thor-Odin (TO) culminations in the Monashee complex and the Malton complex (M). High-grade culminations of the Shuswap metamorphic complex also include the Kettle-Grand Forks (K), Okanagan (OC), Priest River (PR), and Valhalla (V) complexes. Mesozoic-Paleocene thrust faults are the Monashee décollement (MD) and Gwillim Creek shear zones (GCS). Eocene normal faults are the Columbia River fault (CF), Granby fault (GF), Greenwood fault system (GWF), Kettle fault (KF), Newport fault (NF), Okanagan Valley - Eagle River fault system (OF), Purcell Trench fault (PTF), Slocan Lake fault (SLF) and Valkyr shear zone (VS).

FIGURE 2.2 Geology of the Thor-Odin - Pinnacles area and surrounding area

LEGEND

UPPER CRUSTAL ZONE

- **MIDDLE JURASSIC NELSON INTRUSIVE SUITE:** predominantly granodiorite
- **PALEOZOIC - LOWER JURASSIC STRATIFIED ROCKS:**

MIDDLE CRUSTAL ZONE

- **LATE PALEOCENE - EARLY EOCENE LADYBIRD GRANITE SUITE:** biotite granite, quartz monzonite, leucocratic pegmatite (also includes areas with pegmatite with <50% metamorphic rocks)
- **LATE CRETACEOUS WHATSHAN BATHOLITH** (includes Cariboo Creek stock): hornblende biotite bearing K-feldspar megacrystic quartz monzonite, mafic hornblende biotite diorite
- **LATE PROTEROZOIC - MESOZOIC AMPHIBOLITE FACIES METAMORPHIC ROCKS:** FA = Fawn Lake assemblage; GA = Gold Range assemblage

BASEMENT ZONE

- **PROTEROZOIC CRYSTALLINE BASEMENT AND LATE PROTEROZOIC - (?) CAMBRIAN COVER GNEISSES**

GEOLOGIC CONTACT; MAPPED, COMPILED FROM PUBLISHED MAPS, ASSUMED

LOW - MODERATE ANGLE EOCENE NORMAL FAULT (PEGS ON HANGING WALL)

STEEP EOCENE NORMAL FAULT (PEGS ON HANGING WALL)

STEEP EOCENE NORMAL FAULT; SENSE OF DISPLACEMENT UNCERTAIN

LITHOPROBE LINE

BF	BEAVEN FAULT
CF	CHERRYVILLE FAULT
CRF	COLUMBIA RIVER FAULT
GCSZ	GWILLIM CREEK SHEAR ZONES
MD	MONASHEE DECOLLEMENT
OF	OKANAGAN VALLEY - EAGLE RIVER FAULT SYSTEM
SLFZ	SIOCAN LAKE FAULT ZONE
SSZ	SLATE MOUNTAIN SHEAR ZONE
VSZ	VALKYR SHEAR ZONE

Figure 2.3 Generalized cross sections of the Thor-Odin - Pinnacles area integrating geology with LITHOPROBE data. North-south section A-A' parallels LITHOPROBE line 6 and east-west section B-B' parallels lines 7 and 8 (shown on Figure 2.2).

LEGEND

UPPER CRUSTAL ZONE

PJ_s PALEOZOIC - LOWER JURASSIC STRATIFIED ROCKS:

MIDDLE CRUSTAL ZONE

PE_g LATE PALEOCENE - EARLY EOCENE LADYBIRD GRANITE: biotite granite - quartz monzonite, pegmatite

PE_p LATE PALEOCENE - EARLY EOCENE PEGMATITE WITH < 50% METAMORPHIC ROCKS

IK_g LATE CRETACEOUS WHATSHAN BATHOLITH (includes Cariboo Creek stock): hornblende - potassium feldspar megacrystic quartz monzonite; diorite (Whatsan Peak)

12 UNDIVIDED METAMORPHIC ROCKS:

11 SNOW MOUNTAIN SCHIST: sillimanite +/- staurolite pelitic schist with minor psammitic gneiss, marble and quartzite

10 MOUNT MAFIC AMPHIBOLITE GNEISS: hornblende-biotite amphibolite gneiss

9 OUTLET CREEK ULTRAMAFIC BEARING UNIT: semi-pelitic and psammitic gneiss, pelitic schist and amphibolite gneiss with ultramafic boudins and sheets

8 VIDLER CALCSILICATE GNEISS: calcareous quartzite, quartzite, siliceous marble and marble with minor amphibolite gneiss

MOUNT FOSTHALL COMPOSITE UNIT

7b PSAMMITE - SEMI-PELITE MEMBER: rusty semi-pelitic gneiss, psammitic gneiss, amphibolite gneiss, calc-silicate schist, marble, and quartzite

7a CALCSILICATE - PELITE - AMPHIBOLITE -ULTRAMAFIC MEMBER: calc-silicate schist and gneiss, amphibolite gneiss, pelitic schist, marble, quartzite with distinctive ultramafic marker

6 EMPRESS MARBLE: calcite marble marker

5 SYMONDS QUARTZITE BEARING UNIT: quartzite, psammitic gneiss, amphibolite and marble

4 FAWN LAKE ASSEMBLAGE: migmatitic psammitic and semi-pelitic gneiss, amphibolite gneiss

BASEMENT ZONE (LOWER PLATE OF MONASHEE DECOLLEMENT)

3 COVER GNEISSES: quartzite, semi-pelitic paragneiss, pelitic schist, minor marble

2 PROTEROZOIC BASEMENT ORTHOGNEISSES: hornblende biotite granodiorite gneiss, quartz monzonite gneiss

1 PROTEROZOIC BASEMENT PARAGNEISSES: migmatitic biotite quartz-feldspathic gneiss

BF BEAVER FAULT

CF CHERRYVILLE FAULT

CRF COLUMBIA RIVER FAULT

MD MONASHEE DECOLLEMENT

OF OKANAGAN VALLEY - EAGLE RIVER FAULT SYSTEM

SSZ SLATE MOUNTAIN SHEAR ZONE

Figure 2.4 North-south cross section integrated with migrated coherency filtered LITHOPROBE seismic reflection data. (CRF = Columbia River fault; IKg = Late Cretaceous Whatshan batholith; T-O = Thor-Odin culmination; MD = Monashee décollement; P = Pinnacles culmination; SSZ = Slate Mountain shear zone). Solid lines are form surfaces showing regional foliation orientation in line of section; note fold on southern flank of Thor-Odin culmination, Pinnacles culmination and coaxial refolded fold south of Pinnacles.

Line 6

Figure 2.5 Distribution of metamorphic assemblages and minerals in pelitic rocks in the Thor-Odin - Pinnacles area

Figure 2.6 Generalized tectonic and stratigraphic relationships in the Goat Range area, eastern Selkirk mountains (from Klepacki 1985, p 37)

FIGURE 2.7 Geology of the Thor-Odin - Pinnacles area and surrounding area with U-Pb and K-Ar sample locations and ages

LEGEND

UPPER CRUSTAL ZONE

MIDDLE JURASSIC NELSON INTRUSIVE SUITE: predominantly granodiorite

PALEOZOIC - LOWER JURASSIC STRATIFIED ROCKS:

MIDDLE CRUSTAL ZONE

LATE PALEOCENE - EARLY EOCENE LADYBIRD GRANITE SUITE: biotite granite, quartz monzonite, leucocratic pegmatite (also includes areas with pegmatite with <50% metamorphic rocks)

LATE CRETACEOUS WHATSHAN BATHOLITH (includes Cariboo Creek stock): hornblende biotite bearing K-feldspar megacrystic quartz monzonite, mafic hornblende biotite diorite

LATE PROTEROZOIC - MESOZOIC AMPHIBOLITE FACIES METAMORPHIC ROCKS:

BASEMENT ZONE

PROTEROZOIC CRYSTALLINE BASEMENT AND LATE PROTEROZOIC - (?) CAMBRIAN COVER GNEISSES

GEOLOGIC CONTACT: mapped, compiled from published maps, assumed

LOW - MODERATE ANGLE EOCENE NORMAL FAULT (PEGS ON HANGING WALL)

STEEP EOCENE NORMAL FAULT (PEGS ON HANGING WALL)

STEEP EOCENE NORMAL FAULT: sense of displacement uncertain

LITHOPROBE LINE

SC919 **GEOCHRONOLOGY SAMPLE LOCATION WITH U-Pb AND K-Ar AGES;** (h) = K-Ar hornblende; (t) = U-Pb titanite; (z) = U-Pb zircon

BF	BEAVEN FAULT
CF	CHERRYVILLE FAULT
CRF	COLUMBIA RIVER FAULT
GCSZ	GWILLIM CREEK SHEAR ZONES
MD	MONASHEE DECOLLEMENT
OF	OKANAGAN VALLEY - EAGLE RIVER FAULT SYSTEM
SLFZ	SLOCAN LAKE FAULT ZONE
SSZ	SLATE MOUNTAIN SHEAR ZONE
VSZ	VALKYR SHEAR ZONE

Plate 2.1. (a) Basement paragneisses at the foot of Odin glacier. (b) Westward view of intercalated basement and cover gneisses of Cariboo Alp duplex. (c) Biotite-grade mylonitic South Fosthall pluton in the footwall of the Columbia River fault. (d) Beaven fault cataclasite. (e) Low grade argillite in hanging wall of Beaven fault.

Plate 2.2 (a) Westward view from Mount Symonds of south-dipping Fawn Lake assemblage paragneisses. (b) Fawn Lake assemblage psammitic paragneiss and semi-pelitic schist with Ladybird granite boudins (north of Margie Lake). (c) Mylonitic sillimanite-garnet-biotite pelitic schist in the Slate Mountain shear zone (Mount Symonds), viewed southward looking perpendicular to the foliation and parallel to the stretching lineation. Garnets are rimmed by sillimanite and feldspar. (d) Sillimanite lineation on foliation surface of a pelitic schist in the Symonds quartzite bearing unit near the base of the Gold Ranges assemblage (on the north flank of Mount Fosthall).

Plate 2.3. (a) Clean quartzite in the Symonds quartzite bearing unit of the Gold Range assemblage (north Flank of Mount Fosthall) is possibly correlative with quartzites in the Lower Cambrian Mohican Formation. (b) Tight F2 fold refolds rootless hinge (?F1) in the Empress marble (north flank of Mount Fosthall). (c) Calcisilicate gneiss with thin pelitic schist interlayers and quartzo-feldspathic veins in F3 fold hinge (lower member of the Mount Fosthall composite unit on Mount Fosthall ridge top). Note the folded leucocratic stringers. (d) Pelitic sillimanite-garnet-biotite schist with leucocratic porphyroclasts and concordant 62 Ma mylonitic granite sills within the lower member of the Mount Fosthall composite gneiss unit (U-Pb zircon, Carr, Chapter 1)

Plate 2.4. (a) Contact between ultramafic pod and overlying migmatitic pelitic schist of the lower member of the Mount Fosthall composite unit (?Lardeau Group). S2 foliation and S3 folding obscures primary contact relationships. (b) F3 fold hinge in Vidler calcsilicate gneiss on east shore of Sugar Lake. (c) Ultramafic pod within the Outlet Creek ultramafic bearing unit, east of Vidler Ridge, thought to be part of the Kaslo Group. (d) Clasts of diorite, mafic and felsic amphibolite and psammite in the Mount Mafic amphibolite gneiss near Cherry Creek.

Plate 2.5. (a) Psammitic interlayers within the Snow Mountain schist (?Slocan Group). (b) Leucocratic hornblende bearing potassium feldspar megacrystic quartz monzonite of the Whatshan batholith. Weak foliation and weakly developed cataclastic fabrics and fractures. (c) Eastward view from Sugar Mountain of sills of Ladybird granite intruding the Gold Range assemblage. Note: blocks in foreground are in place. (d) North-verging F2 folds refolded by F3 fold (Goat Mountain).

Plate 2.6. (a) Three phases of superposed folds (Twin Peaks). F2 axial surface trace (outlined by pebbles) is folded by upright F3 and overprinted by S4 crenulation cleavage. (b) F3 hinge in calcisilicate gneiss (Mount Fosthall). (c) Steeply plunging biotite bearing L3 lineation (Snow Mountain). (d) Shallow plunging F4 crenulations (Snow Mountain).

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**Appendix 2.1 U-Pb zircon and titanite
ages of three Mesozoic igneous rocks south of the Thor-Odin - Pinnacles area,
southern Omineca Belt, British Columbia**

Introduction

U-Pb zircon and titanite dating of intrusive rocks, from the vicinity south of the Thor-Odin - Pinnacles area between Valhalla complex and the Okanagan Valley, was done in the course of a regional study along Lines 6 to 10 of the 1989 Southern Cordilleran LITHOPROBE seismic reflection transect (Figure 2.8). Rocks generally designated as the Middle Jurassic Whatshan batholith on most previous compilation maps are in fact composed of three igneous bodies of different ages, a Middle Jurassic granodiorite of the Nelson suite, Late Cretaceous quartz monzonite of the Whatshan batholith and Caribou Creek stock and the Paleocene to Eocene Ladybird leucogranite (Figure 2.8). The purpose of this paper is to present the U-Pb geochronology of three Mesozoic rocks and the revised geologic map of the area.

Middle Jurassic Nelson suite

A Middle Jurassic granodiorite, herein named the Spruce Grove batholith, is an irregular shaped body exposed over an area of at least 900 km² mainly southwest of the Monashee Pass on the Monashee Highway. It is a medium grained hornblende and biotite bearing granodiorite and was examined and sampled along the Monashee Highway (SC919, Figure 2.8 and Table 2.4). The contacts shown on Figure 2.8 are based on those mapped by Little (1957) to the south of the highway, and Okulitch (1979) to the north of the highway.

A hornblende bearing leucogranite stock which occurs on the western flank of Scalping Knife Mountain, in the footwall of the Columbia River fault, was also dated (SC545, Figure 2.8). It has a weak protomylonitic fabric and stretching lineation. This

deformation fabric was imposed on the rock during easterly-directed shearing on the east-dipping Columbia River fault (Figure 2.8; Carr 1989).

Late Cretaceous Whatshan batholith

The Whatshan batholith is predominantly a leucocratic quartz monzonite and is lithologically distinct from granodiorite of the Jurassic Nelson suite. The batholith covers an area of at least 1000 km² and extends from east of Arrow Lake to Inonoaklin Mountain ~30 km west of Arrow Lake. The Cariboo Creek stock east of Burton (Hyndman 1968; Read and Wheeler 1976) is considered to be part of the batholith since the rocks are of similar lithology and age (Parrish, unpublished data 1985-1987) and the stock is continuous with the Whatshan batholith.

The most common phase of the Whatshan batholith is a hornblende bearing potassium feldspar - megacrystic leucocratic quartz monzonite to granite; however, a potassium feldspar megacrystic melanocratic diorite phase was mapped on the south flank of Whatshan Peak. Seismic reflection data indicates that the batholith is sheetlike in nature and is probably >2 km thick (Carr, Chapter 2). The Whatshan batholith is variably deformed; igneous flow textures predominate in exposures along the Monashee Highway, chloritized cataclastic fault rocks are present along the traces of north-south steep early Tertiary normal faults (Figure 2.8) and a well developed foliation and stretching lineation is present along the northern contact and on the shores of Lower Arrow Lake. Paragneiss screens in the quartz monzonite on the shores of Arrow Lake have been folded by F2 and F3 coaxial folds (Carr, Chapter 2). The Whatshan was folded by regional F3 folds; outcrop scale minor folds were mapped near Arrow Lake and the near-vertical northern contact of the batholith on Whatshan Mountain lies on the steep limb of an F3 anticline (Carr, Chapter 2). The 77 Ma age of the Whatshan batholith places a maximum limit on F3 folding in the Pinnacles area.

Paleogene Ladybird leucogranite

The Paleocene - Eocene Ladybird leucogranite suite, originally named the "Valhalla series" (Little 1957, 1960, 1961), occurs as pervasive granite plutons, stocks, and sheets and pegmatite sheets and dykes which were emplaced into amphibolite-facies rocks of the Thor-Odin-Pinnacles area, on the west and northern flanks of the Monashee complex, in the Valhalla complex and within amphibolite-facies gneisses between Valhalla complex and the Okanagan Valley (Figure 2.8). The geochronology and field relationships of this suite are presented in Parrish et al. (1988) and Carr (1989, Chapter 1).

U-Pb geochronology

Analytical techniques

Mineral separates were obtained by standard crushing, grinding, Rogers Gold™ table, heavy liquid and Frantz magnetic separation techniques carried out on 20-25 kg rock samples. Zircons and titanites were sieved in alcohol, and small populations of the clearest and most crack-free and inclusion-free grains were selected for analysis. Zircons from SC545 were not abraded; however all zircon fractions from SC919 and SC920 were abraded using techniques based on those of Krogh (1982). Zircon and titanite fractions were dissolved in teflon micro-capsules (Parrish 1987) with a mixed ^{205}Pb - ^{233}U - ^{235}U tracer (Parrish and Krogh 1987). Mineral dissolution, ion exchange column chemistry, mass spectrometry, error prorogation and data reduction were done following procedures described by Krogh (1973), Parrish et al. (1987) and Roddick (1987). Isotopic compositions of Pb and U were measured on a Finnigan-MAT 261 variable multicollector mass spectrometer as described by Roddick et al. (1987). Procedural U blanks were less than 2 pg and Pb blanks generally ranged from 7 to 20 pg. Common Pb corrections were done assuming model Pb compositions derived from the growth curve

of Stacey and Kramers (1975) using ca. 60 Ma model Pb. Decay constants are those recommended by Steiger and Jäger (1977).

Errors in U/Pb ratios reflect one standard error (Table 2.5) and error ellipses on concordia plots are 2 standard errors. An analysis is considered to be concordant if the error ellipse overlaps concordia; the mean intersection of the error ellipse with concordia is interpreted as the age of the rock unless mentioned otherwise. Errors attached to the interpreted age correspond to the deviation of the ellipse from the mean (Parrish et al. 1987).

The discordance of most zircon analyses reflects multiple ages of inheritance; consequently analyses, especially for small numbers of crystals, do not fall on a discordia line (Figures 2.9-2.11).

Age Interpretations

Zircons and titanites from three samples were analysed. Sample locales are described in Table 2.4 and shown on Figure 2.8, analytical data is summarized in Table 2.5 and concordia diagrams are presented in Figures 2.9-2.12. On Table 2.5 and the concordia plots, zircons are designated by letters and titanites by numbers.

Zircons from all three samples are clear and colourless with minor inclusions and cracks. The crystals are faceted and euhedral with sharp terminations, and are interpreted to have an igneous morphology. The clearest most crack-free crystals with small or no apparent cores were chosen for analysis. Slightly cloudy inclusion-ridden cores in the central part of the crystal were commonly observed in the Middle Jurassic samples (SC545 and SC920) and only rarely in the Whatshan sample (SC919). The presence of an inherited Pb component showed up clearly in samples SC545 and SC919.

Titanites are clear and yellow with numerous inclusions. They occur in fragments or as euhedral crystals and are interpreted to have an igneous morphology.

Spruce Grove batholith

The 174.8 $\pm$ 0.8 Ma age interpretation of the Spruce Grove sample SC919 is based on concordant zircon fraction C, which overlaps with the titanite analysis (Figure 2.9). Fractions A and B clearly indicate a component of inherited Pb.

Stock on Scalping Knife Mountain

The U-Pb data for SC545 are discordant and do not allow a precise age determination to be made; however the discordance pattern is consistent with a Middle or Late Jurassic age and substantial Pb loss (Figures 2.10 and 2.11). The titanite age of 64.0 $\pm$ 2.0 Ma is a cooling age and is similar in age to those throughout the Thor - Odin - Pinnacles area (Figure 2.7) and Valhalla complex (Parrish et al. 1988).

Whatshan batholith

Three zircon and one titanite fractions from sample SC920 were analysed and the 77 $\pm$ 0.5 Ma age interpretation is based on concordant fraction C (Figure 2.12). Fractions A and B exhibit small components of inherited radiogenic Pb. The titanite analysis plots above concordia because the Stacey-Kramers common Pb correction that was applied probably does not correctly represent the composition of the common Pb component. The large error ellipse results from a significant common Pb correction within the titanite crystal and its internal inclusions.

The 77 Ma U-Pb zircon age is consistent with U-Pb data from two samples of the lithologically identical Caribou Creek stock near the east shores of Arrow Lake (Parrish, unpublished data 1985).

Conclusions

Igneous rocks along the Monashee Highway between the Valhalla complex and the Okanagan valley that have been previously grouped together and referred to as the Whatshan batholith have been subdivided on the basis of lithology and U-Pb geochronology into the Middle Jurassic Spruce Grove batholith in the west and the Late Cretaceous Whatshan batholith in the east (Figure 2.8). U-Pb zircon dating shows that the Spruce Grove batholith is 174.8 ± 0.8 Ma and the Whatshan batholith is 77 ± 0.5 Ma. The 77 Ma age places a maximum age limit on regional F3 folding in the Pinnacles area.

Table 2.4: U-Pb Sample localities (Mesozoic igneous rocks)

Sample number	Description
SC545	medium grained, hornblende - biotite bearing granite in footwall of Columbia River fault, weakly foliated and lineated, 100 m above the Trading Post on west flank of Scalping Knife Mountain (82 K/4), elevation 1900', UTM 435360E-5545580N
SC919	medium grained, hornblende - biotite granodiorite, ~ 2 km west of Spruce Grove on the Monashee Highway (82 L/2), elevation 3900', UTM 389550E-5547350N
SC920	K-feldspar megacrystic, hornblende bearing, leucocratic quartz monzonite, east of the Kettle River on the Monashee Highway (82 L/2), elevation 4000', UTM 43924000E-5546100N

TABLE 2.5 U-Pb ANALYTICAL DATA (MESOZOIC IGNEOUS ROCKS)

Fraction [†]	Wt. U (mg)	Pb [*] (ppm)	$\frac{206\text{Pb}}{204\text{Pb}}$ (pg)	Pb _c [@] 208Pb ^{**} (%)	$\frac{206\text{Pb}}{238\text{U}}$	$\frac{207\text{Pb}}{235\text{U}}$	Corr. coeff.	$\frac{207\text{Pb}}{206\text{Pb}}$	207Pb/206Pb Age (Ma) ^{^^}		
SC 545											
A	0.107	1790	42.3	16464	18	4.8	0.02485±0.14%	0.1819 ±0.15%	0.98	0.05309±0.03%	332.8±1.3
B	0.090	1169	27.2	5221	31	5.6	0.02434±0.14%	0.1713 ±0.15%	0.96	0.05105±0.04%	243.1±1.7
C	0.040	2438	53.6	10900	13	4.4	0.02330±0.11%	0.1601 ±0.12%	0.96	0.04985±0.03%	187.9±1.5
1	0.084	286	2.97	74	278	12.9	0.01004±0.60%	0.06408±2.0%	0.68	0.04629±1.7%	12.8±79
SC 919											
A	0.057	310	11.2	1206	33	10.5	0.03563±0.09%	0.2700 ±0.12%	0.87	0.05495±0.06%	410.3±2.7
B	0.041	387	14.9	2101	18	13.1	0.03645±0.10%	0.3231 ±0.11%	0.88	0.06429±0.05%	751.2±2.2
C	0.056	330	9.29	1074	31	11.8	0.02747±0.09%	0.1876 ±0.13%	0.85	0.04954±0.07%	173.3±3.2
2	0.107	43.2	2.46	89	113	56.4	0.02739±0.54%	0.1839 ±1.8%	0.69	0.04871±1.5%	133.8±70
SC920											
A	0.089	1157	14.5	3078	27	9.4	0.01259±0.10%	0.08304±0.11%	0.91	0.04782±0.05%	90.3±2.2
B	0.105	1114	13.3	1150	82	5.6	0.01249±0.12%	0.08246±0.17%	0.82	0.04788±0.10%	93.4±4.6
C	0.094	1349	15.5	876	113	5.7	0.01202±0.11%	0.07871±0.20%	0.75	0.04750±0.13%	74.4±6.4
1	0.115	187	3.03	125	154	33.1	0.01206±0.40%	0.07719±1.3%	0.69	0.04644±1.1%	20.7±52

[†]Letters are zircon fractions; numerals are titanite fractions; abr=2-6 hours of abrasion.

^{*}Radiogenic Pb, corrected for spike, fractionation, blank and common Pb.

[@]Measured ratio, corrected only for spike and fractionation.

^aTotal common Pb in analysis.

^{**}Radiogenic ^{208}Pb , expressed as % of total radiogenic Pb.

[^]Uncertainties are 1-sigma %.

^{^^}Uncertainties are 2-sigma in Ma.

FIGURE 2.8 Geology of the Thor-Odin - Pinnacles area and surrounding area with U-Pb and K-Ar sample locations and ages

LEGEND

UPPER CRUSTAL ZONE

MIDDLE JURASSIC NELSON INTRUSIVE SUITE: predominantly granodiorite

PALEOZOIC - LOWER JURASSIC STRATIFIED ROCKS:

MIDDLE CRUSTAL ZONE

LATE PALEOCENE - EARLY EOCENE LADYBIRD GRANITE SUITE: biotite granite, quartz monzonite, leucocratic pegmatite (also includes areas with pegmatite with <50% metamorphic rocks)

LATE CRETACEOUS WHATSHAN BATHOLITH (includes Cariboo Creek stock): hornblende biotite bearing K-feldspar megacrystic quartz monzonite, mafic hornblende biotite diorite

LATE PROTEROZOIC - MESOZOIC AMPHIBOLITE FACIES METAMORPHIC ROCKS:

BASEMENT ZONE

PROTEROZOIC CRYSTALLINE BASEMENT AND LATE PROTEROZOIC - (?) CAMBRIAN COVER GNEISSES

GEOLOGIC CONTACT: mapped, compiled from published maps, assumed

LOW - MODERATE ANGLE EOCENE NORMAL FAULT (PEGS ON HANGING WALL)

STEEP EOCENE NORMAL FAULT (PEGS ON HANGING WALL)

STEEP EOCENE NORMAL FAULT: sense of displacement uncertain

LITHOPROBE LINE

SC919 GEOCHRONOLOGY SAMPLE LOCATION WITH U-Pb AND K-Ar AGES; (h) = K-Ar hornblende; (t) = U-Pb titanite; (z) = U-Pb zircon

BF	BEAVEN FAULT
CF	CHERRYVILLE FAULT
CRF	COLUMBIA RIVER FAULT
GCSZ	GWILLIM CREEK SHEAR ZONES
MD	MONASHEE DECOLLEMENT
OF	OKANAGAN VALLEY - EAGLE RIVER FAULT SYSTEM
SLFZ	SLOCAN LAKE FAULT ZONE
SSZ	SLATE MOUNTAIN SHEAR ZONE
VSZ	VALKYR SHEAR ZONE

Figure 2.9 Concordia diagram of SC919 U-Pb zircon and titanite analyses (see text for interpretation).

Figure 2.10 Concordia diagram of SC545 U-Pb zircon and titanite analyses (see text for interpretation).

Figure 2.11 Detail of SC545 concordia curve.

Figure 2.12 Concordia diagram of SC920 U-Pb zircon and titanite analyses (see text for interpretation).

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Appendix 2.2 U-Pb metamorphic zircon and titanite geochronology from amphibolites in the southern Thor-Odin area, southern Omineca Belt, British Columbia

Introduction

U-Pb ages of metamorphic zircons and titanites from four amphibolite gneisses from the southern flank of Thor-Odin culmination range from 55 to 61 Ma (Figure 2.13 and Table 2.6). Although these rocks have clearly undergone protracted deformation and metamorphism (Carr, Chapter 2), the metamorphic zircons and titanites either did not grow or did not retain radiogenic Pb until the Late Paleocene - Early Eocene.

U-Pb geochronology

Analytical techniques

Mineral separates were obtained by standard crushing, grinding, Rogers Gold™ table, heavy liquid and Frantz magnetic separation techniques carried out on 20-25 kg rock samples. Zircons and titanites were sieved in alcohol, and small populations of the clearest and most crack-free and inclusion-free grains were selected for analysis. Zircon and titanite fractions were dissolved in teflon micro-capsules (Parrish 1987) with a mixed ^{205}Pb -. ^{233}U -. ^{235}U tracer (Parrish and Krogh 1987). Mineral dissolution, ion exchange column chemistry, mass spectrometry, error prorogation and data reduction were done following procedures described by Krogh (1973), Parrish et al. (1987) and Roddick (1987). Isotopic compositions of Pb and U were measured on a Finnigan-MAT 261 variable multicollector mass spectrometer as described by Roddick et al. (1987). Procedural U blanks were less than 2 pg, and Pb blanks generally range from 2 to 11 pg (Table 2.7). Common Pb corrections were done assuming model Pb compositions derived from the growth curve of Stacey and Kramers (1975) using ca. 60 Ma model Pb. Decay constants are those recommended by Steiger and Jäger (1977).

Errors in U/Pb ratios reflect one standard error (Table 2.7) and error ellipses on concordia plots are 2 standard errors. An analysis is considered to be concordant if the error ellipse overlaps concordia; the mean intersection of the error ellipse with concordia is interpreted as the age of the rock unless mentioned otherwise. Errors attached to the interpreted age (Figure 2.13 and Table 2.6) correspond to the deviation of the ellipse from the mean (Parrish et al. 1987).

Titanite error ellipses tend to be large and are not centered on the concordia curve. This probably reflects a large correction due to common Pb within both the crystal and inclusions, and that the common Pb composition predicted by the Stacey-Kramers growth curve does not correctly represent the common Pb correction.

Age Interpretations

Zircons from two of the samples and titanites from three of the samples were analysed. Sample locales are described in Table 2.8 and shown on Figure 2.13, analytical data is summarized in Table 2.7 and concordia diagrams are presented in Figures 2.14-2.17. On Table 2.7 and the concordia plots, zircons are designated by letters and titanites by numbers.

Zircons are present in samples SC5567 and SC575 and are clear and colourless with minor inclusions and cracks and without visible cores. The crystals are generally rounded with some faceted surfaces and are interpreted to have a metamorphic morphology. The exception is fraction D of SC567; the zircon crystals, which are $<74 \mu$, are oval shaped and have visible cores. They are probably inherited zircons with metamorphic overgrowths.

Titanites are clear and yellow with numerous inclusions. They occur in fragments or as euhedral crystals and are interpreted as metamorphic crystals.

The 60.0 $\pm$ 1.0 Ma age of metamorphic zircons in SC567 is based on concordant fractions A, B, and C (Figure 2.14) and is coincident with titanite fraction 1. Fraction D is discordant due to a component of inherited radiogenic Pb.

The 61.0 $\pm$ 0.5 age of SC575 metamorphic zircons (Figure 2.15) is based on the lower intercept of a regression line through all three fractions (MSWD = 1). The upper intercept of the regression line is 1424 $\pm$ 150 and reflects a Proterozoic inherited component.

Three overlapping analyses from titanites in SC559 are 55.0 $\pm$ 1.0 Ma. The age is based on the intersection of the concordia curve and the centre of the error ellipse of fraction 3, the fraction with the smallest error (Figure 2.16).

The 58.0 $\pm$ 4 Ma titanite age of four fractions from SC569 is based on the intersection of the error ellipses with the concordia curve (Figure 2.17).

Conclusions

Metamorphic zircon and titanite from four samples of amphibolite gneiss from the southern flank of the Thor-Odin culmination yield ages that range from 55-61 Ma. The best constrained ages are 60 and 61 Ma metamorphic zircon ages from samples SC567 and SC575.

Table 2.6: Summary of U-Pb metamorphic zircon and titanite ages of amphibolites from the southern flank of the Thor-Odin culmination

Sample number	Location	Mineral	Age (Ma)
SC559	Gold Range assemblage; north flank of Mount Fosthall; hanging walls of the Monashee décollement and the Slate Mountain shear zone	titanite	55.6 +/- 1.0
SC567	Gold Range assemblage; south flank of Mount Fosthall; hanging walls of the Monashee décollement and the Slate Mountain shear zone	zircon titanite	60.0 +/- 1.0 61.0 +/- 3.0
SC569	Paragneiss thrust slice within the Cariboo duplex, Monashee décollement	titanite	58.0 +/- 4.0
SC575	Fawn Lake assemblage; hanging wall of the Monashee décollement zone and footwall of the Slate Mountain shear	zircon	61.0 +/- 0.5

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

TABLE 2.7: U-Pb ANALYTICAL DATA

Fraction ¹	wt. U (mg)	U (ppm)	Pb ^a (ppm)	$\frac{206\text{pb}}{204\text{pb}}$	Pb _c ^a (pg)	208Pb^{**} (%)	$\frac{206\text{pb}}{238\text{U}}$	$\frac{207\text{pb}}{235\text{U}}$	Corr. coeff.	$\frac{207\text{pb}}{206\text{pb}}$	$\frac{207\text{pb}}{206\text{pb}}$ Age (Ma)
SC 567											
A	0.061	90.7	1.54	63	41	61.8	0.009413 ± 1.9%	0.06059 ± 3.3%	0.68	0.04669 ± 2.4%	33.3 ± 116
B	0.084	89.9	1.51	66	54	58.9	0.009351 ± 1.8%	0.06079 ± 3.2%	0.68	0.04715 ± 2.3%	56.7 ± 111
C	0.068	179	2.13	114	42	41.3	0.009370 ± 0.86%	0.06070 ± 1.5%	0.67	0.04698 ± 1.1%	48.2 ± 55
D	0.063	743	14.4	125	478	19.3	0.017195 ± 0.51%	0.13086 ± 1.4%	0.69	0.05520 ± 1.1%	420.2 ± 48
1	0.189	26.4	0.408	30	271	43.3	0.009589 ± 2.9%	0.05796 ± 13.0%	0.63	0.04383 ± 11.3%	-120.0 ± 580
SC559											
1	0.050	60.0	1.40	41	76	48.4	0.008743 ± 2.0%	0.05605 ± 6.5%	0.69	0.04649 ± 5.3%	23.2 ± 255
2	0.095	64.6	0.373	62	78	47.2	0.008723 ± 1.0%	0.05638 ± 3.3%	0.68	0.04688 ± 2.7%	42.9 ± 128
3	0.147	72.2	0.599	86	86	34.0	0.008606 ± 0.68%	0.05615 ± 2.2%	0.67	0.04732 ± 1.8%	65.4 ± 88
SC 575											
A	0.023	1917	4.27	2469	12	7.0	0.009597 ± 0.11%	0.06336 ± 0.13%	0.85	0.04788 ± 0.07%	93.5 ± 3.2
B	0.173	849	8.42	1867	53	5.1	0.010408 ± 0.12%	0.07336 ± 0.15%	0.84	0.05112 ± 0.08%	246.1 ± 3.7
C	0.154	1383	12.3	7451	17	3.0	0.009576 ± 0.12%	0.06267 ± 0.13%	0.96	0.04746 ± 0.03%	72.6 ± 1.6
SC 569											
2	0.106	44.6	0.792	26	403	50.8	0.009484 ± 7.5%	0.07632 ± 19.0%	0.69	0.05836 ± 14.9%	543.5 ± 687
3	0.199	44.8	0.789	27	623	50.8	0.009417 ± 6.3%	0.07651 ± 15.6%	0.69	0.05892 ± 12.1%	564.2 ± 548
4	0.312	46.3	0.830	27	1019	51.1	0.009543 ± 6.3%	0.08486 ± 14.4%	0.69	0.06450 ± 11.0%	758.0 ± 477
5	0.192	54.4	0.968	26	799	52.0	0.009281 ± 6.1%	0.08260 ± 14.2%	0.68	0.06455 ± 11.0%	759.8 ± 475

¹Letters are zircon fractions; numerals are titanite fractions.

^aRadiogenic Pb, corrected for spike, fractionation, blank and common Pb.

[#]Measured ratio, corrected only for spike and fractionation.

^gTotal common Pb in analysis.

^{**}Radiogenic 208Pb , expressed as % of total radiogenic Pb.

[†]Uncertainties are 1-sigma %.

^{††}Uncertainties are 2-sigma in Ma.

**TABLE 2.8 U-Pb METAMORPHIC ZIRCON AND TITANITE
SAMPLE DESCRIPTIONS AND LOCATIONS**

Sample number	Description
SC559	foliated, folded, hornblende - plagioclase amphibolite gneiss, south flank of Mount Fosthall, ultramafic locale (82 L/8), elevation 6500', UTM 413660E-5589900N
SC567	well foliated hornblende - plagioclase bearing amphibolite gneiss, north flank of Mount Fosthall (82 L/8), elevation 7100', UTM 4132230E-5592160N
SC569	folded, foliated hornblende - plagioclase bearing amphibolite gneiss, Cariboo Alp (82 L/9), elevation 7200', UTM 415150E- 559660N
SC575	foliated hornblende - biotite - plagioclase bearing amphibolite gneiss, west of Mount Symonds (82 L/8), elevation 7200', UTM 420540E-5592400N

FIGURE 2.13 Geology of the Thor-Odin - Pinnacles area and surrounding area with U-Pb and K-Ar sample locations and ages

LEGEND

UPPER CRUSTAL ZONE

MIDDLE JURASSIC NELSON INTRUSIVE SUITE: predominantly granodiorite

PALEOZOIC - LOWER JURASSIC STRATIFIED ROCKS:

MIDDLE CRUSTAL ZONE

LATE PALEOCENE - EARLY EOCENE LADYBIRD GRANITE SUITE: biotite granite, quartz monzonite, leucocratic pegmatite (also includes areas with pegmatite with <50% metamorphic rocks)

LATE CRETACEOUS WHATSHAN BATHOLITH (includes Cariboo Creek stock): hornblende biotite bearing K-feldspar megacrystic quartz monzonite, mafic hornblende biotite diorite

LATE PROTEROZOIC - MESOZOIC AMPHIBOLITE FACIES METAMORPHIC ROCKS:

BASEMENT ZONE

PROTEROZOIC CRYSTALLINE BASEMENT AND LATE PROTEROZOIC - (?) CAMBRIAN COVER GNEISSES

GEOLOGIC CONTACT: mapped, compiled from published maps, assumed

LOW - MODERATE ANGLE EOCENE NORMAL FAULT (PEGS ON HANGING WALL)

STEEP EOCENE NORMAL FAULT (PEGS ON HANGING WALL)

STEEP EOCENE NORMAL FAULT: sense of displacement uncertain

LITHOPROBE LINE

SC919

GEOCHRONOLOGY SAMPLE LOCATION WITH U-Pb AND K-Ar AGES;(h) = K-Ar hornblende; (t) = U-Pb titanite; (z) = U-Pb zircon

BF	BEAVEN FAULT
CF	CHERRYVILLE FAULT
CRF	COLUMBIA RIVER FAULT
GCSZ	GWILLIM CREEK SHEAR ZONES
MD	MONASHEE DECOLLEMENT
OF	OKANAGAN VALLEY - EAGLE RIVER FAULT SYSTEM
SLFZ	SLOCAN LAKE FAULT ZONE
SSZ	SLATE MOUNTAIN SHEAR ZONE
VSZ	VALKYR SHEAR ZONE

Figure 2.14 Concordia plot of SC567 metamorphic zircons and titanites

Figure 2.15 Concordia plot of SC575 metamorphic zircons and titanites

Figure 2.16 Concordia plot of SC559 metamorphic titanites

Figure 2.17
Concordia plot of SC 569 metamorphic titanites

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CHAPTER 3

Late Cretaceous - Eocene tectonic evolution of Thor-Odin - Pinnacles area and implications for the southern Omineca Belt, British Columbia

Abstract

The culmination of the penetrative contractional deformation and the accompanying metamorphic peak attained within gneisses of the Shuswap metamorphic complex is Cretaceous-Paleogene. A substantial part of the motion on the Monashee décollement occurred at this time as part of a Cretaceous - Paleocene thrust system that transferred shortening eastward to the Rocky Mountain Foreland Belt. The rocks at higher structural levels show little evidence of deformation at this time, indicating that contractional strain was partitioned within the crust during the youngest part of the compressional history of the southern Omineca Belt. Rocks in the Thor-Odin - Pinnacles area and Valhalla complex cooled rapidly at rates of $\sim 25^{\circ}\text{C/Ma}$ during the early Tertiary, consistent with denudation on crustal-scale normal faults known to be active in the Eocene.

Introduction

The Mesozoic - early Tertiary tectonic evolution of the southern Canadian Cordillera includes Early-Middle Jurassic and Late Cretaceous suturing of superterrane to the western margin of North America, Mesozoic-Paleogene contraction and crustal thickening, Cretaceous-Paleogene strike-slip faulting and Paleogene crustal extension (Monger et al. 1982; Price et al. 1985, and references therein; Parrish et al. 1988).

The Omineca Belt (Figure 3.1) comprises allochthonous Proterozoic - Early Jurassic rocks of the Intermontane Superterrane that were obducted onto and imbricated with Proterozoic-Paleozoic rocks deposited on the western margin of ancient North America. In the southern Omineca Belt, the accretion of the Intermontane Superterrane, contractional Early-Middle Jurassic polyphase deformation and metamorphism, and the intrusion of post-tectonic Middle Jurassic plutons is well documented (Monger et al. 1982, and references therein; Klepacki 1985; Upper Crustal Zone, Figure 3.1).

Renewed orogenesis in the Cretaceous-Paleocene included the accretion of the Insular Superterrane to the western margin, deformation in the western part of the orogen and progressive easterly directed shortening in the Foreland Belt (Monger et al. 1982; Price et al. 1985).

The present crustal structure of the southern Omineca Belt is a result of Eocene crustal extension and crustal thinning superimposed on a crust that was thickened to ~60 km during Mesozoic - early Tertiary compression and shortening. In the Shuswap metamorphic complex, high-grade gneisses with an early Tertiary cooling history are exposed in structural culminations, such as the Monashee, Okanagan and Valhalla complexes (Figure 3.1). They were polydeformed during contraction, were exhumed from depths in excess of 20 km, in part during Eocene crustal extension by movement on low- to moderate-angle plastic-brittle normal faults, such as the Okanagan Valley - Eagle River, Columbia River and Valkyr - Slocan Lake fault systems (Figure 3.1), and cooled in the early Tertiary.

In the Omineca Belt at the latitude of the Thor-Odin - Pinnacles area, the rocks in the hanging walls of the extensional faults (Upper Crustal Zone, Figure 3.1) underwent penetrative contractional deformation and metamorphism prior to and during the Middle Jurassic (Read and Wheeler 1976; Parrish and Wheeler 1983). They were uplifted and cooled during the Mesozoic (Archibald et al. 1983; Parrish et al. 1988, and references therein), and there is little evidence of Late Cretaceous - Paleocene orogenesis at this structural level in this part of the Omineca Belt.

Prior to the recognition of the importance and extent of Eocene extensional faulting in the southern Omineca Belt and prior to U-Pb studies within the gneiss complexes, the unequivocal pre-Middle Jurassic timing of deformation in the Upper Crustal Zone lent support to the inference that metamorphism and deformation within the gneiss complexes had occurred in the Middle Jurassic as well (Okulitch 1984; Brown et al. 1986, and references therein). U-Pb geochronology related studies in Valhalla complex revealed

the existence of profound plutonism and deformation that was Late Cretaceous and younger (Parrish 1984; Carr et al. 1987; Parrish et al. 1988) as does this study (Carr, Chapters 1 and 2). These data require a reevaluation of the timing of deformation within the southern Omineca Belt. This paper summarizes relevant data from the Thor-Odin - Pinnacles area (Carr, Chapters 1 and 2) and reviews published data from Valhalla complex and the Monashee complex which demonstrate that the *culmination* of penetrative contractional deformation and the accompanying metamorphic peak *within* the high-grade complexes occurred during the Late Cretaceous-Paleogene, contrary to views entrenched in the literature.

While recognizing the importance of Jurassic deformation and metamorphism in the Omineca Belt as a whole, a significant amount of deformation and the peak of metamorphism within the Middle Crustal Zone occurred in the Late Cretaceous to Paleocene. The data are consistent with the view that contractional deformation and crustal thickening occurred throughout the Mesozoic - Paleocene, that peak temperature and pressure conditions in rocks now exposed in the Monashee, Okanagan and Valhalla complexes were attained in the Late Cretaceous-Paleogene and that a significant amount of polydeformation within the gneisses and movement on deep-seated thrust faults occurred in the Late Cretaceous-Paleogene and fed into the Foreland Belt. Deformation and metamorphism in mid-crustal rocks outlasted that at higher structural levels, implying that strain was partitioned within the crust during the youngest compressional history of the Omineca Belt. The data also indicate that extensional deformation closely followed or overlapped with the final stages of thrusting in the latest Paleocene - earliest Eocene.

Southern Omineca Belt - regional geology

The superposition of crustal-scale extension on a crust that was deformed and thickening during compression has resulted in the juxtaposition of three crustal zones at

the surface in the southern Omineca Belt at the latitude of the Thor-Odin - Pinnacles area and Valhalla complex. These are the Basement, Middle Crustal and Upper Crustal zones (Figure 3.1). They were deformed and cooled at different times, and are separated from each other by regional-scale shear zones. The deepest crustal level, the Basement Zone, is exposed in the Monashee complex, a tectonic window within the Middle Crustal Zone. Middle Crustal Zone rocks were carried in the hanging walls of deep-seated thrust faults, such as the Monashee décollement, and are bounded on the top by a system of outwardly dipping crustal-scale normal faults (Figure 3.1). Together the Basement Zone and Middle Crustal Zone make up the Shuswap metamorphic complex. The Middle Crustal Zone is characterized by penetrative early Tertiary plastic strain (Parrish et al. 1988), intrusion of the Late Paleocene - Eocene leucogranite suite (Carr 1989; Carr, Chapter 1) and an early Tertiary cooling history (Carr, Chapter 2 and references therein). In contrast, rocks of the Upper Crustal Zone, in the hanging walls of the extensional faults, experienced Middle Jurassic deformation, Mesozoic plutonism and cooling (Brown and Tippet 1978; Read and Wheeler 1976; Parrish and Wheeler 1983; Parrish and Armstrong 1988) and predominantly brittle extensional deformation during the Eocene.

Basement Zone - Monashee complex

The Basement Zone consists mainly of crystalline North American basement exposed in the Monashee and Malton complexes (Figure 3.1). The Monashee complex is exposed in the footwall of the Monashee décollement, a crustal-scale easterly directed ductile thrust fault with ~100 km of displacement, which is arched over the Monashee complex and is exposed on its margins (Brown et al. 1990, and references therein). The décollement is a fundamental detachment which stripped cover from basement rocks.

Frenchman Cap and Thor-Odin are second order domal culminations within the Monashee complex. The rocks in the complex comprise Early Proterozoic para and orthogneisses of the North American crystalline basement (Evenchick et al. 1984, and

references therein; Parrish and Ross 1989, 1990,) which are unconformably overlain by a depositionally attenuated Proterozoic to Cambrian cover gneiss sequence (Höy and Goodwin 1988; Parrish and Scammell 1988; Scammell and Brown 1990, and references therein).

Three phases of folding have been documented in the Monashee complex, and there is no clear evidence of a phase of deformation that predates deposition of the cover gneiss (McMillan 1970; Wheeler 1965; Read 1989; Höy 1987; Brown 1980; Read and Klepacki 1981; Reesor and Moore 1971; Journeay 1986). Easterly verging D1 folds and thrusts imbricate basement and cover rocks in the core of Frenchman Cap culmination in the footwall of the Monashee décollement. This first phase of deformation occurred prior to the peak of metamorphism. The timing of deformation is uncertain, and it has been suggested by previous workers that the deformation is Precambrian, Paleozoic or Middle Jurassic (Okulitch 1984, and references therein; Brown et al. 1986, and references therein). A Cambrian common Pb date from sulfides in the Cottonbelt deposit within the upper part of the cover gneiss sequence may preclude a Precambrian age (Höy and Goodwin 1988).

Second phase tight to isoclinal northeasterly and northerly verging folds are syn-metamorphic and are, in part, synchronous with early movement on the Monashee décollement (Journeay 1986). F3 northeasterly verging folds postdate the metamorphic peak and most of the shearing associated with the Monashee décollement.

Middle Crustal Zone

Thor-Odin - Pinnacles area

Amphibolite-facies Middle Crustal Zone rocks of the Thor-Odin - Pinnacles area were carried in the hanging wall and are bounded at the base by the Monashee décollement. The Columbia River and Okanagan Valley - Eagle River extensional fault systems (Figure 3.1) form the upper boundary of the Middle Crustal Zone. These fault

systems are exposed on the east and west margins of the area (Figure 3.2). Two tectonostratigraphic packages within the area, the Fawn Lake and Gold Range assemblages are thought to be correlative, respectively, with the semipelite-amphibolite division of the Early Proterozoic Horsethief Creek Group and with the Cambrian to Mesozoic strata of North America, Kootenay terrane and Quesnellia (Carr 1989, Chapter 2). Middle Crustal rocks are intruded by plutons, stocks and pegmatite of the Paleocene to Eocene Ladybird granite (Carr, Chapter 1).

Early pre-metamorphic thrusts and folds throughout the area are overprinted and transposed by syn-metamorphic folds and shear zones; however, there is evidence, based on regional arguments, that at least part of this early deformation history may be Jurassic (Carr, Chapter 2). The formation of the predominant metamorphic foliation (S2) and north verging tight to isoclinal F2 folds were, in part, synchronous with the metamorphic peak and with shearing on the Monashee décollement (Carr, Chapter 2; Coleman 1989, 1990). The timing of the onset of D2 and associated thrust faults is uncertain; however, U-Pb dating of syn-tectonic and cross cutting granitoids proves that the Monashee décollement was active in the latest Paleocene and that motion had ceased by 58 +/- 0.5 Ma. F3 folds that formed during waning metamorphic conditions deformed Late Paleocene Ladybird leucogranites (Carr, Chapter 1). The Columbia River and Okanagan Valley - Eagle River normal fault systems were active in the Early and Middle Eocene, respectively (Parrish et al. 1988), although the time of the initiation of these faults is not certain.

Valhalla complex

The Valhalla complex comprises sheet-like layers of variably deformed paragneiss and Late Cretaceous to Eocene igneous rocks that are bounded on the top by the easterly directed Valkyr - Slocan Lake normal fault system (Parrish 1984; Carr 1986; Carr et al. 1987). The Valkyr shear zone is a plastic shear zone which is arched over the complex and was active between 59 and 56 Ma. The Slocan Lake fault zone is a plastic-brittle

normal fault that bounds the eastern margin of the complex, dips 30° to the east and extends to at least mid-crustal depths (Cook et al. 1987). Upper Crustal Zone rocks with a Cretaceous and older cooling history are confined to the hanging walls of the normal faults (Carr et al. 1987).

Sheets of the Late Cretaceous (100 Ma) Mulvey granodioritic gneiss and sheets of paragneiss are duplicated by spectacular plastic shear zones, the Gwillim Creek shear zones, at the deepest exposed levels of the complex (Figure 3.1). The shear zones are interpreted as deep-seated thrusts that are part of a décollement zone that accommodated eastward shortening of the Foreland Belt in the Late Cretaceous and Paleocene (Parrish et al. 1987; Parrish et al. 1988). High strain in the 100 Ma Mulvey gneiss and in an 88 Ma deformed pegmatite in the Gwillim Creek shear zone indicates that a substantial amount of motion is Cretaceous (Carr et al. 1987; Parrish et al. 1988; Parrish unpublished data 1985-1987). Field evidence indicates that the shear zones predate the emplacement of the 63 Ma Airy quartz monzonite (Reesor 1965; Carr et al. 1987).

Upper Crustal Zone (Kootenay Arc - Selkirk allochthon)

The first recognized evidence of Paleozoic and younger contractional deformation in the Upper Crustal Zone includes the following: an episode of penetrative deformation in rocks which predate a Devonian-Mississippian unconformity in the Paleozoic strata of the Kootenay Arc (Read and Wheeler 1976), talc schists and sheared horizons in the Cambrian-Ordovician Lardeau Group that are thought to represent a suture (Gehrels and Smith 1987) and Permian thrusts in the Kaslo Group (Klepacki 1985, Figure 2.5). Three phases of folding and metamorphism in the Early-Middle Jurassic include the obduction of the Intermontane Superterrane, an episode of westerly verging shortening during underthrusting and progressive easterly verging folding and shortening (Price et al. 1985, and references therein; Brown et al. 1986, and references therein). Early westward structures include the Scrip and Cairnes nappes, which are regional-scale recumbent folds

that have inverted limbs up to 60 km long (Raeside and Simony 1983; Simony et al. 1980; Brown and Lane 1989). F2 syn-metamorphic folds which occupy a large fan structure in the Selkirk Mountains are refolded by F3 folds (Brown and Tippet 1978). F1 and F2 structures and metamorphic isograds are crosscut by Middle Jurassic plutons (Read and Wheeler 1976; Parrish and Wheeler 1983). Post-tectonic Middle Cretaceous plutons have pressure aureoles, indicating that rocks that were deformed at 20-24 km were uplifted to ~10 km during the Mesozoic (Archibald et al. 1983).

Review of timing of deformation and thermal history within the Shuswap metamorphic complex

The following discussion reviews the evidence for the timing of deformation, metamorphism and cooling within the Middle Crustal Zone of the Thor-Odin - Pinnacles area and Valhalla complex and the Basement Zone of the Monashee complex.

Thor-Odin - Pinnacles area

Timing of deformation

A substantial Paleozoic and Jurassic contractional history predated the culmination of deformation and metamorphism (Carr, Chapter 2). The timing of the onset of D2 in the Thor-Odin - Pinnacles area is uncertain and may have been diachronous; however, a significant part of D2 deformation occurred in the Late Cretaceous-Paleogene. The deformed and folded 77 Ma Whatshan batholith in the southern part of the region indicates that development of the penetrative S2 regional foliation, at least in part, and regional F3 folding is younger than 77 Ma (Carr, Chapter 2). Deformed sillimanite-grade 62-59 Ma syn-tectonic Ladybird intrusions in the immediate hanging wall of the Monashee décollement indicate that the last stages of compressional shearing and F3 folding were ongoing in the latest Paleocene. Thrusting had ended by 58 +/- 0.5 Ma, the age of a crosscutting pegmatite (Carr, Chapter 1).

The ages of plutons and syn-kinematic minerals in the Columbia River fault indicate that extensional faulting was underway in the Early Eocene (Table 3.1; Parrish et al. 1988; Carr 1989).

Metamorphism

In Thor-Odin culmination there is evidence for protracted thrust movement on the Monashee décollement followed by annealing and then quenching of mineral assemblages. Further north, on the west flank of Frenchman Cap culmination there is evidence of a protracted shearing history, the later part of which includes a low-pressure movement history superimposed upon a syn-kinematic high-pressure - high-temperature movement history (Journeay 1986; Scammell 1986).

Peak assemblages in both hanging wall and footwall of the Monashee décollement in Thor-Odin culmination are synchronous with some F2 folding and shearing on the Monashee décollement (Figure 3.3; Moore, unpublished manuscript 1970; Reesor and Moore 1971; Duncan 1982, 1984; Coleman 1989, 1990; this study). In the Monashee complex, in the footwall of the Monashee décollement, the pre- and syn-kinematic peak mineral assemblage contains kyanite, sillimanite and melt in equilibrium and is interpreted as a high-pressure - high-temperature assemblage (Figures 3.3 and 3.4; Reesor and Moore 1971; Coleman 1990) that equilibrated at conditions of >7.1 kb and $>673^{\circ}\text{C}$ (bathozone 6, Carmichael 1978). This assemblage is progressively overgrown by sillimanite followed by cordierite (Reesor and Moore 1971).

The metamorphic mineral assemblages in the upper plate of the décollement in the Thor-Odin - Pinnacles area are summarized on Figure 3.3. At the deepest exhumed structural levels on the southern flank of the Thor-Odin culmination, a syn-kinematic equilibrium sillimanite - potassium feldspar - melt assemblage is interpreted to have formed at temperatures of $>673^{\circ}\text{C}$ (Figure 3.4; Reesor and Moore 1971; Coleman 1990); peak pressure conditions are not constrained. The shear zone itself is annealed and is overgrown by sillimanite.

Post kinematic staurolite +/- kyanite +/- andalusite overprint peak minerals and fabrics in the sillimanite-muscovite zone, and retrograde greenschist facies minerals are pervasive within the footwall of the Columbia River fault (Figure 3.3).

It is not possible to constrain a P-T-t path for the Thor-Odin - Pinnacles area without pressure data; however, rocks in the sillimanite - potassium feldspar zone did not enter the sillimanite-muscovite field, and rocks in the sillimanite-muscovite field did not enter the kyanite field, implying rapid cooling or isothermal decompression. The peak conditions are a result of heating and burial during compression, but isothermal decompression and/or rapid cooling are consistent with extensional thermal models.

Cooling history

The metamorphic peak in the Thor-Odin - Pinnacles area was synchronous with plastic thrusting on the Monashee décollement and with regional F2 folding (Reesor and Moore 1971; Carr, Chapter 2; Coleman 1990). The fabrics in the Late Cretaceous Whatshan batholith and in Paleocene leucogranite, migmatite and pegmatite indicate that at least part of this deformation and metamorphism is younger than the 77 and 62 Ma U-Pb zircon ages of these rocks (Carr, Chapters 1 and 2).

Mineral dating is consistent with the interpretation that the metamorphic peak occurred in the Late Cretaceous - Paleocene and indicates that relatively rapid cooling occurred in the latest Paleocene and Eocene. Figures 3.5 and 3.6 summarize the cooling history of Middle Crustal Zone rocks in the Thor-Odin - Pinnacles area. They are based on a compilation of mineral dates obtained with different isotopic systems that have a spectrum of closure temperatures (Table 3.1; Figure 3.7). The high-temperature part of the cooling curves is defined by the U-Pb ages of magmatic zircon crystals from *in situ* melts and metamorphic zircons in amphibolite gneisses. U-Pb closure temperatures for zircon and titanite are >800°C and ~600°C respectively (Mattinson 1978; Parrish and Roddick 1985; Ghent et al. 1988). Peak metamorphic conditions were concurrent with melting (Reesor and Moore 1971; Carr, Chapter 2; Coleman 1990). A 62 Ma U-Pb date

obtained from magmatic zircons from a strained sillimanite bearing migmatite leucosome (Carr, Chapter 1) indicates that the onset of melting occurred in the latest Paleocene. The rest of the cooling history is based on conventional hornblende K-Ar ages and Rb-Sr muscovite and feldspar ages (Table 3.1). The Rb-Sr muscovite closure is about 500°C, feldspar is about 350°C and K-Ar hornblende is 530° +/- 40° C (Ghent et al. 1988).

Rocks on the southern flank of the Thor-Odin culmination cooled ~5 Ma later than those in the Pinnacles area (Figures 3.5 and 3.6); this is consistent with the former occupying a deeper structural position. Figures 3.5 and 3.6 indicate that the rocks cooled from ~650°C to ~350°C in ~10-15 Ma at rates of ~25 +/- 5°C/Ma. This cooling rate during the Paleogene is consistent with denudation on normal faults.

Valhalla complex

Timing of deformation

There is evidence that early folding within paragneisses in Valhalla complex predated the emplacement of the 100 Ma Mulvey granodiorite gneiss and the subsequent deformation associated with the Gwillim Creek shear zones (Reesor 1965; Carr 1986). A substantial amount of deformation associated with thrusting on the Gwillim Creek shear zones is: (1) younger than the magmatic age of the 100 Ma Mulvey granodiorite gneiss, which is repeated by, and penetratively deformed in the shear zones, and (2) younger than an 88 Ma deformed sillimanite bearing pegmatite within the lower of the two shear zones (Parrish, unpublished data, 1985-1987). Thrusting was over before the emplacement of the 63 Ma Airy quartz monzonite (Carr 1986; Carr et al. 1987); therefore, a significant amount of strain and displacement on the Gwillim Creek shear zones occurred in the Late Cretaceous.

Detailed mapping and U-Pb geochronology clearly demonstrate that extensional deformation in the Valhalla complex was underway by the beginning of the Early Eocene. The 59 +/- 1 Ma Ladybird granite is penetratively deformed in the Valkyr shear

zone (Carr et al. 1987; Parrish et al. 1988). The shear zone is crosscut by a 56 Ma intrusion. Extensional motion was transferred to the Slocan Lake fault, which was active in the Early Eocene based on mineral dating of syn-kinematic micas in the mylonitic footwall (Parrish et al. 1988).

Metamorphism

Paragneisses in Valhalla complex contain sillimanite - potassium feldspar - melt equilibrium assemblages that are interpreted to have equilibrated at temperatures in excess of $\sim 673^{\circ}\text{C}$. This assemblage was stable during the early stages of motion on the Slocan Lake fault at ~ 56 Ma. Relict kyanite mantled by sillimanite - potassium feldspar in one thin section hints at an earlier high-pressure assemblage (Parrish et al. 1985). Preliminary geothermobarometry on pelitic rocks indicates that rocks of the overriding and uppermost thrust sheet, in the hanging wall of the Gwillim Creek shear zones, equilibrated at 3-4 kb higher pressure than rocks in the overthrust sheet exposed in the deepest structural level exposed in Gwillim Creek (Carr, unpublished data, 1988). The preservation of this relationship requires that Valhalla complex was rapidly quenched following thrusting.

Cooling history

Detailed U-Pb zircon, titanite and allanite studies and K-Ar and Rb-Sr mineral ages show that a thermal peak of $\sim 700^{\circ}\text{C}$ was attained between 75 and 70 Ma and that cooling from 650 to 250°C occurred at a rate of $20 \pm 5^{\circ}\text{C/Ma}$ between 60 and 45 Ma (Parrish and Carr 1989; Carr and Parrish 1989).

Frenchman Cap culmination

Timing of deformation

At present, the movement history of the Monashee décollement and timing of polydeformation in the Basement Zone have not been directly dated; published timing arguments are based on correlations with deformation in the Upper Crustal Zone in the hanging wall of the shear zone. Previous models which attribute D1 and D2 deformation

to the Early to Middle Jurassic (Read and Brown 1981; Brown and Read 1983; Journeay 1986; Brown et al. 1986) were based, in part, upon relationships of the Galena Bay stock, once thought to cut the Monashee complex and now shown to be in the hanging wall of the Columbia River fault and in fault contact with the Monashee décollement (Parrish et al. 1988; Parrish and Armstrong 1987).

Journeay and Parrish (1989) carried out U-Pb dating on very weakly deformed 57 and 55 Ma pegmatites in the immediate vicinity the Monashee décollement on the western and northern flanks of Frenchman cap. The fabrics are westerly directed extensional fabrics (R. L. Brown, personal communication, 1990) and indicate that the northeasterly directed Monashee décollement was inactive at this time. Metamorphic zircons from the Monashee complex are latest Paleocene and earliest Eocene in age. Metamorphic zircons and zircon overgrowths in the Mount Copeland syenite are 59 ± 1 Ma (Parrish and Scammell 1988) and metamorphic zircons from a kyanite bearing schist on the northern flank of Frenchman Cap are 55 ± 0.10 Ma (Journeay and Parrish 1989; Journeay and Parrish, unpublished data 1989).

Metamorphism

D2 northeasterly verging folds, thrust faults and shearing on the Monashee décollement were synchronous with peak metamorphic conditions of > 6.2 kb and $> 673^{\circ}\text{C}$ (Journeay 1986; Scammell 1986). Motion on the décollement (MD1) was followed by a period of uplift and low-pressure - high-temperature static metamorphism. Finally, low-pressure - high-temperature syn-kinematic metamorphism occurred during renewed movement on the décollement.

The juxtaposition of the upper plate with a sillimanite - potassium feldspar stable assemblage against the low-pressure sillimanite and andalusite bearing footwall, which represents an inverted metamorphic gradient, is thought to have been brought about by the overthrusting of a hotter plate over a cooler plate (Journeay 1986). The preservation of this inverted metamorphism requires rapid quenching and uplift (Journeay 1986).

Journeay (1986) suggested that MD1 was active in the Early-Middle Jurassic at > 21 km, that it was uplifted by progressive development of an underlying basement duplex and that the shear zone was reactivated at 10-12 km depth in the Late Cretaceous to early Tertiary.

Discussion

Late Cretaceous - Paleocene piggyback thrusting

Thrusting on the deep-seated Gwillim Creek shear zones in the Valhalla complex occurred between 100 and 63 Ma. Part of the compressional deformation in the Thor-Odin - Pinnacles area and thrusting on the Monashee décollement is younger than the emplacement of the deformed 77 Ma Whatshan batholith and the deformed 62 and 59 Ma Ladybird granitoids. Assuming that the latest Cretaceous - Paleocene shortening that is evident in the Thor-Odin - Pinnacles area was translated eastward then the Valhalla complex could have been carried on a deeper fault.

This is consistent with geologic reconstructions made in conjunction with LITHOPROBE seismic reflection data (Carr and Brown 1990; Brown et al. 1990). Blind thrust sheets are evident in the hanging wall of the Monashee décollement in the subsurface beneath the southwest flank of Thor-Odin on lines 7-10 and beneath the Pinnacles culmination on line 6 (Carr and Brown 1990; Carr, Chapter 2, Figure 2.4). The roof thrust of the blind thrust sheet imaged beneath the Pinnacles culmination can be correlated with the Valhalla reflections (Brown et al. 1990) which are thought to be the reflection image of the Gwillim Creek shear zones (Cook et al. 1987).

It is reasonable to infer that the Monashee décollement was a floor thrust relative to the Gwillim Creek shear zones and that it was active while the Gwillim Creek shear zones were in motion sometime during the Late Cretaceous. This, together with timing arguments from the Thor-Odin - Pinnacles area, suggests that the Monashee décollement was active, perhaps on and off, throughout the Late Cretaceous and Paleocene.

If the shear zone was active for 30-40 Ma at rates of $1-4 \text{ cm a}^{-1}$, the minimum displacement is 30 km and the maximum is 160 km.

Timing of the Monashee décollement

On the basis of peak metamorphic assemblages (Reesor and Moore 1971; Journeay 1986; Scammell 1986; Coleman 1990; Carr, Chapter 2), the Basement Zone (Monashee complex) in both Thor-Odin and Frenchman Cap culminations were deformed and metamorphosed at depths of $> 21 \text{ km}$. Deformation of the Basement Zone and motion on the Monashee décollement occurred at temperatures of $> 673^\circ\text{C}$ and pressures of $> 6.4 \text{ kb}$ in both culminations. In Thor-Odin culmination, fabrics and mineral assemblages indicate that the Monashee décollement experienced a protracted movement history, but the pre-peak history is not known. The last stages of motion are known to have occurred in the latest Paleocene as 62 and 59 Ma Ladybird granitoids are strained in the shear zone. After the shear zone became inactive by 58 Ma, a period of annealing was followed by rapid quenching.

The peak conditions of shearing on the Monashee décollement in Thor-Odin culmination are generally the same as those of MD1 in Frenchman Cap culmination. Therefore, the timing of MD1 in Frenchman Cap is interpreted to be the same as in the southern part of the area, and this phase of the movement history is interpreted to have occurred in the Late Cretaceous and Paleocene, rather than in the Middle Jurassic as suggested by Journeay (1986) and Brown et al. (1986). An earlier Jurassic displacement history is consistent with the regional evolution of the Omineca and Foreland belts; however, it would have occurred prior to the peak of metamorphism.

In Frenchman Cap, the high-pressure - high-temperature syn-kinematic MD1 metamorphic assemblages are overprinted by a low-pressure syn-kinematic assemblage during MD2 reactivation of the shear zone at $\sim 10-12 \text{ km}$ depth. Since no structure has been identified between Frenchman Cap and Thor-Odin which could accommodate MD2 displacement and since the décollement in Thor-Odin culmination did not have a low-

pressure reactivation, then either motion on the décollement was diachronous from north to south (younger in the north) or the shear zones were at different crustal levels when thrusting ceased. If the shear zone moved more or less synchronously, then the timing arguments presented above imply that the MD2 reactivation occurred in the latest Paleocene or early Eocene. Given that the shear zone moved synchronously, and that MD2 in Frenchman Cap was active during final motion on the décollement in Thor-Odin (prior to 58 Ma), then the shear zone was deeper in the south than the north. This requires that unroofing of the region must have been diachronous. At ~60 Ma, MD2 in Frenchman Cap was at ~10 km depth whereas at this time the shear zone at the latitude of Thor-Odin was much deeper. This could be explained if the initiation of extension occurred earlier in the north than the south. This model implies that the displacement on MD2 was not substantial. It also implies that at the latitude of Frenchman Cap, extensional denudation and final stages of thrusting occurred synchronously. This model has a similar geometric relationship and tectonic setting to that of the Himalayas, where extensional faults at high levels are coincident in time with thrusting at deeper levels.

Conclusions

While recognizing the importance of Jurassic deformation and metamorphism in the southern Omineca belt, it is clear that the rocks *within* the gneiss culminations of the Shuswap metamorphic complex in the southern Omineca Belt have a substantial penetrative deformation and metamorphic history which is Late Cretaceous to Paleogene. In particular, at least part of D2 deformation and D3 deformation in the Thor-Odin and Pinnacles area is Late Cretaceous and Paleocene.

The rocks in the high-grade complexes also experienced peak conditions of metamorphism during the Cretaceous - Paleocene. This is consistent with thermal and timing data from the Thor-Odin - Pinnacles area (Carr, Chapters 1 and 2), the Valhalla complex (Carr et al. 1987; Parrish et al. 1987; Carr and Parrish 1989; Parrish and Carr 1989) and the Monashee complex (Journeay and Parrish 1989; Parrish and Journeay unpublished data 1989).

Contractional deformation and metamorphism accompanied displacement on crustal-scale shear zones that fed into the basal décollement of the Foreland Belt (Parrish et al. 1987; Brown et al. 1990). This implies that during the Cretaceous-Paleogene, strain was partitioned within the crust in what is now the Omineca Belt; upper crustal rocks were transported relatively passively to the east on deep-seated structures that fed into the Foreland Belt, whereas mid-crustal rocks were being penetratively deformed.

At least part of the movement on the Monashee décollement, including displacement at peak metamorphic conditions, occurred in the Late Cretaceous-Paleogene. This is a modification of models proposed by Journeay (1986), Scammell (1986) and Brown et al. (1986), in which early movement on the Monashee décollement (MD1) and peak high-pressure 6.4- 7.1 kb metamorphic conditions were attained in the Middle Jurassic and renewed shearing (MD2) and low-pressure 2.0-3.0 kb metamorphism occurred in the Late Cretaceous to early Tertiary. A Jurassic movement history is consistent with known geology in the Omineca and Foreland belts; however, ductile shearing at conditions of high pressure and temperature at depths of >21 km occurred in the Cretaceous-Paleogene.

Rocks in the Thor-Odin - Pinnacles area and the Valhalla complex cooled rapidly at rates of 20-25 +/- 5°C/Ma in the early Tertiary. This cooling rate is consistent with denudation on crustal-scale normal faults known to be active in the Eocene.

Table 3.1 Summary of U-Pb, Rb-Sr and K-Ar mineral dates

Sample Number	Dating method, mineral	Age (Ma)	Reference
<u>Southern flank of Thor-Odin culmination</u>			
(1) SC559	U-Pb, titanite	55.0 +/- 1.0	Appendix 2.2
(2) SC567	U-Pb, metamorphic zircons	60.0 +/- 1.0	Appendix 2.2
(3) SC569	U-Pb, titanite	58.0 +/- 4.0	Appendix 2.2
(4) SC575	U-Pb, metamorphic zircons	61.0 +/- 0.5	Appendix 2.2
(5) Fosthall-1	Rb-Sr, muscovite and feldspar	53.9 +/- 0.8	Parrish et al. 1988
(6) Fosthall-1	K-Ar, muscovite	45.5 +/- 0.9	Parrish et al. 1988
(7) Fosthall-2	Rb-Sr, muscovite and feldspar	56.0 +/- 0.9	Parrish et al. 1988
(8) Fosthall-2	K-Ar, muscovite	47.1 +/- 1.3	Parrish et al. 1988
(9) Pingston Ck	Rb-Sr, muscovite and feldspar	59.7 +/- 1.2	Parrish et al. 1988
(10) Pingston Ck	K-Ar, muscovite	47.1 +/- 0.9	Parrish et al. 1988
<u>Scalping Knife Mountain - Whatshan batholith - Pinnacles culmination</u>			
(11) SC545	U-Pb, titanite	64.0 +/- 2.0	Appendix 2.1
(12) SC857	K-Ar, hornblende	64.7 +/- 1/1	Table 2.2
(13) SC928	K-Ar, hornblende	57.3 +/- 1.1	Table 2.2
(14) SC920	U-Pb, titanite	75.5 +/- 1.5	Appendix 2.1

Figure 3.1 Tectonic map of southern Omineca Belt, modified from Parrish et al. (1988). Insets locate the geologic belts of the Cordillera and the Intermontane (IM) and Insular (IS) superterrane. The Omineca Belt lies between the southern Rocky Mountain Trench (SRMT) in the northeast and the Fraser-Straight Creek (FSF), Yalakom (YF), Hozameen (HF), and Pasayten (PF) strike slip faults in the southwest. The unpatterned area in the Omineca Belt represents the Upper Crustal Zone (see text). Rocks of North American affinity (NA) are separated from the Intermontane Superterrane (IM) by the Terrane Accretion Boundary (TAB). Features shown with patterns form the Shuswap metamorphic complex. The Middle Crustal Zone (diagonal stripes) consists of metamorphic rocks characterized by 45-60 Ma K-Ar mica dates. Basement rocks of the Basement Zone (dark grey) are exposed in Frenchman Cap (FC) and Thor-Odin (TO) culminations in the Monashee complex and the Malton complex (M). High-grade culminations of the Shuswap metamorphic complex also include the Kettle-Grand Forks (K), Okanagan (OC), Priest River (PR), and Valhalla (V) complexes. Mesozoic-Paleocene thrust faults are the Monashee décollement (MD) and Gwillim Creek shear zones (GCS). Eocene normal faults are the Columbia River fault (CF), Granby fault (GF), Greenwood fault system (GWF), Kettle fault (KF), Newport fault (NF), Okanagan Valley - Eagle River fault system (OF), Purcell Trench fault (PTF), Slocan Lake fault (SLF) and Valkyr shear zone (VS).

FIGURE 3.2 Geology of the Thor-Odin - Pinnacles area and surrounding area

LEGEND

UPPER CRUSTAL ZONE

MIDDLE JURASSIC NELSON INTRUSIVE SUITE: predominantly granodiorite

PALEOZOIC - LOWER JURASSIC STRATIFIED ROCKS:

MIDDLE CRUSTAL ZONE

LATE PALEOCENE - EARLY EOCENE LADYBIRD GRANITE SUITE: biotite granite, quartz monzonite, leucocratic pegmatite (also includes areas with pegmatite with <50% metamorphic rocks)

LATE CRETACEOUS WHATSHAN BATHOLITH (Includes Cariboo Creek stock): hornblende biotite bearing K-feldspar megacrystic quartz monzonite, mafic hornblende biotite diorite

LATE PROTEROZOIC - MESOZOIC AMPHIBOLITE FACIES METAMORPHIC ROCKS: FA = Fawn Lake assemblage; GA = Gold Range assemblage

BASEMENT ZONE

PROTEROZOIC CRYSTALLINE BASEMENT AND LATE PROTEROZOIC - (?) CAMBRIAN COVER GNEISSES

GEOLOGIC CONTACT; MAPPED, COMPILED FROM PUBLISHED MAPS, ASSUMED

LOW - MODERATE ANGLE EOCENE NORMAL FAULT (PEGS ON HANGING WALL)

STEEP EOCENE NORMAL FAULT (PEGS ON HANGING WALL)

STEEP EOCENE NORMAL FAULT; SENSE OF DISPLACEMENT UNCERTAIN

LITHOPROBE LINE

BF	BEAVEN FAULT
CF	CHERRYVILLE FAULT
CRF	COLUMBIA RIVER FAULT
GCSZ	GWILLIM CREEK SHEAR ZONES
MD	MONASHEE DECOLLEMENT
OF	OKANAGAN VALLEY - EAGLE RIVER FAULT SYSTEM
SLFZ	SIOCAN LAKE FAULT ZONE
SSZ	SLATE MOUNTAIN SHEAR ZONE
VSZ	VALKYR SHEAR ZONE

Figure 3.3 Distribution of metamorphic assemblages and minerals in pelitic rocks in the Thor-Odin - Pinnacles area

Figure 3.4 Idealized P-T petrogenetic grid for part of the K_2O - Na_2O - FeO - MgO - Al_2O_3 - SiO_2 - H_2O system pertinent to metamorphism of pelitic rocks (modified from Carmichael 1978). The invariant points that bound bathozones of Carmichael (1978) are indicated by square symbols. Star symbol shows Basement Zone (Monashee complex) metamorphic peak sillimanite-kyanite-melt assemblage. Hatched pattern shows possible field for sillimanite - K-feldspar zone (Figure 3.3) and shading shows possible field for sillimanite-muscovite zone. -

Figure 3.5 Cooling curve for the southern flank of the Thor-Odin culmination. Mineral ages are summarized on Table 3.1 and closure temperatures are discussed in the text.

Figure 3.6 Cooling curve for the Pinncles area. Mineral ages are summarized on Table 3.1 and closure temperatures are discussed in the text.

FIGURE 3.7 Geology of the Thor-Odin - Pinnacles area with U-Pb and K-Ar sample locations and ages

LEGEND

UPPER CRUSTAL ZONE

MIDDLE JURASSIC NELSON INTRUSIVE SUITE: predominantly granodiorite

PALEOZOIC - LOWER JURASSIC STRATIFIED ROCKS:

MIDDLE CRUSTAL ZONE

LATE PALEOCENE - EARLY EOCENE LADYBIRD GRANITE SUITE: biotite granite, quartz monzonite, leucocratic pegmatite

LATE PALEOCENE - EARLY EOCENE LADYBIRD PEGMATITE WITH <50% METAMORPHIC ROCKS

LATE CRETACEOUS WHATSHAN BATHOLITH (includes Cariboo Creek stock): hornblende biotite bearing K-feldspar megacrystic quartz monzonite, mafic hornblende biotite diorite

LATE PROTEROZOIC - MESOZOIC AMPHIBOLITE FACIES METAMORPHIC ROCKS:

BASEMENT ZONE

PROTEROZOIC CRYSTALLINE BASEMENT AND LATE PROTEROZOIC - (?) CAMBRIAN COVER GNEISSES

GEOLOGIC CONTACT: mapped, compiled from published maps, assumed

LOW - MODERATED ANGLE EOCENE NORMAL FAULT (PEGS ON HANGING WALL)

STEEP EOCENE NORMAL FAULT (PEGS ON HANGING WALL)

STEEP EOCENE NORMAL FAULT: sense of displacement uncertain

THRUST FAULT

SC919

GEOCHRONOLOGY SAMPLE LOCATION WITH U-Pb AND K-Ar AGES; (h) = K-Ar hornblende; (t) = U-Pb titanite; (z) = U-Pb zircon

BF

BEAVEN FAULT

CF

CHERRYVILLE FAULT

CRF

COLUMBIA RIVER FAULT

MD

MONASHEE DECOLLEMENT

SSZ

SLATE MOUNTAIN SHEAR ZONE

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

TECTONIC MAP OF SOUTH CENTRAL BRITISH COLUMBIA; BOX SHOWS LOCATION OF MAP 1.

Inserts locate the geologic belts of the Cordillera and the Intermontane (IM) and Insular (I) superterrane. The Omineca Belt lies between the southern Rocky Mountain Trench (SRMT) in the northeast and the Fraser-Straight Creek (FSF), Yalakom (YF), Hozomeen (HF), and Pasayten (PF) strike slip faults in the southwest. The unpatterned area in the Omineca Belt represents the Upper Crustal Zone (see text). Rocks of North American affinity (NA) are separated from the Intermontane Superterrane (IM) by the Terrane Accretion Boundary (TAB). Features shown with patterns form the Shuswap metamorphic complex. The Middle Crustal Zone (diagonal stripes) consists of metamorphic rocks characterized by 45-60 Ma K-Ar mica dates. Basement rocks of the Basement Zone (dark grey) are exposed in Frenchman Cap (FC) and Thor-Odin (TO) culminations in the Monashee complex and the Malton complex (M). High grade culminations of the Shuswap metamorphic complex also include the Kettle-Grand Forks (K), Okanagan (OC), Priest River (PR), and Valhalla (V) complexes. Mesozoic-Paleocene thrust faults are the Monashee décollement (MD) and Gwillim Creek shear zones (GCS). Eocene normal faults are the Columbia River fault (CF), Granby fault (GF), Greenwood fault system (GWF), Kettle fault (KF), Newport fault (NF), Okanagan Valley - Eagle River fault system (OF), Purcell Trench fault (PTF), Slocan Lake fault (SLF) and Valkyr shear zone (VS).

LEGEND

Mv MIOCENE PLATEAU BASALTS: basalt, olivine basalt, andesite

UPPER CRUSTAL ZONE (UPPER PLATE OF NORMAL FAULTS)

Ev EOCENE KAMLOOPS GROUP: rhyolite, dacite, locally conglomerate and sandstone

Esy EOCENE CORYELL INTRUSIONS: syenite, monzonite, shonkinite, granite

mJgd MIDDLE JURASSIC NELSON INTRUSIVE SUITE: granodiorite, granite, syenite

PJs PALEOZOIC - LOWER JURASSIC STRATIFIED ROCKS: (Carboniferous or older Anarchist Group in northern Kettle River area; Carboniferous and Permian Thompson Assemblage, Slocan and Rossland Groups east of Vernon; Badshot Formation and Lardeau, Milford, Kaslo, Slocan and Rossland Groups east of the Columbia River)

MIDDLE CRUSTAL ZONE (LOWER PLATE OF NORMAL FAULTS)

PEg LATE PALEOCENE - EARLY EOCENE LADYBIRD GRANITE: biotite granite - quartz monzonite, pegmatite

PEp LATE PALEOCENE - EARLY EOCENE PEGMATITE WITH < 50% METAMORPHIC ROCKS

Pg PALEOCENE AIRY QUARTZ MONZONITE (Valhalla complex): hornblende - potassium feldspar megacrystic quartz monzonite

IKg LATE CRETACEOUS WHATSHAN BATHOLITH (includes Cariboo Creek stock): hornblende - potassium feldspar megacrystic quartz monzonite; diorite (Whatshan Peak)

gn UNDIVIDED METAMORPHIC ROCKS (northwest of Sugar Lake; south of the Monashee highway; Valhalla complex)

GOLD RANGE ASSEMBLAGE

12 UNDIVIDED METAMORPHIC ROCKS: 12 - undivided; 12/PEp - undivided with > 50% Ladybird pegmatite; 12a - amphibolite; 12c - calcsilicate; 12m - marble; 12p - pelitic schist; 12q - quartzite

11 SNOW MOUNTAIN SCHIST: sillimanite +/- staurolite pelitic schist with minor psammitic gneiss, marble and quartzite

10 MOUNT MAFIC AMPHIBOLITE GNEISS: hornblende-biotite amphibolite gneiss

9 OUTLET CREEK ULTRAMAFIC BEARING UNIT: semi-pelitic and psammitic gneiss, pelitic schist and amphibolite gneiss with ultramafic (Sum) boudins and sheets

8 VIDLER CALCSILICATE GNEISS: calcareous quartzite, quartzite, siliceous marble and marble with minor amphibolite gneiss

MOUNT FOSTHALL COMPOSITE UNIT

7b PSAMMITE - SEMI-PELITE MEMBER: rusty semi-pelitic gneiss, psammitic gneiss, amphibolite gneiss, calcsilicate schist, marble, and quartzite; 7b/PEp with > 50% Ladybird pegmatite

ULTRAMAFIC MEMBER: calc-silicate schist and gneiss, amphibolite gneiss, pelitic schist, marble,

9 OUTLET CREEK ULTRAMAFIC BEARING UNIT: semi-pelitic and psammitic gneiss, pelitic schist and amphibolite gneiss with ultramafic (9um) boudins and sheets

8 VIDLER CALCSILICATE GNEISS: calcareous quartzite, quartzite, siliceous marble and marble with minor amphibolite gneiss

MOUNT FOSTHALL COMPOSITE UNIT

7b PSAMMITE - SEMI-PELITE MEMBER: rusty semi-pelitic gneiss, psammitic gneiss, amphibolite gneiss, calcsilicate schist, marble, and quartzite; 7b/PEp with >50% Ladybird pegmatite

7a CALCSILICATE - PELITE - AMPHIBOLITE - ULTRAMAFIC MEMBER: calc-silicate schist and gneiss, amphibolite gneiss, pelitic schist, marble, quartzite with distinctive ultramafic marker (7um); 7a/PEp with >50% Ladybird pegmatite

6 EMPRESS MARBLE: calcite marble marker

5 SYMONDS QUARTZITE BEARING UNIT: quartzite, psammitic gneiss, amphibolite and marble

4 FAWN LAKE ASSEMBLAGE: migmatitic psammitic and semi-pelitic gneiss, amphibolite gneiss

BASEMENT ZONE (LOWER PLATE OF MONASHEE DECOLLEMENT)

3 COVER GNEISSES: quartzite, semi-pelitic paragneiss, pelitic schist, minor marble

2 PROTEROZOIC BASEMENT ORTHOGNEISSES: hornblende biotite granodiorite gneiss, quartz monzonite gneiss

1 PROTEROZOIC BASEMENT PARAGNEISSES: migmatitic biotite quartzo-feldspathic gneiss

— — — — — GEOLOGIC CONTACT: mapped, assumed, inferred,

— — — — — GEOLOGIC CONTACT: compiled from other workers (see below)

BEDDING; S2 FOLIATION; L2 LINEATION: average of 10-50 measurements

F2 SYNCLINE: upright, inclined

F3 SYNCLINE: upright, inclined

F2 ANTICLINE: upright, inclined

F3 ANTICLINE: upright, inclined

STEEP TERTIARY NORMAL FAULT (teeth on hanging wall): mapped, assumed

— — — — — STEEP TERTIARY NORMAL FAULT: sense of displacement uncertain

— — — STEEP TERTIARY NORMAL FAULT: sense of displacement uncertain

LOW- TO MODERATE-ANGLE EOCENE NORMAL FAULT (pegs on hanging wall): mapped, assumed, inferred

SYN-METAMORPHIC THRUST FAULT (teeth on hanging wall): mapped, assumed, inferred

SYN-METAMORPHIC SHEAR ZONE (? thrust): mapped, assumed, compiled from other workers

SYN-METAMORPHIC SHEAR ZONE (? normal fault - half circle on hanging wall): mapped, assumed

★ SC545 U-Pb GEOCHRONOLOGY SAMPLE LOCALE

BF BEAVEN FAULT
CF CHERRYVILLE FAULT
CRF COLUMBIA RIVER FAULT
DSZ DIVIDE SHEAR ZONE
MD MONASHEE DECOLLEMENT
OF OKANAGAN VALLEY - EAGLE RIVER FAULT SYSTEM
SSZ SLATE MOUNTAIN SHEAR ZONE
VSZ VALKYR SHEAR ZONE

Note: This map includes original mapping by S. Carr (1966, 1967, 1968 and 1969) of Middle Crustal Zone rocks between the Columbia River valley and the Okanagan Valley (see Map 2 for station locations) and a compilation and modification, in part, of previous work (Little 1957, 1959, 1960; Jones 1959; Hyndman 1968; Reesor and Moore 1971; Read and Wheeler 1976; Read 1979, 1980; Okulitch 1979; Duncan 1982; Parrish et al. 1988; Parrish, unpublished data 1987 [west side of Valhalla complex]; Parrish and Armstrong 1988; Coleman, unpublished 1990 [trace of the Monashee decollement]; Johnson and Brown, unpublished data 1989 [southeast of Vernon]; Tempelman-Kluit 1989).

MAP 1: GEOLOGY OF THE THOR-ODIN - PINNACLES AREA

The map displays the Kettle River area in British Columbia, Canada. Key features include the Kettle River, Kettle River Provincial Forest, and the Columbia Mountains. Handwritten annotations in black ink are scattered across the map, including 'PJs', 'PEg', 'mJgd', 'gn', 'IKg', and 'OF?' with arrows pointing to specific locations. The map also shows the provincial boundary and the Columbia River.

MAP 1: GEOLOGY OF THE THOR-ODIN - PINNACLES AREA

S. D. CARR (1990)

END

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