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**THE MONASHEE DECOLLEMENT AT CARIBOO ALP AND REGIONAL
KINEMATIC INDICATORS, SOUTHEASTERN BRITISH COLUMBIA**

by

VICKI J. COLEMAN, B.Sc.

A thesis submitted to the Faculty of
Graduate Studies and Research in partial fulfilment
of the requirements for the degree of
Master of Sciences, Department of Earth Sciences

Carleton University

Ottawa, Ontario

November 14, 1990

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KINEMATIC INDICATORS, SOUTHEASTERN BRITISH COLUMBIA**

submitted by Vicki Jean Coleman, B.Sc.,
in partial fulfilment of the requirements for
the degree of Master of Science

Thesis Supervisor

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December 21, 1990

ABSTRACT

The Monashee décollement is a crustal-scale, compressional shear zone in the Omineca Belt of the southern Canadian Cordillera. The décollement delineates a regional tectonic boundary, separating rocks of the Selkirk allochthon from those of the underlying Monashee Complex. The Monashee Complex is an elongate domal culmination containing orthogneisses and heterogeneous paragneisses, interpreted to be Precambrian North American basement, unconformably overlain by a metasedimentary cover gneiss succession.

In Cariboo Alp, on the southwest flank of Thor-Odin culmination, movement on the décollement resulted in an imbrication of the immediate footwall and formation of a footwall duplex, herein called the Cariboo duplex. Alternating horses of basement and cover gneisses are bounded by discrete shear zones in between southwest-dipping floor and roof thrusts that form the Cariboo duplex.

Displacement on the décollement may have been initiated during pre-peak metamorphic first phase folding. Second phase tight to isoclinal northeast-verging folds are syn-peak metamorphic and synchronous with major movement on the décollement. A high pressure footwall assemblage containing kyanite is inferred to have nucleated either prior to or during the initial stages of D2 deformation and was progressively replaced by syn-kinematic sillimanite. Open, upright third phase folds post-date the metamorphic peak and deform the mylonitic fabrics. Isotopic (U-Pb zircon, monazite) dating of syn-kinematic leucosome and pegmatite constrains final stages of thrusting to the latest Paleocene. All the thrust slices and structures in Cariboo Alp are cut by an undeformed 58 Ma pegmatite dyke, indicating that movement on the southern flank of Thor-Odin had ended by this time.

Upper amphibolite facies paragneisses and orthogneisses with annealed mylonitic textures mark the boundary of the Monashee décollement. These rocks are strongly foliated, with a predominantly southwest-dipping shear foliation, and have a strong, penetrative, southwest-plunging stretching lineation. A diverse assemblage of meso- and microscopic kinematic indicators, including C-S fabrics, asymmetrical extensional shears, rotated porphyroclasts, rotated asymmetric boudins, foliation fish, and strain-insensitive foliations, consistently record an upper-member-to-the-northeast sense of shear along the length of the décollement.

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ORIGINAL CONTRIBUTION

Data were collected over a period of 3 months of field work during the summers of 1988 and 1989. I completed detailed mapping at a scale of approximately 1:15 000 on the southern flank of the Monashee Complex (portions of the 1:50 000 82L/8 and 82L/9 sheets; see Maps 1,2,3). I also did reconnaissance mapping at the scale of 1:50 000 on the eastern (adjoining margins of 82K/5 and 82K/12) and the western (82L/8, 82L/9 and adjoining margin of 82L/16) flanks of the Monashee Complex (see Maps 4,5).

Zircons and monazites from 3 samples were dated utilizing the U-Pb method at the Geological Survey of Canada (G.S.C.) geochronology laboratory. I completed all the stages of rock crushing and grinding, mineral separation, and mineral selection for all samples. I performed chemistry in the G.S.C. clean lab on all zircon and monazite fractions, except 2 monazite fractions from 2 rocks. Mass spectrometry was completed by technicians at the G.S.C.

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THE MONASHEE DECOLLEMENT AT CARIBOO ALP, SOUTHERN FLANK OF THE MONASHEE COMPLEX, SOUTHEASTERN BRITISH COLUMBIA

1

INTRODUCTION

The Monashee décollement is a crustal-scale shear zone in the hinterland (Omineca Belt) of the southern Canadian Cordillera (Figure 1). In this study the décollement has been examined in detail on the southern flank of Thor-Odin culmination of the Monashee Complex (Figure 2), in order to document its kinematics, timing constraints, geometry and structural style, as well as to elucidate stratigraphic relationships, and structural and metamorphic evolution of its hanging wall and footwall.

Data were collected over a period of 3 months of field work during the summers of 1988 and 1989 and in the lab during the intervening time from fall 1988 to spring 1990. Extensive exposure above tree line facilitated detailed mapping at the southern end of the Monashee Complex, on Cariboo Alp, at a scale of approximately 1:15 000 (Maps 1-3, back pocket). Laboratory analysis of thin sections was undertaken to document metamorphic textures and grade. Under the direction of Dr. R.R. Parrish, the complete analyses of three geochronology samples (see Appendix 1) from Cariboo Alp were done at the Geological Survey of Canada geochronology lab.

Reconnaissance mapping at the scale of 1:50 000 was completed in the company of Dr. R.L. Brown along the previously unmapped western flank of Thor-Odin (Maps 4,5, back pocket). In addition, kinematic indicators were documented along the length of the western flank of the Monashee Complex using outcrop, hand sample and thin section examples.

GEOLOGIC SETTING

The Omineca Belt of the Canadian Cordillera (see inset of Figure 1) straddles the western boundary of the North American paleocontinental margin and accreted oceanic and island arc terranes (Monger et al., 1982). The present crustal structure of the southern Omineca Belt is a result of protracted compression accompanied by crustal thickening and followed by crustal extension (Brown et al., 1986; Brown and Journeay, 1987; Parrish et al., 1988). Crustal thickening of the orogenic belt occurred during the Jurassic to Paleocene (Price and Mountjoy, 1970; Wheeler, 1970; Monger et al., 1982; Brown et al., 1986; Brown and Journeay, 1987; Carr and Brown, 1990ab; Brown and Carr, 1990). Shearing on the Monashee décollement during this period of crustal thickening transported deformed and metamorphosed North American continental margin and oceanic accreted terranes (Selkirk allochthon) eastward across basement of the Monashee Complex.

During Eocene crustal extension, high grade rocks that had

FIGURE 1

Tectonic map of southern Omineca Belt from Brown and Carr (1990). 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. Rocks of North American affinity (NA) are separated from the Intermontane Superterrane (IM) by the Terrane Accretion Boundary (TAB). The unpatterned areas in the Omineca Belt represents the upper crustal zone in the hanging wall of normal faults. Features shown with patterns form the Shuswap metamorphic core complex. The middle crustal zone (diagonal stripe) consists of metamorphic rocks characterized by 45-60 Ma K-Ar mica dates. Basement rocks of the Monashee Terrane (dark grey) are exposed in Frenchman Cap (FC) and Thor-Odin (TO) culminations and the Malton complex (M). High grade culminations of the Shuswap metamorphic core 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).

been buried during Mesozoic to Paleocene compression were rapidly uplifted and tectonically denuded by movement along plastic-brittle, low to moderate angle normal fault systems (Columbia River, Granby, Greenwood, Kettle, Newport, Okanagan Valley-Eagle River, Purcell Trench, Slocan Lake-Valkyr faults, Figure 1) forming the Shuswap Complex. The Shuswap Complex is a Cordilleran metamorphic core complex (Coney, 1980; Armstrong, 1982; Brown, 1989) consisting of these high grade rocks collectively exposed in domal culminations of the Kettle-Grand Forks, Monashee, Okanagan, Priest River, and Valhalla Complexes.

Three crustal zones are presently exposed at the surface of the southern Omineca Belt (Carr and Brown, 1989; Brown and Carr, 1990; Carr, 1990; Figure 1): an upper crustal zone in the hanging walls of the north-trending extensional normal faults, a middle crustal zone in the footwall of the normal faults (together these two zones form the Selkirk allochthon), and the deepest crustal level, the Monashee Complex, exposed as a tectonic window beneath the middle crustal zone.

The Monashee Complex is an elongate, north-south trending, domal structure with distinct northern (Frenchman Cap) and southern (Thor-Odin) culminations in the footwall of the Monashee décollement (Figure 2). Basement rocks exposed in the complex include Precambrian orthogneisses and migmatitic heterogeneous paragneisses (Reesor and Moore, 1971; Read, 1979; Parrish and Armstrong, 1983; Duncan, 1984). Rb-Sr whole rock dating suggests that the paragneisses are as old as 2.8 Ga

FIGURE 2

Map of the Monashee Complex modified after Journeay and Brown (1986), Parrish and Armstrong (1987), Parrish et al. (1988), Johnson (1989a), Coleman (1989), and Carr (1990). The complex, which lies in the footwall of the Monashee décollement (MD), is composed of two structural culminations of basement affinity (dark grey): Frenchman Cap (FC) and Thor-Odin (TO) culminations. These basement gneisses are unconformably overlain by a thin metasedimentary cover (dot pattern). The middle crustal zone (diagonal stripe) consists of metamorphic rocks characterized by 45-60 Ma K-Ar mica dates. The blank undifferentiated area represents pre-Middle Jurassic greenschist to lower amphibolite facies rocks locally intruded by Paleozoic and Mesozoic plutons and overlain by Eocene volcanic rocks (v pattern). (MD = Monashee décollement; OF = Okanagan fault; ERF = Eagle River fault; CRF = Columbia River fault; SCF = Standfast Creek fault).

(Duncan, 1978). Orthogneisses that intrude the heterogeneous paragneisses as discrete sheets and lenses (Reesor and Moore, 1971) have yielded U-Pb zircon ages as old as 2.1 Ga in Frenchman Cap dome (Parrish and Armstrong, 1983) and 1.96 Ga in Thor-Odin culmination (Wanless and Reesor, 1975).

A stratified sequence of metasedimentary rocks unconformably overlie the Precambrian paragneisses and orthogneisses within the Monashee Complex (Reesor and Moore, 1971; McMillan, 1973; Hoy and Brown, 1981; Hoy, 1982, 1987; Brown and Read, 1983; Journeay, 1986; Scammell, 1986; Scammell and Brown, 1990). These cover gneisses are Late Proterozoic to Early Cambrian(?) in age. The lower part of the cover gneiss succession is intruded by the ca. 740 Ma (U-Pb; zircon) Mt. Copeland syenite, which is consistent with a Late Proterozoic age for part of the sequence (Parrish and Scammell, 1988). Model Pb-isotope ages on the stratiform Cottonbelt Pb-Zn deposit indicate that the cover rocks may be in part Cambrian (Hoy and Godwin, 1988). Detrital zircon studies from cover gneisses indicate predominantly an Early Proterozoic source terrane for these gneisses (Parrish et al., 1989; this study).

Infolds and imbricated slices of the cover gneisses occur within the basement gneisses (Reesor and Moore, 1971; Read, 1979; Duncan, 1984; Journeay, 1986; Coleman, 1989). The cover gneisses preserve evidence of a shallow platformal marine environment that was disturbed by syn-sedimentary intrusions and extrusions interpreted to be evidence of rifting (Scammell and

Brown, 1990). Platformal metasediments, which are at upper amphibolite grade of metamorphism, include metapelites, calcsilicates, metacarbonates and quartzites, all occurring as laterally extensive layers. A stratigraphic succession has been established (Scammell and Brown, 1990), and local correlations have been made throughout the complex, despite intense penetrative strain and recrystallization. Preserved thickness of the cover gneiss succession ranges from greater than 2000 m on the north flank of Frenchman Cap dome (Journeay, 1986; Scammell, 1986), to 750 m between Frenchman Cap and Thor-Odin culminations (Read, 1980), to only 200 m in the southern part of Thor-Odin (this study; see Scammell and Brown, 1990).

The Monashee Complex has been interpreted to be an antiformal duplex of basement-cored horses bounded above by the northeasterly-verging, compressional Monashee décollement (Brown et al., 1986; Monger et al., 1986; Journeay, 1986). Crustal thickening of the complex is manifested in at least three deformation events and in two high temperature syn-kinematic prograde metamorphic episodes (Journeay, 1986; Scammell, 1986).

The Monashee décollement delineates a regional tectonic boundary separating rocks of the Monashee Complex from those of the overlying Selkirk allochthon (Brown, 1980; Read and Brown, 1981; Brown and Read, 1983; Brown et al., 1986, 1990) and has a displacement on the order of 80 - 100 km. The décollement is arched over Frenchman Cap and Thor-Odin culminations, enveloping the southern, western, and northern flanks of the Monashee

Complex, and is truncated by the east-dipping Tertiary Columbia River normal fault along the eastern margin of the complex (Figure 2) (Lane, 1984; Brown and Journeay, 1987).

The décollement, which has been examined along nearly its entire 200 km of exposed length (Brown, 1980; Read and Brown, 1981; Brown and Read, 1983; Journeay, 1986; Scammell, 1986; Journeay and Brown, 1986; Bosdachin and Harrap, 1988; Bosdachin, 1989; Coleman, 1989; Harrap, 1990; this study), is a ductile shear zone with a width of intense strain commonly 0.5 to 2 km in thickness that involves both hanging wall and footwall rocks. Exposed rocks in the Monashee Complex beneath the décollement are commonly imbricated and isoclinally folded (Reesor and Moore, 1971; Duncan, 1984; Brown et al., 1986; Journeay, 1986; Map 5, this study).

The Monashee décollement had a protracted displacement and thermal history. Journeay (1986) and Brown et al. (1986) proposed a Jurassic period of deformation and deep burial, followed by uplift, renewed metamorphism and deformation at middle crustal levels in the latest Cretaceous to Paleocene (see Brown and Journeay, 1987). This model is based on petrological and structural data from the west flank of Frenchman Cap, together with tectonic modelling and balanced cross sections. The Middle Jurassic age of early deformation and associated metamorphism in the Monashee Complex was proposed on the basis of correlation with deformation in the Selkirk allochthon and Kootenay Arc to the east (Brown, 1980; Brown and Read, 1983;

Brown et al., 1986). Geochronological data in support of Jurassic movement on the Monashee décollement has not been acquired. Carr (Carr, 1989; Carr and Brown, 1990a; Carr, 1990) has demonstrated that on the southern flank of Thor-Odin culmination the décollement was active in the latest Paleocene and that motion had terminated by 58 Ma.

Structurally overlying the Monashee Complex is the Selkirk allochthon, which may be divided into a middle crustal zone and an upper crustal zone (Figure 1). The middle crustal zone is composed of polydeformed upper amphibolite facies metamorphic rocks, including Late Proterozoic Windermere strata and overlying lower Paleozoic to Triassic paragneisses and schists, intruded by extensive Eocene leucocratic granite and pegmatite formed primarily during extensional deformation (Carr, 1989, 1990). The middle crustal zone is characterized by penetrative Eocene strain, which overprints compressional fabrics and mineral assemblages (Parrish et al., 1988; Carr, 1989; Johnson, 1988, 1989a, 1989b), and by an early Tertiary cooling history (Armstrong, 1982; R.L. Armstrong, unpublished data file, 1984; Parrish et al., 1988). The upper boundary of this zone is defined by outward-dipping Eocene normal faults, including the Columbia River and Okanagan Valley-Eagle River fault systems (see Figure 2).

Rocks of the upper crustal zone are exposed in the hanging walls of the normal faults (Carr 1989, 1990). This uppermost tectonic zone consists of Upper Proterozoic to Jurassic rocks of

variable but predominantly low to medium metamorphic grade with a late Paleozoic to Middle Jurassic metamorphic history, which were uplifted and cooled before the Late Cretaceous (Archibald et al., 1983; R.L. Armstrong, unpublished data file, 1984; Parrish et al., 1988). These rocks are overlain in part by unmetamorphosed Eocene volcanic and sedimentary strata.

GEOLOGY OF CARIBOO ALP

INTRODUCTION

In Cariboo Alp, on the southern flank of Thor-Odin culmination, the Monashee décollement is well exposed as a highly strained zone approximately 2 km thick (Figure 3, Maps 1-3). The hanging wall of the décollement is composed of rocks of the lower part of the Selkirk allochthon. In the immediate footwall is an imbricated zone of allochthonous Monashee Complex basement and cover gneisses (Plate 1; see also Reesor and Moore (1971) and Duncan (1984)). This disrupted zone, which has the geometry of a classical duplex (Boyer and Elliot, 1982) with a sole thrust, a roof thrust, and horses bounded by discrete ductile shear zones in between, has been called the Cariboo duplex (Coleman, 1989). Below the sole thrust of the imbricated zone are basement gneisses of the Monashee Complex with infolds of overlying stratified cover gneisses.

FIGURE 3

Simplified map of Cariboo Alp. MD = Monashee décollement. Basement gneisses (grey pattern) and F1 infolds of unconformably overlying stratified cover gneisses (blank) lie below the sole thrust of the Cariboo duplex. The predominant basement lithology is migmatitic biotite-quartz-feldspar augen paragneiss. Cover gneisses include interlayered quartzites, pelites, calcsilicates and carbonates. The Cariboo duplex is composed of alternating, imbricated basement and cover gneiss thrust slices. Above the roof thrust of the duplex, the Monashee décollement, there is a 5 km thick package of metasediments (diagonal stripe) of the Selkirk allochthon consisting of rusty metasandstones and semipelites with up to 30% amphibolite and intruded by extensive leucogranite. Cross-section A-B is found in Figure 5.

PLATE 1:

View looking north through Cariboo Alp to Thor-Odin culmination (TO) of the Monashee Complex, showing imbricated slices of basement gneisses (B) and darker grey cover gneisses (C) of the Cariboo duplex. Undeformed pegmatite dykes (P) cut across all the horses of the duplex. ST = sole thrust.

HANGING WALL ROCKS

Lithology

Immediately overlying the Monashee décollement in Cariboo Alp is a well exposed 1.5 to 3 km thick package of metasediments, which has been referred to as the Fawn Lake Assemblage (Carr, 1990), consisting mainly of rusty-weathering semipelitic schists and quartzofeldspathic paragneisses (Plate 2A). The semipelitic schists, interlayered with very thin pelitic schists, are migmatitic with leucosome pods and lenses comprising up to 50% of the rock by volume in some places. The quartzofeldspathic paragneisses (some of which are calcareous) are thinly layered and consist mainly of roughly 5 cm thick mica-poor layers separated by thin schistose partings, giving the rock a characteristic "platy" appearance. Quartzite, marble and diopside-bearing calcsilicate gneiss make up a minor portion of this sequence of rocks. Amphibolite boudins and layers (biotite-plagioclase-hornblende+/-garnet) are very abundant, up to 30% of the outcrop in some places. The package of rocks is intruded by 15 to 40% early Tertiary Ladybird pegmatite (both discordant, weakly deformed and concordant, highly strained, mylonitic pegmatite) (Carr, 1989, 1990). The top of the Fawn Lake assemblage is defined by an unannealed shear zone (refer to Carr (1990) for further details of the shear zone and this package of rocks).

This metasedimentary package is probably best correlated with rocks of the semipelite-amphibolite division of the Late

PLATE 2:

- (A) In the hanging wall of the Monashee décollement, metasediments of the Selkirk allochthon consist of rusty metasandstones and semipelites with up to 30% amphibolite and are intruded by extensive pegmatite and leucogranite.
- (B) Migmatitic biotite-quartz-feldspar paragneiss of a basement horse of the Cariboo duplex. Asymmetric pinch and swells in ductile boudins and shear bands give a northeast-directed sense of shear. Photo is taken looking southeast, on a face parallel to the stretching lineation.
- (C) "Clot rock", with abundant diopside-hornblende-quartz clasts in a calcareous to siliceous paragneiss matrix, within the middle basement slice of the Cariboo duplex.
- (D) Large phase two fold deforming psammite, semipelitic schist, calcsilicate gneiss, and impure marble of the southernmost cover gneiss horse of the Cariboo duplex.

Proterozoic Horsethief Creek Group strata of the Windermere Supergroup north of the Monashee Complex based on lithological similarities (e.g. Raeside and Simony, 1983; Pell and Simony, 1987). Similar correlations, based on stratigraphic similarities, have been made for migmatitic paragneisses of the Shuswap assemblage in the Hunters Range (Johnson, 1988, 1989a, 1990) and rocks in the immediate hanging wall of the Monashee décollement on the western and northwestern flanks of the Monashee Complex (Brown, 1980; Brown and Read, 1983; Journeay, 1986; Scammell, 1986, 1990; Scammell and Dixon, 1989; Harrap, 1990).

Metamorphic Grade

Mineral assemblages and textures indicate that the peak thermal conditions coincided with F2 folding and D2 shearing on the Monashee décollement (described below). The pelitic metamorphic assemblage of the upper amphibolite facies rocks in the hanging wall of the Monashee décollement is sillimanite - K-feldspar - leucosome - biotite - garnet - plagioclase - quartz. Sillimanite is the only aluminosilicate, occurring as fibrous sprays and mats on foliation planes; no kyanite has been found above the décollement. Many of the paragneisses are migmatitic with leucocratic feldspar-quartz layers and pods. These leucosomes, which are part of the high grade equilibrium assemblage, have been interpreted to represent in situ melt (Carr, 1990). Rocks above the décollement lie above the

muscovite breakdown reaction boundary, requiring minimum temperatures of ca. 670°C (Carmicheal, 1978); no peak pressure constraints are available. Refer to the P-T petrogenetic grid (Figure 11) for the possible P-T field of rocks in the immediate hanging wall of the décollement. Further south than the map area, at a higher structural level within the middle crustal zone, peak assemblages and D2 structures are overprinted by lower pressure kyanite +/- andalusite assemblages, which are interpreted (Carr, 1990) to have been formed during uplift and unroofing, probably due to extensional faulting.

Within a couple of kilometres of the trace of the Columbia River normal fault, upper amphibolite facies rocks in the footwall of the fault are overprinted by fabrics and greenschist facies mineral assemblages (chlorite-muscovite-epidote). These retrograde minerals occur in a belt which parallels the Columbia River fault and are interpreted to have been generated during extensional ductile deformation (described below).

Structure

Above the Monashee décollement, highly strained and attenuated hanging wall gneisses are transposed into parallelism with the décollement in a zone approximately 5 km thick. This is interpreted as a high strain zone formed during movement of the Monashee décollement (see also Carr, 1990). Predominant structures include a southwest-dipping mylonitic foliation (designated S2) which contains a penetrative

southwest-plunging stretching lineation (L2; defined by sillimanite, hornblende, fibrolite-biotite mats and quartz rodding). The lineation orientation in these highly sheared rocks is inferred to be approximately parallel to the transport direction of the Selkirk allochthon (see chapter 2 for further discussion).

At least three phases of deformation have been recorded in the hanging wall rocks. Although they cannot be correlated across the décollement, the hanging wall structures are similar in geometry and orientation to structures in the footwall (described in detail below). Pre-peak metamorphic first phase folds occur in outcrop as refolded folds and rootless isoclines with fold hinges parallel to the stretching lineation. Syn-peak metamorphic phase two folds are tight to isoclinal, north-verging folds which are synchronous with movement on the Monashee décollement (D2). F2 fold hinges have been rotated towards the stretching lineation; sheath folds are also locally present. Open, upright post-metamorphic phase three minor folds deform the mylonitic fabric and crenulate the penetrative stretching lineation. Further to the south, at a higher level within the "middle crustal zone", major third phase folds become the dominant control on the map pattern (Carr, 1990).

There is a substantial amount of leucogranite and pegmatite which is predominantly concordant or sub-concordant with the metamorphic foliation. Some of the pegmatite above the Monashee décollement is strongly foliated, lineated, and boudinaged, with

unannealed protomylonitic to mylonitic fabrics (Carr, 1989, 1990), as opposed to the annealed mylonitic fabrics in footwall rocks. This high penetrative strain decreases southward, away from the décollement.

Mineral stretching lineations are transposed from a southwest-plunging orientation (Figure 4A) into an east-west orientation in a belt within a couple of kilometres of the trace of the Columbia River fault (Figure 4B). Within the footwall of the fault, sillimanite-zone rocks are overprinted by unannealed fabrics and chlorite-muscovite-bearing stretching lineations. These fabrics are interpreted to have formed during motion on the Columbia River normal fault under greenschist facies conditions.

FOOTWALL ROCKS: THE CARIBOO DUPLEX

Lithology

The Cariboo duplex is comprised of fault-bounded imbricate slices of allochthonous Monashee Complex basement and cover gneisses (Figure 3). Basement thrust slices are composed mainly of migmatitic biotite-quartz-feldspar augen paragneiss (Plate 2B) with interlayers of sillimanite-kyanite-garnet-biotite pelitic schist and garnet- and biotite-bearing quartzofeldspathic paragneiss. These rocks are correlated on the basis of lithological similarity with basement of the Monashee Complex immediately below the imbricated zone. The

FIGURE 4

(a) Stereonet plot of stretching lineations (crosses) and poles to the shear foliation (filled squares) of the hanging wall rocks of the Monashee décollement. L2 = 20 points; poles to S2 = 25 points.

(b) Stereonet plot of stretching lineations (65 points) within a couple of kilometres of the trace of the Columbia River normal fault.

Figure 4a **Figure 4b**

basement paragneisses are characterized by distinct segregations of leucocratic and melanocratic minerals which define the foliation. Rare lenses of gedrite-cordierite-kyanite-sillimanite-biotite schist and phlogopite-gedrite schist lie parallel to the foliation within the basement paragneisses (see also Duncan, 1984).

The middle basement horse contains siliceous paragneisses and layers, up to 20 m in thickness, with diopside-hornblende-quartz clasts in a calcareous to siliceous matrix (Plate 2C). This distinctive "clot rock" outlines a possible first phase fold within the slice. Rocks of the middle basement horse cannot be easily correlated with basement rocks immediately below the Cariboo duplex (correlation of the other basement thrust slices is unambiguous), although these lithologies are common elsewhere within heterogeneous basement paragneisses of the Monashee Complex.

Cover gneiss horses are composed of interlayered paragneisses including: rusty-weathering migmatitic sillimanite-biotite-garnet+/-kyanite semipelitic schist with thin pelitic interlayers; thickly-bedded biotite-garnet-bearing psammitic gneiss; quartzite layers up to 5 m in thickness; and diopside-bearing calcsilicate gneiss with minor impure marble interlayers (Plate 2D). Although internal disruptions such as folding and imbrication of the units are present, the lithostratigraphy of the cover gneiss horses can be correlated, in a general way, with that of the infolded cover gneisses below

the Monashee décollement.

Boudins and discontinuous layers of amphibolite are common throughout the Cariboo duplex, both within basement and cover gneiss horses. A suite of undeformed sillimanite-bearing pegmatite dykes cut through all the thrust slices of the duplex (Plate 1).

Metamorphic Grade

The main metamorphic foliation (S2), north-verging F2 folds and northeast-directed mylonitic fabrics of the Monashee décollement that formed during D2 are synchronous with the peak of metamorphism. In the footwall of the Monashee décollement, the pelitic metamorphic assemblage is sillimanite +/- kyanite - K-feldspar - leucosome - biotite - plagioclase - garnet - quartz +/- muscovite. Both sillimanite and kyanite are oriented parallel with the metamorphic foliation, occur within the axial planes of F2 folds and define the stretching lineation. Ragged crystals of kyanite, with sweeping extinction and kinks in thin section, suggest that the mineral is pre- to syn-shearing. Although some pristine blue kyanite exists, most of the bladed kyanite grains have been progressively replaced and overgrown by syn-kinematic sillimanite and sillimanite-biotite-feldspar mats (Plates 3A,B,C), suggesting that kyanite is a metastable phase of the metamorphic assemblage. Mats of sillimanite occur on discrete shear surfaces which truncate F2 folds and related fabrics; some of the sillimanite post-dates both kyanite and

PLATE 3:

- (A) Bladed kyanite grains, overgrown by syn-kinematic sillimanite, within coarse pelitic schist of the cover gneisses.
- (B) Kyanite (K) replaced by fibrous sillimanite (S), which is somewhat unoriented. Note bent kyanite grain with undulose extinction below the large kyanite grain. X-nicols.
- (C) Fibrous sillimanite mats replacing kyanite along the pulled-apart margins of kyanite. Some of the sillimanite mats are pulled-apart with muscovite growing in the pull-aparts. X-nicols.
- (D) Typical strong southwest-plunging stretching lineation, within basement gneisses of the Cariboo duplex, defined by the orientation of mats of sillimanite.

older sillimanite. Prismatic blades and mats of sillimanite are occasionally pulled apart and have muscovite in the pull-aparts (Plate 3C).

Based on these textural and metamorphic observations, a high pressure assemblage containing kyanite is inferred to have nucleated either prior to or during the initial stages of D2 deformation and subsequently was replaced by syn-kinematic sillimanite as deformation proceeded. Refer to the P-T petrogenetic grid in Figure 11 for a possible P-T path for the footwall rocks.

Structure

In between southwest-dipping sole and roof thrusts, alternating horses of basement and cover gneisses of the Caribou duplex vary between 50 and 500 m in thickness, with most averaging between 200 and 300 m (Figure 3). Throughout the duplex, mylonitic rocks are strongly foliated with a predominantly southwest-dipping mylonitic shear foliation (S2). S2 is parallel to the compositional layering and probably represents a composite fabric into which earlier formed fabrics, including bedding, have been transposed. S2 contains a strong, consistent, penetrative, southwest-plunging stretching lineation (L2), which is defined by the preferred alignment of elongate minerals including sillimanite, fibrolite-biotite mats, kyanite, hornblende, and quartz and by the long axes of pressure shadows composed of quartz, feldspar and biotite (Plate 3D). S2 and L2

contain the peak metamorphic assemblages, which are annealed.

East of Cariboo Alp, towards the trace of the Columbia River normal fault, horses of the duplex become greatly attenuated and some are sheared-out (Figure 3). Around the western side of Thor-Odin, attenuated horses shear-out into a narrower ductile fault zone which has no clear evidence of footwall imbrication.

Figure 5 is a southwest-northeast cross-section through Cariboo Alp (see location of cross-section in Figure 3, Map 3) which has been extrapolated above and below the present erosion surface to represent an interpreted geometry of the Cariboo duplex. Greater attenuation and shearing-out of some of the horses (as is seen in the map pattern of the duplex) could quite possibly occur in the extrapolated vertical dimension, although this has not been shown in the interpreted cross-section.

There are insufficient data to determine the amount of displacement across the duplex, but it is probably quite large as one of the basement horses is not readily correlated with the basement gneisses immediately below the duplex, and metasediments of the cover horses are not readily correlated on a one to one basis with cover gneisses preserved as infolds below the duplex. The minimum amount of displacement on the duplex is roughly 15 km, a value obtained by pulling the horses of the duplex apart and restoring them to a stratigraphic position immediately below the duplex. Restoration of the original position of the basement and cover horses was done

FIGURE 5

A possible geometry for the Cariboo duplex. See Figure 3 and Map 3 for the location of the southwest-northeast section A-B and a description of the symbols. Fold patterns represent the vergence of F2 minor folds. Horizontal scale = vertical scale.

assuming that infolds of cover gneisses within basement gneisses occurred below the duplex. The true amount of displacement on the duplex is probably much greater than 15 km as this estimated minimum assumes that the allochthonous basement and cover horses are from immediately below the duplex, a condition which is not believed to be valid.

Northeast-directed movement on the Monashee décollement resulted in formation of the Cariboo duplex by imbrication of the footwall, perhaps by movement on splays. The amount of displacement on the décollement is unconstrained but it is the locus of most of the movement on the fault system. In Cariboo Alp the décollement truncates major structures, juxtaposes packages of rocks with different metamorphic assemblages, separates different stratigraphic packages, and juxtaposes rocks with different structural styles (i.e. the number of minor folds decreases markedly above the duplex). Late Paleocene to Eocene Ladybird leucogranite is found primarily as a few discrete dykes below the décollement and substantially increases in the immediate hanging wall (see Carr (1990) for details of Ladybird granitic rocks). Although the Cariboo duplex has the geometry of a classical duplex (e.g. Boyer and Elliot, 1982), the roof thrust (the décollement) was probably not progressively abandoned, which is common with duplex formation, as most of the total displacement and the final movement on the fault system occurred on the décollement.

Displacement on the Monashee décollement outlasted or post-

PLATE 4:

- (A) Pre-metamorphic first phase rootless isocline in basement rocks, with fold hinge parallel to the stretching lineation. F2 z-folds overprint the F1 fold.
- (B) F2 folds with sheared-off limbs and transposed bedding in southern basement slice of the Cariboo duplex. Syn-metamorphic phase two folds are the dominant fold type observed in outcrop. F2 folds have been variably rotated towards parallelism with the stretching lineation, and sheared-off limbs of these folds are common.
- (C) F2 folds disrupted by discrete shears in southern basement slice. Undeformed sillimanite-bearing pegmatite dyke cross-cuts these structures.
- (D) Post-metamorphic open, upright third phase folds post-date the upper-plate-to-the-northeast mylonitic fabric. F3 folds within the middle basement horse crenulating the sillimanite and biotite, which define the stretching lineation.

dated early pre-peak metamorphic first phase folding and outlasted syn-metamorphic phase two folding. Post-peak metamorphic third phase folds post-date the strong mylonitic fabrics.

Pre-peak metamorphic, first phase folds are north-verging, overturned structures that occur in outcrop as refolded folds (type 3 interference patterns with F2 folds) or as rootless isoclinal folds with hinges parallel to the stretching lineation (Plate 4A). The minor structures and fabrics associated with this phase of folding have mostly been overprinted and transposed by later high grade metamorphism, folding and shear strain; thus they are rare in the field. The limbs of minor F1 folds display moderate to extreme attenuation. S1 axial planar cleavage associated with the F1 folds is defined by the planar preferred alignment of biotite, elongate quartz and feldspar. A lack of sillimanite in the S1 axial planar foliation indicates that F1 folds formed prior to the peak of metamorphism. A possible large F1 syncline, marked by stratigraphic symmetry (see Map 2), occurs within the middle basement thrust slice of the Cariboo duplex.

Syn-peak metamorphic north-verging phase two folds plunge gently to moderately to the west and are the dominant fold type observed in outcrop (Plate 2D). They are asymmetric, tight to isoclinal folds with axial planes at varying low angles to the shear foliation. In this area of high strain phase two folds with sheared-off limbs are common (Plates 4B,C), and early F2

folds have been rotated, resulting in sheath fold geometries, some up to a metre in size.

Stretching lineations and the axes of F2 folds form two clusters on a stereonet plot (Figure 6A) indicating that phase two folds have been variably rotated towards parallelism with the stretching lineation. The folds vary in style and geometry: the tighter, more flattened folds with sheared-off limbs have axes inclined at lower angles to the lineation. This suggests that the folds may have nucleated continuously or episodically during shearing deformation and became progressively tightened, flattened, and rotated towards the shear plane.

Phase two folding was closely associated in time with the development of mylonitic fabrics associated with shearing on the Monashee décollement, since the folds both deform the mylonitic fabrics and are disrupted by superimposed discrete shears within the zone. Mineral assemblages and leucosome pods associated with the peak conditions of metamorphism define the shear foliation (S2) and are folded by F2 structures; however these peak assemblages are also contained within F2 axial surfaces indicating that at least part of the folding occurred during peak metamorphic conditions. These folds nucleated after a strong foliation had already formed, possibly as a result of flow instabilities in a highly anisotropic material (Platt, 1983), and were progressively amplified, flattened and rotated during continuing flow in the mylonite zones (cf. Quinquis et al., 1978; Cobbold and Quinquis, 1980; Bryant and Reed, 1969;

FIGURE 6

(a) Stereonet plot of stretching lineations (crosses) and fold axes of F2 folds (filled squares) within the Cariboo duplex. Note the two clusters of L2 and F2 points on the plot. Phase two folds have been variably rotated towards parallelism with the stretching lineation. L2 = 274 points; F2 = 190 points.

(b) Stereonet plot of the fold axes (crosses) and poles to axial planes (filled squares) of F3 folds within the Cariboo duplex. Fold axes = 40 points; poles to axial planes = 40 points.

Figure 6a **Figure 6b**

Figure 7: Basement and cover horses of the Cariboo duplex are sheared-off limbs of large F2 folds. The vergence of phase two minor folds changes abruptly at each thrust contact, possibly as a result of thrust faults propagating through fault tip folds as shown.

Sanderson, 1973; Carreras et al., 1977; Rhodes and Gayer, 1977; Bell, 1978). Fold axes, possibly formed initially at a high angle to the elongation direction, rotated with an increase in strain towards parallelism with the stretching lineation.

Within the Cariboo duplex, the vergence of phase two minor folds changes abruptly at each thrust contact of the horses (see Figures 3, 5; Map 3), indicating that the horses are sheared-off limbs of large F2 folds. This is perhaps a result of thrust faults propagating through fault tip folds (Figure 7). Shearing deformation and imbrication which formed the Cariboo duplex outlasted phase two folding.

Post-metamorphic open, upright third phase folds plunge gently to the northwest and have steep southwest-dipping axial planes (Figure 6B). In outcrop phase three folds are broad warps and crenulations that fold the peak metamorphic mineral assemblages within the southwest-plunging stretching lineation and the mylonitic shear fabric (Plate 4D). Locally, second phase folds are refolded by phase three folds to form basin and dome interference patterns at the outcrop scale. No major F3 folds were mapped within the Cariboo duplex or the basement below; there are no vergence reversals in F3 minor folds (all F3 minor folds are z-folds). Phase three structures are overprinted by randomly oriented retrograde minerals including chlorite and muscovite.

Sense of Shear

Independent and consistent kinematic indicators are well preserved throughout the Cariboo duplex and have been studied in outcrop, hand sample, and thin section (see chapter 2 for details of kinematic indicators). The direction of shearing is interpreted to be parallel to the strong, penetrative southwest-northeast mineral stretching lineation (described above), and the sense of movement is determined by an assemblage of asymmetric structures. Kinematic indicators used as criteria in determining the sense of shear include C-S fabrics (Berthe et al., 1979), asymmetrical extensional shears (Platt and Vissers, 1980; White et al., 1980; Platt, 1984), strain-insensitive foliations (Means, 1981; Simpson and Schmid, 1983), rotated porphyroclasts and rotated asymmetric boudins (Passchier and Simpson, 1986; Hanmer, 1984, 1986). These mylonitic fabrics consistently record a northeast-directed sense of shear and extend into both hanging wall and footwall rocks.

Duncan (1984) interpreted the evolution of Thor-Odin dome to be as a result of fold interference; fault-bounded slices on the southern flank were interpreted to have northerly-directed movement, oriented at right angles to local F2 fold hinges. Duncan, however, did not recognize the significance of the uniform attitude of the pervasive northeast-southwest stretching lineations. Phase two fold axes are not perpendicular to, but are subparallel to the regional transport direction.

FOOTWALL ROCKS: THE MONASHEE COMPLEX*Lithology***Basement Gneisses**

Basement gneisses of the Monashee Complex structurally below the Cariboo duplex (Mt. Gunnarsen, Mt. Skade areas; see Figure 3, Map 2) include both paragneisses and orthogneisses. Very homogeneous, white-weathering, felsic orthogneiss, ranging in composition from hornblende-biotite granodiorite to leucocratic quartz monzonite, forms monotonous sheets within a heterogeneous migmatitic paragneissic sequence. The predominant basement lithology is migmatitic biotite-quartz-feldspar paragneiss (+/-garnet, +/-sillimanite, +/-kyanite), which is characterized by strongly contrasting biotite-rich and quartzofeldspathic layers that alternate on the scale of millimetres to centimetres (Plate 5A). Leucosome lenses, pods and layers contain quartz and feldspar +/- biotite and comprise up to 30% of the rocks by volume.

Minor interlayers, which are discontinuous along strike, consist of semipelitic, pelitic, psammitic, calcsilicate and amphibolite gneisses and schists. Thin (20 cm to 2 m), aluminous, rusty-weathering pelitic and semipelitic schists contain abundant fibrolitic sillimanite intergrown with biotite, bladed sillimanite and/or kyanite, and garnet porphyroblasts. Psammitic paragneiss, which contains up to 50% quartz and varying amounts of plagioclase, potassium feldspar, biotite +/- sillimanite +/- garnet, is quite uniform in texture and has a

PLATE 5:

- (A) Banded migmatitic biotite-quartz-feldspar paragneiss, which is characterized by strongly contrasting biotite-rich and quartzofeldspathic layers, on Mt. Gunnarsen, below the Cariboo duplex.
- (B) Discordant, undeformed pegmatite which cuts across all the thrust slices and structures in Cariboo Alp has been dated at 58 ± 0.5 Ma (U-Pb zircon date) (Carr, 1990).
- (C) Cliff displaying a zone which contains very disrupted lenses of pelitic, semipelitic and quartzofeldspathic rocks and sheared concordant pegmatite marks the trace of the Monashee décollement on the northwestern flank of the Thor-Odin culmination.
- (D) Mylonites within the shear zone, displayed in a cliff on the northwestern flank of Thor-Odin culmination, are strongly foliated with a predominantly southwest-dipping shear foliation and a well developed southwest-plunging mineral extension lineation. The assemblage of kinematic indicators includes C-S fabrics, asymmetric extensional shears, rotated porphyroclasts, and rotated asymmetric boudins.

homogeneous appearance in outcrop. Distinctive pale green diopside-bearing calcsilicate gneiss is a moderately foliated to massive rock with layers that contain clots of diopside-quartz+/-hornblende in a psammitic matrix. Rare, distinct elongate lenses and boudins of coarse-grained, poorly foliated gedrite-cordierite-kyanite-sillimanite-biotite schist and phlogopite-gedrite schist are typically aligned parallel to the foliation of the heterogeneous paragneisses which enclose them (see also Duncan, 1984). These rocks contain abundant, pale, bladed gedrite, and cordierite has been found mantling relict patches of prismatic sillimanite. Amphibolite (biotite-plagioclase-hornblende and garnet-plagioclase-biotite-hornblende) lenses, boudins, and discontinuous layers vary from a centimetre wide and several centimetres long up to ten metres wide and many tens of metres long. Zones containing abundant amphibolite boudins can be traced for up to 100 metres.

Cover Gneisses

Cover gneisses are preserved as infolds (Gladshiem Lake and Mt. Skade synclines, Figure 3) within basement gneisses structurally below the Cariboo duplex. The preserved thickness of the cover gneiss succession in the southern part of Thor-Odin is only 200 m.

Overlying the basement gneisses below the Cariboo duplex, a basal quartzite ranges from an average thickness of 5 to 10 m, up to 20 m in some places (Unit 2a, Map 2). The unit is

dominated by beds of massive, well-sorted quartzite with centimetre-scale laminations and minor feldspar- or biotite-rich layers. No other primary sedimentary structures were observed. Common accessory minerals include tourmaline, zircon, and apatite. A minor amount of quartz-pebble conglomerate, with up to 30% ellipsoidal quartz pebbles, is present on the northern limb of the Mt. Skade infold (Figure 3) near the contact with the basement gneisses; this is a feature of the basal quartzite also described in other localities (see Mutti, 1978; Hoy, 1982, 1987; Journeay, 1986; Bosdachin, 1989). Thin (up to 5 m) layers of garnet-hornblende-biotite semipelitic schist are gradational into both underlying basement gneisses and overlying quartzite and quartz-pebble conglomerate of the cover sequence.

Overlying the basal quartzite is a heterogeneous succession, between 75 and 100 m thick, of interlayered pelitic and semipelitic schist, calcsilicate gneiss with minor impure marble, psammitic gneiss and minor quartzite (Unit 2b, Map 2). Horizontal facies changes result in a lenticular and interfingering distribution. Rusty-weathering semipelitic schists are migmatitic, layered on the centimetre scale, and contain interlayers of psammitic gneiss with minor thin-bedded, impure quartzite. Very coarse-grained, aluminosilicate-rich pelitic schist is approximately 5 m in thickness and contains large porphyroblasts of garnet, sillimanite and kyanite. Abundant massive to banded calcsilicate gneiss is composed primarily of plagioclase, quartz and diopside, with biotite,

calcite, potassic feldspar, scapolite, and garnet as minor constituents. Very thin interlayers (up to a maximum of 3 m thick) of impure, brown-weathering, diopside-phlogopite-bearing marble and rare anthophyllite-phlogopite pods occur locally.

The top of the heterogeneous unit is defined by the lower contact with a quartzite unit which is 10 - 30 m thick (Unit 2c, Map 2). Pelitic and semipelitic interlayers separate 0.5 to 3 m thick quartzite layers which are thinly bedded and contain up to 20% feldspar. Some of the quartzite layers contain heavy mineral laminae, up to 10 cm thick, which contain biotite, magnetite, ilmenite, graphite, garnet, zircon and monazite. Feldspathic layers are more common towards the boundaries of this unit; thick, pure, massive, vitreous quartzite occurs in the central portion.

Stratigraphically above the second quartzite unit is a unit dominated by thickly bedded psammitic gneisses containing layers of diopsidic quartzite up to a metre in thickness and rusty-weathering migmatitic semipelitic schist with thin pelitic interlayers (Unit 2d, Map 2). Rusty semipelite grades upward into massive diopsidic calcsilicate gneiss at the top of the preserved cover gneiss succession. Discontinuous layers and boudins of amphibolite are present throughout the cover gneiss sequence.

The cover gneiss succession described above can be correlated with the lowest part of the cover gneiss stratigraphy (below the stratabound carbonatite unit) described in the

northern Monashee Complex (Scammell, 1986; Journeay, 1986; Scammell and Brown, 1990). The Monashee décollement cuts down the stratigraphic section to the south, so that rocks exposed in the footwall at the northern end of the Monashee Complex are stratigraphically higher than those in the southern end (see Scammell and Brown, 1990). Thickness variations of cover gneiss may also be a result of non-deposition corresponding to pre-existing basement topography.

Metamorphic Grade

Kyanite, sillimanite and leucosome coexist in the footwall rocks of the Monashee Complex, although kyanite has been progressively replaced by syn-kinematic sillimanite (as described above in the Cariboo duplex). Refer to Figure 11 for a possible P-T path of the footwall rocks.

Structure

The dominant structures of the footwall rocks are the strong southwest-dipping foliation and the penetrative southwest-plunging stretching lineation. The regional metamorphic foliation (S2), marked by schistosity and gneissic layering, is defined by the dimensional preferred orientation of phyllosilicate and prismatic mineral grains, plastically deformed grains, and concordant lenses of leucosome. It generally parallels transposed and recrystallized primary compositional layering in the metasedimentary rocks and limbs of

phase one folds. These planar and linear fabrics are strongly developed throughout the examined footwall rocks, but become slightly less pronounced and more variable in orientation away from the décollement zone.

The geometry of the footwall rocks is controlled by at least three phases of deformation which post-date the deposition of cover on basement rocks. Some of the deformation and metamorphism in the basement gneisses probably occurred prior to the deposition of the cover rocks but has been obscured by younger events. Large F1 folds dominate the map-scale distribution of lithologic units. They are well defined by stratigraphy and were mapped on the basis of stratigraphic symmetry (inversion and repetition of regionally continuous markers) as infolds of cover gneiss within the basement gneisses. Large map-scale first phase folds, such as the Gladsheim Lake syncline and the Mt. Skade syncline (Figure 3, Map 3), have long attenuated limbs; the overturned limb being more attenuated and sheared off results in missing and structurally thinned stratigraphy. The original bedding (S_0) is unequivocally identified only in the metasedimentary gneisses in extensive infolds within the basement gneisses. Phase two and three folds are as described above in the Cariboo duplex; however, phase two folds are not as commonly disrupted by superimposed discrete shear zones.

GEOCHRONOLOGY

Age of cover gneisses of the Monashee Complex

Depositional ages and the relationship of the cover gneiss succession to rocks of cratonic North America is uncertain; therefore a detrital zircon study of a quartzite (VC-106) from the cover gneiss succession within Cariboo Alp, in sheared contact with basement gneisses of Thor-Odin, was undertaken (Plate 6A; location on Map 1). The upper amphibolite grade quartzite is well foliated and lineated, with annealed textures in thin section (Plate 6B). Layers of heavy minerals within the quartzite are up to 10 cm thick and contain zircon and monazite. Constraints on the age and provenance of this quartzite were obtained from U-Pb analyses of abraded single detrital zircon grains. Analytical procedures used in the U-Pb method for zircon and monazite are summarized in Appendix 1 and the data are presented in Table 1.

The detrital zircons could be divided into two morphological populations: a very rounded population with rough, slightly pitted or "frosted" surfaces (zircons A,G,H) and a faceted population with sharp, flat faces (zircons N,S,W). These two fractions perhaps represent different sources and distances of travel from their source. The sharp facets on the one population of zircons may have been metamorphic overgrowths (which were partially or fully removed by abrasion). The two populations, however, are quite well intermixed on the concordia diagram (zircons are represented by letters on Figure 8).

PLATE 6:

- (A) Quartzite with heavy mineral bands within sheared pelitic schists in the cover horse immediately above basement rocks of the Monashee Complex.
- (B) Thin section of quartzite showing annealed textures. The shear foliation is defined by discontinuous layers of biotite +/- sillimanite +/- accessory minerals. X-nicols.
- (C) Deformed basement paragneiss with up to 30% leucosome lenses and layers. Rotated leucosome pods reveal an upper-plate-to-the-northeast sense of shear.
- (D) Thin section of deformed basement paragneiss with annealed mylonitic fabric. Shear fabric defined by the orientation of sillimanite-biotite mats. A leucosome pod composed of quartz and K-feldspar is at the top of the photo. X-nicols.

TABLE 1: U-Pb ANALYTICAL DATA

Fraction ¹	U mg	Pb ^a ppm	206Pb/ 204Pb	Pb ^c 208Pb/ 208Pb	206Pb/ 238U	206Pb/ 238U	207Pb/ 235U	Corr. Coeff.	207Pb/ 206Pb	207Pb/206Pb Age (Ma)	207Pb/206Pb Age (Ma)		
VC-106													
A	0.032	276	80	12017	12	13.4	0.2606	0.2606 ± 0.06%	4.350 ± 0.10%	0.96	0.12109 ± 0.03%	1972.3 ± 1.0	1972.2
G	0.029	133	27	5753	8	8.3	0.1930	0.1930 ± 0.09%	2.994 ± 0.10%	0.94	0.11252 ± 0.03%	1840.4 ± 1.3	1840.3
H	0.021	352	92	9961	12	9.7	0.2483	0.2483 ± 0.09%	3.702 ± 0.10%	0.95	0.10814 ± 0.03%	1768.3 ± 1.2	1768.2
M	0.046	918	270	51299	15	4.7	0.2947	0.2947 ± 0.09%	4.402 ± 0.10%	0.96	0.10833 ± 0.03%	1771.5 ± 1.0	1771.4
S	0.020	206	51	9131	7	1.5	0.2557	0.2557 ± 0.08%	3.774 ± 0.10%	0.95	0.10705 ± 0.03%	1749.7 ± 1.1	1749.6
W	0.017	205	61	10340	10	7.2	0.2878	0.2877 ± 0.09%	4.529 ± 0.10%	0.96	0.11414 ± 0.03%	1866.4 ± 1.1	1866.3
1	0.013	2734	111	1442	14	80.3	0.5088	0.0088 ± 0.10%	0.056 ± 0.15%	0.75	0.04588 ± 0.10%	-8.6 ± 4.7	-3.0
2	0.037	4990	130	1985	59	66.0	0.0098	0.0098 ± 0.11%	0.063 ± 0.16%	0.82	0.04697 ± 0.08%	47.5 ± 4.0	47.6
3	0.008	4192	103	932	21	66.5	0.0091	0.0091 ± 0.10%	0.058 ± 0.18%	0.69	0.04618 ± 0.13%	7.0 ± 6.4	7.2
4	0.006	2628	120	858	11	82.3	0.0089	0.0089 ± 0.12%	0.056 ± 0.20%	0.65	0.04573 ± 0.15%	-16.4 ± 7.5	-9.4
VC-362													
A	0.037	1463	12	4607	7	0.8	0.008953	0.008936 ± 0.11%	0.06090 ± 0.12%	0.86	0.04943 ± 0.06%	168.3 ± 2.8	163.9
B	0.029	2321	20	1054	39	0.5	0.009430	0.009413 ± 0.10%	0.06162 ± 0.16%	0.77	0.04748 ± 0.11%	73.4 ± 5.1	69.3
C	0.023	657	10	1091	13	10.0	0.014557	0.014541 ± 0.12%	0.10795 ± 0.14%	0.78	0.05384 ± 0.09%	364.6 ± 3.9	362.0
D	0.108	780	16	8500	13	6.3	0.021224	0.021208 ± 0.10%	0.23238 ± 0.11%	0.96	0.07947 ± 0.03%	1183.8 ± 1.2	1182.3
E	0.095	631	13	5640	14	8.8	0.020380	0.020363 ± 0.09%	0.20644 ± 0.10%	0.94	0.07353 ± 0.03%	1028.5 ± 1.3	1026.9
1	0.029	2064	120	949	39	85.0	0.009672	0.009683 ± 0.10%	0.06169 ± 0.16%	0.69	0.04621 ± 0.12%	8.5 ± 5.6	11.3
2	0.015	2282	127	680	31	84.1	0.009757	0.009767 ± 0.10%	0.06104 ± 0.19%	0.73	0.04533 ± 0.13%	-38.1 ± 6.5	-35.7
3	0.011	2312	139	531	30	84.9	0.010041	0.010053 ± 0.13%	0.06388 ± 0.24%	0.64	0.04609 ± 0.18%	2.1 ± 8.8	4.9
VC-363													
A	0.102	1020	9	3021	23	0.6	0.010239	0.010222 ± 0.10%	0.06716 ± 0.12%	0.88	0.04765 ± 0.06%	81.9 ± 2.7	78.1
B	0.076	1011	9	3632	14	0.7	0.010309	0.010292 ± 0.09%	0.06746 ± 0.11%	0.92	0.04754 ± 0.04%	76.3 ± 2.0	72.5
C	0.060	1080	9	2619	14	0.7	0.009085	0.009068 ± 0.10%	0.05925 ± 0.12%	0.86	0.04739 ± 0.06%	68.9 ± 2.9	64.6
1	0.018	10711	175	2385	45	52.1	0.008671	0.008679 ± 0.10%	0.05458 ± 0.12%	0.92	0.04561 ± 0.05%	-23.2 ± 2.3	-21.1
2	0.011	2982	126	573	35	80.3	0.009119	0.009196 ± 0.12%	0.05597 ± 0.23%	0.64	0.04414 ± 0.18%	-102.6 ± 8.7	-82.0
3	0.015	13747	187	2352	51	61.0	0.008924	0.008923 ± 0.10%	0.05401 ± 0.13%	0.88	0.04390 ± 0.06%	-116.3 ± 3.0	-116.6

¹Letters are zircon fractions; numerals are monazite fractions;^aRadiogenic Pb, corrected for spike, fractionation, blank and common Pb;^bMeasured ratio, corrected only for spike and fractionation;^cTotal common Pb in analysis;^dRadiogenic 208Pb, expressed as % of total radiogenic Pb;^e206Pb/238U corrected for unsupported Pb from 230Th;^f207Pb/206Pb age recalculated from Th corrected 206Pb/238U;^gUncertainties are 1-sigma %^hUncertainties are 2-sigma in Ma.

FIGURE 8

Detrital zircon study of a quartzite within a cover gneiss thrust slice above the Monashee décollement. Abraded single grain U-Pb analyses of detrital zircon grains give a range of ages of 1.75 - 2.0 Ga. $^{207}\text{Pb}/^{206}\text{Pb}$ ages are used for tentative age assignment. Monazites also dated from the rock record a Late Paleocene-Eocene metamorphic event. Zircon data points (letters) are thorium corrected values. Monazite data (numbers) include both uncorrected and corrected results (i.e. 1, 1' respectively).

VC-106

Zircons from the quartzite are 1.75 - 2.0 Ga old. $^{207}\text{Pb}/^{206}\text{Pb}$ ages are generally used for tentative age assessment. The scatter in data points is interpreted to be as a result of a range in source ages (as well as different amounts of Pb loss); therefore, it is inappropriate to put a regression line through a number of points on the concordia plot. The data are quite discordant despite low to moderate U contents and strong abrasion. Multiple periods of Pb loss in the zircons prior to erosion and deposition in the sediment, during sediment diagenesis, and during polydeformation and metamorphism of the quartzite are probable, thus complicating the data.

The monazite crystals analyzed are pale yellow, quite rounded with some facets and are interpreted to be metamorphic monazites. All of the monazite data is reversely discordant, plotting above concordia (monazites are represented by numbers on Figure 8). This is as a result of "unsupported ^{206}Pb " in the mineral, a consequence of monazite incorporating excess ^{230}Th upon its formation (Scharer, 1984). The reverse discordance of monazites and description of the thorium corrections applied to the data as a result of the excess ^{230}Th are more fully described in Appendix 1. Uncorrected and thorium-corrected data are presented in Table 1. $^{207}\text{Pb}/^{235}\text{U}$ ages of the monazites are taken to be the correct ages.

There is a quasi-linear scatter of the monazite data. This scatter may indicate that the monazite data represent a mixing line between metamorphic monazite and an older inherited

(detrital or older metamorphic) component as it is possible for monazite to contain inherited radiogenic lead (see Copeland et al., 1988; Parrish, 1990). Alternatively, the scatter may reveal the length of time that the rock remained at a high temperature and metamorphic monazite crystals were formed or crystallized monazites remained as open systems and lost Pb. The monazite data are interpreted to record a Late Paleocene-Eocene thermal event.

The detrital zircon data indicate that rocks ranging in age from 1.75 to 2.0 Ga were exposed when the cover gneisses were deposited and that the quartzite studied is younger than 1.75 Ga, although there are no constraints on how much younger. Probable sources for the detrital zircons are the 1.8 - 2.1 Ga basement gneisses of the Monashee Complex (Wanless and Reesor, 1975; Parrish and Armstrong, 1983; Duncan, 1984; Armstrong and van der Heyden, 1989).

The 1.75 - 2.0 Ga old detrital zircons have ages very similar to ages from exposed North American cratonic shield to the east and zircon ages from the drilled basement in the Alberta basin (Evenchick et al., 1984; Parrish et al., 1989; Parrish and Ross, 1989, 1990; Parkinson, 1990). These comparative studies of U-Pb ages and deep seismic reflection studies (Brown et al., 1990) support the view that the basement gneisses of the Monashee Complex most likely represent remobilized attenuated North American basement.

Timing constraints of the Monashee décollement

Tight timing constraints have been placed on the final displacement of the compressional shear zone by dating (U-Pb zircon and monazite) syn-tectonic leucogranites in the Thor-Odin - Pinnacles area (Carr, 1989, 1990). Deformed sillimanite-bearing 62 to 59 Ma syn-tectonic leucogranites above the Monashee décollement indicate that compression was still ongoing in the Late Paleocene.

Basement rocks within the horses of the Cariboo duplex are polydeformed and are of upper amphibolite facies metamorphic grade. U-Pb zircon and monazite dating of a sillimanite-biotite-quartz-feldspar augen paragneiss (VC-362; Plate 6C) within a basement horse and a folded sillimanite-bearing pegmatite (VC-363) within the paragneiss (locations on Map 1) was undertaken in order to attempt to constrain the timing of final movement of the duplex. Sample 362 is a highly deformed sillimanite-biotite-quartz-feldspar paragneiss containing up to 30% leucosome lenses and pods. The paragneiss is strongly foliated with a penetrative stretching lineation and has annealed mylonitic fabrics in thin section (Plate 6D).

The data for this deformed rock are presented in Figure 9 and Table 1; much of the zircon data are scattered and discordant. Many of the zircons in the sample contain visibly distinct cores, but there were a number of crystals which were free of both visible cores and other inclusions. Zircon morphologies include well faceted, somewhat rounded equant and

FIGURE 9

U-Pb concordia diagram (VC-362) showing analyses of monazite (numbers) and zircon (letters) from a highly deformed sillimanite-biotite-quartz-feldspar augen paragneiss of a basement thrust slice of the Cariboo duplex. Uncorrected and thorium-corrected data are displayed (i.e. 1, 1' respectively).

VC-362

semi-facettted elongate crystals (fractions C,D,E; interpreted to be metamorphic morphologies) and long needle-shaped crystals (fraction A; perhaps an igneous morphology). Many of the zircons probably contain a detrital or older metamorphic component. The scattered discordant zircon fractions are interpreted to have different ages and amounts of inheritance and/or different amounts of Pb loss; therefore they do not lie on a discordia chord.

Zircons of fraction B have bipyramidal prism morphologies, which are generally interpreted as an igneous morphology (van Breemen et al., 1987). Perhaps these zircons formed in small migmatitic melt zones (leucosomes). Although fraction B is very slightly discordant (<1% discordant), it has a very high U content (2321 ppm as opposed to U contents of 600-700 ppm for fractions C,D,E) and as a result has probably experienced a significant amount of Pb loss. Therefore the age of these magmatic zircons is best interpreted by the $^{207}\text{Pb}/^{206}\text{Pb}$ age of 69.3 Ma. Peak thermal conditions are interpreted to have occurred in the late Paleocene. Clear, bright yellow, rounded, semi-facettted metamorphic monazites have $^{207}\text{Pb}/^{235}\text{U}$ ages of 60.8 +/- 0.2 (fraction 1) and 60.2 +/- 0.2 Ma (fraction 2).

Sample VC-363 is a deformed medium-grained pegmatite with a southwest-plunging sillimanite-bearing stretching lineation. The pegmatite, which is approximately 30 cm thick, is folded by a tight F2 fold and therefore has been involved in some of the D2 deformation. The folded pegmatite dyke has well-defined

FIGURE 10

U-Pb concordia diagram (VC-363) showing analyses of monazite (numbers) and zircon (letters) from a folded sillimanite-bearing pegmatite within deformed paragneisses of a basement thrust slice of the Cariboo duplex. Uncorrected and thorium-corrected data are displayed (i.e. 1, 1' respectively).

boundaries and cuts across strained leucosome lenses and pods of the deformed basement paragneiss that it intrudes (Sample VC-362).

Data from the pegmatite are presented in Figure 10 and Table 1 and are not easily interpreted. Zircon morphologies from the sample include clear, long, needle-shaped crystals (fractions A,B), which are interpreted to be an igneous morphology (van Breemen et al., 1987), and somewhat rounded, faceted, equant crystals (fraction C), which may represent a metamorphic morphology. This sample, which was strained during motion on the Monashee décollement, has a discordance pattern in which the zircon analyses are slightly discordant and are spread along the concordia curve. This pattern could be due to Pb loss as a result of high temperatures accompanied by deformation following formation of the pegmatite at perhaps roughly 66 Ma and terminating by approximately 58 Ma.

The monazite ages in the sample are distinctly younger ($^{207}\text{Pb}/^{235}\text{U}$ ages of 54.0 $\pm$ 0.1, 55.3 $\pm$ 0.2, and 53.4 $\pm$ 0.1 Ma). These younger monazite ages may have been a result of either growth of monazite while the rock was still hot (i.e. above the closure temperature of monazite) or a loss of Pb in monazite crystals subsequent to crystallization while the rock was at high temperature conditions perhaps from high temperature induced diffusion. All of the monazite data from this sample and from sample VC-362 show reverse discordance, which is described more fully in Appendix 1.

Although the data from samples VC-362 and VC-363 are not conclusive, they are in agreement with the data of Carr (1989, 1990) and B. Johnson (unpublished data, 1989), reinforcing the interpretation that final compressional deformation occurred in the latest Paleocene.

A suite of discordant, undeformed pegmatite which cuts across all the thrust slices and structures in Cariboo Alp (Plate 5B) has been dated at 58 ± 0.5 Ma (Carr, 1989, 1990), indicating that thrusting in the duplex had ended by this time.

DISCUSSION

The evidence preserved on the southern flank of Thor-Odin culmination reveals a one-stage movement history for the Monashee décollement, in contrast with a two-stage movement history preserved in Frenchman Cap (Journeay, 1986; Scammell, 1986). Pre-peak metamorphic shearing on the décollement, the age of which is unknown, occurred during loading of the Monashee Complex.

The predominant foliation (S₂), north-verging tight to isoclinal F₂ folds and the northeast-directed fabrics of the Monashee décollement formed during D₂ and are synchronous with the peak of metamorphism in both the hanging wall and footwall in Thor-Odin. There are no constraints on the timing of the onset of D₂; however, a significant part of D₂ deformation and

all of D3 deformation occurred in the Late Cretaceous - Paleocene (Carr, 1990; this study) with the culmination of penetrative compressional deformation and the accompanying metamorphic peak. The last stages of motion are known to have occurred in the latest Paleocene, as 62 and 59 Ma granitoids are strained in the shear zone (Carr, 1990). Movement on the décollement had ceased by 58 Ma (Carr, 1990) and was followed by a period of static annealing and rapid quenching of mineral assemblages, probably as a result of uplift on extensional normal faults.

Mineral dating is consistent with the interpretation that the metamorphic peak occurred in the Late Cretaceous-Paleocene. In the immediate hanging wall of the décollement a 62 Ma U-Pb date for magmatic zircons from a strained sillimanite-bearing migmatite leucosome indicates that the onset of melting occurred in the latest Paleocene (Carr, 1990). The thermal peak in the footwall occurred in the late Paleocene with the growth of magmatic zircons in leucosome melt pods and the growth of metamorphic monazite (this study). The growth of metamorphic zircons in amphibolite gneiss in the footwall (Carr, 1990) also supports a Late Paleocene thermal peak. Sillimanite present in the stretching lineation and axial planes of folded sheets of Late Paleocene leucogranites in the hanging wall (Carr, 1990) and deformed pegmatite and migmatite leucosome in the footwall (this study) indicate that the high temperature sillimanite-bearing assemblages were stable in the early Tertiary.

The apparent one-stage movement history is in contrast with data from the northwestern flank of Frenchman Cap where there is evidence for a two-stage shearing history on the décollement. Journeay (1986) (see also Scammell (1986)) has documented a zone of inverted low-pressure metamorphic isograds in the footwall of the Monashee décollement that overprints previously quenched syn-kinematic high pressure assemblages. The inverted metamorphic sequence is thought to have been caused by a transfer of heat into the lower plate from the upper plate during renewed thrusting. The high pressure and high temperature movement history (MD1) is thought (Journeay, 1986) to have occurred at greater than 25 km depth (>6.4 kb, $>670^{\circ}\text{C}$) during the Middle Jurassic. The rocks were then cooled by 200°C and uplifted 10-15 km before being remylonitized and reheated in the Late Cretaceous to early Tertiary (MD2) (a sufficient time span is required to uplift and cool the rocks within the complex before reheating them). In order to preserve this inverted metamorphism, rapid quenching and uplift are required (Journeay, 1986).

In contrast with Frenchman Cap, in Thor-Odin final shearing occurred during the culmination of regional deformation and metamorphism; there is no evidence of a low pressure reactivation of the Monashee décollement. Figure 11 is a petrogenetic grid for pelitic rocks. A proposed P-T path for footwall rocks is based on textural and metamorphic observations. A high pressure assemblage containing kyanite and

FIGURE 11

P-T petrogenetic grid for minerals of the pelitic system (SiO_2 - Al_2O_3 - FeO - MgO - Na_2O - K_2O - H_2O) modified after Carmichael (1978). Proposed P-T path of footwall rocks is marked. Striped pattern shows possible field for rocks in the immediate hanging wall of the décollement. Δ = aluminosilicate, b = biotite, g = garnet, K = K-feldspar, melt = granitic melt, mu = muscovite, Na = Na-feldspar, q = quartz, st = staurolite.

K-feldspar is inferred to have nucleated either prior to or during the initial stages of D2 deformation. As deformation proceeded, kyanite became unstable and was progressively replaced (overprinted) by syn-kinematic sillimanite. D2 may have had a protracted history, and there are no constraints on whether or not stable kyanite was part of the Late Cretaceous - Eocene event. Pull-aparts in some of the D2 syn-kinematic sillimanite filled with muscovite are inferred to record decreasing temperature conditions during the final stages of mylonitization (continued shearing on the unloading curve perhaps into the sillimanite-muscovite zone). This was followed by a period of static annealing and rapid quenching of mineral assemblages.

Peak metamorphic conditions were concurrent with melting as leucosome lenses and pods are within the axial planes of F2 folds and the shear plane. Assuming that sillimanite and/or kyanite plus melt are the products of peak metamorphic conditions (since kyanite is in equilibrium with K-feldspar in kyanite-bearing rocks; no muscovite is present), then peak conditions lie at least within bathozone 5. The minimum pressure is approximately 6.4 kb, the pressure at which kyanite = sillimanite and quartz + muscovite + plagioclase = aluminosilicate + melt. The corresponding minimum temperature is ca. 640°C. The striped pattern shows the possible P-T field for rocks in the immediate hanging wall of the décollement; no pressure constraints for these rocks are available.

Although no isograds could be mapped as one moved deeper into footwall rocks of the Monashee Complex at Cariboo Alp, the overprinting of kyanite by sillimanite is inferred to be as a result of heat transferred into the footwall from the hot overlying thrust sheet. Evidence for heat being transferred from above is found in the footwall on the northern and western flanks of Frenchman Cap (see Journeay, 1986; Scammell, 1986) and on the western flank of Thor-Odin culmination on Blanket Mountain (Map 5).

The pressure and temperature conditions of MD1 in Frenchman Cap are the same as the peak-loading conditions of the décollement in Thor-Odin; therefore, it seems reasonable to assume that this syn-metamorphic movement occurred at the same time. Latest movement on the décollement on the northern flank of Frenchman Cap (MD2) occurred at 10 km depth (Journeay, 1986). On the southern flank of Thor-Odin, since kyanite is not part of the stable footwall assemblage, there are not good constraints on the crustal level of final movement. However, final shearing in Thor-Odin occurred in the latest Paleocene at peak metamorphic conditions and therefore perhaps deeper crustal levels. It is suggested by Carr (1990) that initiation of extension earlier in the northern part of the complex, while compression was still underway, would result in movement on the décollement at a higher crustal level (as a result of uplift caused by extensional denudation) than in the south where extension had not yet begun.

CONCLUSIONS

The Monashee décollement marks the western and southern boundary of Thor-Odin culmination, separating rocks of the Selkirk allochthon from those of the underlying Monashee Complex. Rocks in the immediate hanging wall of the shear zone are interpreted to be correlative with Late Proterozoic Windermere Supergroup strata on the basis of lithological similarities. The footwall is composed of rocks of the Monashee Complex, which include orthogneisses and heterogeneous paragneisses interpreted to be Precambrian North American basement unconformably overlain by a metasedimentary cover gneiss succession which is only 200 m in thickness in the southern part of Thor-Odin.

In Cariboo Alp, on the southern flank of Thor-Odin, structural style of the immediate footwall of the Monashee décollement is an imbrication of alternating horses of basement and cover gneisses in between southwest-dipping sole and roof thrusts: the Cariboo duplex. Throughout the duplex there is a consistent southwest-dipping shear foliation and a penetrative southwest-plunging stretching lineation.

Displacement on the Monashee décollement outlasted or post-dated early pre-peak metamorphic first phase folding and outlasted syn-metamorphic phase two folding. Post-peak metamorphic third phase folds post-date the strong mylonitic fabrics. Northeast-directed movement on the Monashee

décollement resulted in formation of the Cariboo duplex by imbrication of the footwall. The minimum amount of displacement required to form the Cariboo duplex is roughly 15 km. Most of the movement on the shear zone occurred on the roof thrust of the duplex, the Monashee décollement, although the amount of displacement is unconstrained.

The predominant foliation (S2), north-verging tight to isoclinal F2 folds and the northeast-directed fabrics of the Monashee décollement formed during D2 and are synchronous with the peak of metamorphism in both the hanging wall and footwall in Thor-Odin. A high pressure assemblage containing kyanite is inferred to have nucleated either prior to or during the initial stages of D2 deformation. As deformation proceeded, kyanite became unstable and was progressively replaced (overprinted) by syn-kinematic sillimanite. There are no constraints on the timing of the onset of D2; however, a significant part of the deformation occurred in the Late Cretaceous - Paleocene with the culmination of penetrative compressional deformation and the accompanying metamorphic peak.

Annealed mylonitic fabrics throughout the Cariboo duplex exhibit a consistent upper-plate-to-the-northeast sense of shear. These fabrics are cut by an undeformed 58 Ma dyke, indicating that movement on the Monashee décollement in Cariboo Alp had ended by this time.

A KINEMATIC ANALYSIS OF THE MONASHEE DECOLLEMENT, SOUTHEASTERN BRITISH COLUMBIA

2

INTRODUCTION

Kinematic indicators are well preserved along the entire length of the Monashee décollement and have been studied in outcrop, hand sample and thin section. The purpose of this chapter is to describe the mylonitic rocks marking the décollement, to review the processes that form kinematic indicators, and to document the sense of movement of the Monashee décollement utilizing these shear sense indicators.

Along the western boundary of the Monashee Complex, detailed field and laboratory work, including kinematic studies, have been completed (Figure 2) in the northern and northwestern parts of Frenchman Cap by Scammell (1986) and Journeay (1986) respectively, in between Frenchman Cap and Thor-Odin culminations by Bosdachin (1989) and Harrap (1990), and in the southern part of Thor-Odin by Coleman (1989, and this study). Reconnaissance mapping and examination of the sense of movement of the Monashee décollement was carried out by Journeay and Brown (1986) on the western flank of Frenchman Cap and the southwestern flank of Thor Odin; samples collected were studied by Coleman (1987). Reconnaissance mapping has also been carried

out on the western flank of Thor Odin by V. Coleman and R. Brown (described in this study; Maps 4,5).

At several localities along the western flank of the Monashee Complex, northeast-directed mylonitic fabrics, formed as a result of movement on the Monashee décollement, have been overprinted by younger discrete shear zones with an upper member-to-the-west sense of shear. These younger fabrics are easily distinguished; they are unannealed and generally at lower metamorphic grade than fabrics associated with the Monashee décollement. West-directed fabrics are observed only rarely in the footwall of the Monashee décollement, but become increasingly evident at higher structural levels in the hanging wall, where they become regionally penetrative and are ascribed to shearing associated with the development of low angle normal shear zones and faults that developed during the Eocene extensional deformation (Journey and Brown, 1986; Brown and Journey, 1987; Parrish et al., 1988; Johnson 1988, 1989a, 1989b; Johnson and Brown, 1990). This period of extensional strain is not considered here; documentation is restricted to the earlier deformation that is related to emplacement of the overlying thrust sheet (Selkirk allochthon).

Kinematic indicators are meso- to microscopic-scale deformation structures which can be utilised as reliable indicators of the sense of movement in sheared rocks. It is important to identify an assemblage of mechanically independent structures, all of whose histories of progressive development

indicate a consistent sense of shear. Shear sense observations should be made in the XZ plane of the finite strain ellipsoid (see Ghosh, 1982; Treagus, 1983). In strongly sheared rocks, one can assume that the stretching lineation measured on the ground is sub-parallel to the direction of transport (e.g. Escher and Watterson, 1974; Choukroune et al., 1986; Takagi, 1986; Lacassin, 1987; Malavieille, 1987; Hanmer, 1988).

Mylonitic Rocks

The term "mylonite" is used here to describe those rocks in which it is clear that deformation has resulted in grain-size reduction due to strain-induced recrystallization without loss of cohesion (Bell and Etheridge, 1973; White et al., 1980; Brown and Murphy, 1982; Tullis et al., 1982).

The mylonitic rocks marking the trace of the Monashee décollement include both paragneisses and orthogneisses which have been deformed at high metamorphic grade (upper amphibolite facies). Most of the gneisses are recrystallized and show high grade annealed textures. The gneisses are strongly deformed (Plate 5C), contain reoriented and attenuated F1 and F2 minor folds (Journeay, 1986; Scammell, 1986; Bosdachin, 1989; Coleman, 1989, this study) and sheath folds (cf. Quinquis et al., 1978; Cobbold and Quinquis, 1980). Mylonites within the shear zone are strongly foliated with a predominantly southwest-dipping shear foliation (Plate 5D). A well developed mineral stretching lineation consistently plunges to the southwest and is defined

by elongate minerals, including kyanite, sillimanite, fibrolite-biotite mats, hornblende, and quartz, and by pressure shadows of quartz, feldspar and biotite (Plate 3D). The stretching lineation orientation in these highly sheared rocks is inferred to be approximately parallel to the transport direction of the hanging wall rocks of the Selkirk allochthon. Sense of shear asymmetry was determined using an assemblage of meso- and microscopic asymmetric structures in the shear zone rocks. Kinematic indicators used as criteria in determining the sense of shear include C-S fabrics, asymmetrical extensional shears, rotated porphyroclasts, rotated asymmetric boudins, foliation fish and strain-insensitive foliations (described below).

MESO- AND MICROSCOPIC SHEAR CRITERIA INDICATORS

While the mineral stretching lineation measured in mylonite outcrops gives the trend of displacement along the shear zones, the sense of displacement is determined by structures which exhibit an asymmetry (with respect to the shear foliation and shear zone boundaries) and which developed during the shearing process. Rocks along the Monashee décollement have preserved a diverse assemblage of asymmetric structures which show a remarkably consistent sense of asymmetry, both among different features in the same outcrop and between widely separated outcrops. Petrological criteria indicate various asymmetric structures developed syn-tectonically with mylonite formation

(Journeay, 1986; Scammell, 1986; Coleman, 1987).

Mesoscopic asymmetric structures, at the scale of tens to hundreds of grains, are generally better preserved than the microstructures; high syn- and post-tectonic temperatures apparently induced recrystallization and grain boundary adjustments that tend to mask the strain-induced microstructures.

C-S Fabrics

Composite fabrics composed of C and S planes, first described by Berthe et al. (1979), form in mylonites as the result of an imposed non-coaxial strain. They form by predominantly ductile processes and may be used to determine the sense of movement in deformed rocks.

C surfaces are initiated and remain aligned parallel to the main shear boundary with progressive deformation. They are considered to be spaced movement surfaces with a sense of shear the same as that of the overall shear zone. In the outcrops, hand samples and thin sections examined, C foliations are parallel to the compositional layering (e.g. Plate 7A). They are defined by continuous and discontinuous domains of biotite-rich concentrations, elongate quartz ribbons, biotite-sillimanite intergrowths, concentrations of accessory minerals, and layers of matrix. C foliations are generally planar; however, they do wrap around rigid porphyroclasts. S planes represent a penetratively developed flattening fabric which

attempts to track the XY plane of the finite strain ellipsoid (Berthe et al., 1979). In the rocks studied (e.g. Plate 7A), the S planes are defined by the preferred orientation of flattened mineral aggregates and elongate minerals and have a sigmoidal shape between the C planes. The trace of the S foliation, in a plane normal to S and parallel to its stretching lineation, is defined by the long axes of grains of kyanite, sillimanite, and feldspar (some of which are pulled apart perpendicular to the stretching lineation), sigmoidal quartz grains, the long axes of mica "fish", and the orientation of recrystallized polymineralic pressure shadows of porphyroclasts.

Each individual C plane is a narrow shear zone, bounded on either side by strain gradients. With increasing strain, reorientation of the finite strain axes occurs (Berthe et al., 1979), and the angle between C and S surfaces decreases from an initial angle of approximately 45° (first increment of strain in simple shear). The observed sigmoid S surfaces curve asymptotically into near parallelism with the shear surfaces, conforming to the shear zone model of Ramsay and Graham (1970). It is assumed that the C and S foliations developed simultaneously as there is no evidence that one truncates or post-dates the other and fabric elements defining the S foliation are asymptotic to the C foliation.

Plate 7B demonstrates very well developed C-S fabric in a mylonitic quartzofeldspathic paragneiss. The angle between the trace of the flattening foliation (S), defined by the long axes

PLATE 7:

- (A) Sheared gneisses in the hanging wall of the Monashee décollement on the northwest flank of Thor-Odin culmination. C-S fabrics and asymmetrical extensional shears indicate a northeast-directed sense of shear. The light-coloured layer is concordant, deformed pegmatite with a protomylonitic fabric.
- (B) Very well developed C-S fabric in quartzofeldspathic gneiss. The trace of the flattening foliation (S foliation) is defined by the long axes of feldspar and biotite porphyroclasts, and the trace of the shear foliation (C foliation) is defined by compositional layering and discontinuous biotite-rich concentrations. Note the thin shear bands, marked by very fine grained biotite, linking trails of porphyroclasts. Photo is looking southeast in the plane of the stretching lineation and perpendicular to the foliation. This fabric is interpreted to indicate that the upper member of the shear couple moved to the northeast. Sample from the southwestern flank of Thor-Odin.
- (C) Set of asymmetrical extensional shears, up to several millimetres thick by up to 5 cm long, are oriented between 15-25° to the shear foliation and reveal a northeast-directed sense of movement. They are very fine grained, thin, dark coloured zones which are sigmoidal in shape and curve listrically into the shear foliation.
- (D) Shear band, in semipelitic sample, is approximately 1.5 mm long and curves listrically into the C foliation where it terminates at both ends. The shear band is a very fine-grained, dark coloured zone composed of biotite and opaques. Layers of matrix, elongate quartz grains, and grains of kyanite show marked curvature and rotation as they are deflected into the shear band. Photo is looking southeast in the plane of the mineral stretching lineation and perpendicular to the foliation. This fabric is interpreted to indicate that the upper member of the shear couple moved to the northeast. Sample is from the western flank of Frenchman Cap dome. Plane polarized light.

of feldspar and biotite porphyroclasts, and the trace of the shear foliation (C), defined by the compositional layering and discontinuous biotite-rich concentrations, gives an upper-plate-to-the-northeast sense of shear. Also note the thin asymmetrical extensional shears (described below) marked by very fine-grained biotite, linking trails of porphyroclasts.

Asymmetrical Extensional Shears

Asymmetrical extensional shears are very commonly observed in the mylonites studied. They seem to have developed later in the shearing deformation history as they generally overprint earlier structures.

Asymmetrical extensional shears, also known as shear bands, extensional crenulation cleavage or C' bands are discrete, discontinuous surfaces of concentrated strain (White et al., 1980; Berthe et al., 1979; Platt and Vissers, 1980; Passchier, 1984; Weijermars and Rondeel, 1984; Platt, 1984). Mylonites subjected to non-ideal simple shear along the shear plane often respond, perhaps as a result of increased strain hardening (Platt, 1984), by developing a set of discrete shears; slip on the shears results in extension of the bulk shear plane (Platt and Vissers, 1980; Harris and Cobbold, 1984; Platt, 1984). Ideally, only one set of shears is developed, whose sense of slip is synthetic to the slip on the bulk shear plane; however, it is not uncommon for a conjugate, but numerically subordinate, set to form (Harris and Cobbold, 1984; Behrmann, 1987).

The traces of the extensional shears are displayed on rock faces oriented perpendicular to the foliation and parallel to the stretching lineation and vary from being sporadically to more homogeneously distributed. The extensional shears examined in this study occur as single sets, consistently oriented between 15-25° to the shear foliation, and have a sense of movement synthetic to the overall sense of shear, as determined by independent kinematic indicators. They are very fine-grained, thin, dark coloured zones commonly up to several millimetres thick by up to 10 cm long which are sigmoidal in shape and curve listrically into the shear foliation (Plate 7C).

Extensional shears are commonly observed in thin section and are geometrically similar to the mesoscopic examples. Plate 7D is of a shear band in a semipelite, defined by a thin zone of very fine-grained biotite and opaques approximately 1.5 mm long, which curves listrically at both ends into the C foliation where it terminates. Layers of matrix, elongate quartz grains, pressure shadows of porphyroclasts, and grains of sillimanite show marked curvature and rotation as they are deflected into the shear band. This structure is interpreted to indicate a northeast-directed sense of shear.

Rotated porphyroclasts

Asymmetric structures, which reveal the sense of shear, can be formed as the result of the rigid body rotation of porphyroclasts and tectonic inclusions within a more ductile

matrix (Ghosh and Ramberg, 1976; Davidson et al., 1982; Hanmer, 1984; Passchier and Simpson, 1986; van den Driessche and Brun, 1987). Components of porphyroclasts include different geometrical elements of varying shapes, such as stubby clasts with long, thin tails. The kinematic significance of a structure is generally deduced from the asymmetry derived from the relative rotations of its component parts, which are a function of the strain rate and aspect ratio (Ghosh and Ramberg, 1976; Passchier and Simpson, 1986; van den Driessche and Brun, 1987).

Asymmetric porphyroclasts are ubiquitous in the Monashee décollement and range in scale from polycrystalline tectonic inclusions to single crystals, 1 mm or less in diameter, observed in thin section. Individual porphyroclasts, commonly feldspar or biotite, are often connected by long recrystallized tails of the same mineral. Elongate porphyroclasts (plagioclase, alkali feldspar, amphibole, and biotite have been observed in outcrop) show recrystallized tails emanating from upper leading and lower trailing edges. These are equivalent to the sigma-porphyroclasts of Passchier and Simpson (1986).

Equant porphyroclasts (plagioclase, alkali feldspar, and garnet have been observed in outcrop) have tails which are commonly straight, lying in a single plane which passes through the centre of the inclusion and which is parallel to the shear plane of the deformation, except for the deflection of the tails immediately adjacent to the porphyroclast (Plate 8A). These

structures are equivalent to the delta-porphyroclasts of Passchier and Simpson (1986) and the "rolling structures" of van den Driessche and Brun (1987).

Quartz-feldspar+/-biotite leucosome pods and feldspar porphyroclasts are quite possibly the relics of pegmatite which has undergone extensive dynamic grain size reduction (Plates 8B,C). The fine-grained polycrystalline tails attached to these inclusions are composed of monomineralic feldspar or quartzofeldspathic aggregates. Plate 8C is an elongate feldspar porphyroclast (F) with tails of recrystallized feldspar and quartz, emanating from the upper leading and lower trailing edges, which lie in the shear plane. There is a "stair-step" Z-shape to the tail-inclusion-tail, which gives a sinistral sense of rotation (upper-member-to-the-northeast).

Back-rotated foliation segments

Shear-sense indicators which rotate antithetically with respect to the sense of the imposed bulk shear are common along the length of the Monashee décollement and include foliation fish, back-rotated anisotropic "pinch-and-swell" structures (Hanmer 1984, 1986) and mica fish (Lister and Snoke, 1984). The back-rotated "swells" and boudins (commonly quartz-feldspar+/-biotite leucosome pods or biotite-garnet-hornblende amphibolite boudins) are structures which are associated with discrete asymmetrical extensional shears; the ends of the swells and any internal layering deflects into these discrete shears (Plate

2

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

PLATE 8:

- (A) Equant porphyroclasts of feldspar with polycrystalline tails of quartz and feldspar which are straight, lying in a single plane which passes through the centre of the inclusion and which is parallel to the shear plane of the deformation. This structure is equivalent to a delta-porphyroclast of Passchier and Simpson (1986) and is interpreted to indicate an upper-member-to-the-northeast sense of shear. Sample from the western flank of Frenchman Cap dome. X-nicols.
- (B) Sheared gneisses in the footwall of the Monashee décollement on the western flank of Frenchman Cap culmination. Asymmetric leucosome pods and shear foliation indicate a northeast-directed sense of shear.
- (C) Deformed rocks in the hanging wall of the Monashee décollement on Blanket Mountain, western flank of Thor-Odin. Note the feldspar porphyroclast (F) with long, thin tails of recrystallized feldspar and quartz lying in the shear plane. The long axis of the feldspar porphyroclast is oriented within the extensional quadrant, making an angle with the shear plane, and resulting in the determination of a northeast-directed sense of shear.
- (D) Back-rotated asymmetrical boudins within sheared basement gneisses of the Cariboo duplex indicate an upper-member-to-the-northeast sense of shear. Discrete zones of shear (analogous to asymmetrical extensional shears) are present at the ends of the boudins, oriented at angles less than 30° to the shear plane. The ends of the boudins and the internal layering is deflected into these discrete shears.

8D). The back-rotation of the boudin or swell is simply a consequence of the slip on the extensional shears which bound them (Hanmer, 1986).

Foliation fish (Hanmer, 1984, 1986) are elliptical domains, on all scales, whose internal foliation is oblique with respect to the general foliation of the enveloping rocks. Foliation fish are direct analogues to asymmetric pull-aparts. Plate 9A is an example of asymmetric foliation boudinage: a back-rotated lozenge of mylonite within mylonite. Backrotation of the swells could be a response to slip along the internal anisotropy planes (Lister and Williams, 1983) which causes oblique extension of the swells and local deviation from ideal simple shear (Hanmer, 1984, 1986). As with the pull-aparts, the boundaries of the packets and the internal layering deflects into the shear zone.

Mica "fish", described by Lister and Snoke (1984) are single-crystal analogues to foliation fish. They are asymmetric in shape and the (001) cleavage of the mica is either tilted back against the sense of shear or sub-parallel to the shear surfaces. Plates 9B and 9C are examples of a biotite "fish", within a matrix of biotite-sillimanite mats, with their cleavage oblique to the shear foliation. Antithetic rotation of the mica "fish" could be as a result of displacement along discrete extensional shears located between them or slip along the internal planes of anisotropy (cleavage). Mica "fish" are commonly linked by trails of very fine-grained material that, where they are extensively developed, "stair-step" from one mica

PLATE 9:

- (A) Small duplex, a back-rotated lozenge of mylonite within mylonite, gives an upper-plate-to-the-northeast sense of shear within sheared basement gneisses of the Cariboo duplex.
- (B) Biotite "fish" within a matrix of less deformed biotite grains and biotite-sillimanite mats. Antithetic rotation of the "fish" is as a result of displacement along discrete extensional shears located at its boundaries. This fabric is interpreted to indicate that the upper member of the shear couple moved to the northeast. Sample from the southwestern flank of Thor-Odin. X-nicols.
- (C) Biotite "fish" with its (001) cleavage oblique to the shear foliation. Note that the displacements along the cleavage traces are antithetic to the overall displacement in this rock. This fabric is interpreted to indicate that the upper member of the shear couple moved to the northeast. Sample from the southwestern flank of Frenchman Cap. X-nicols.
- (D) Typical dynamically recrystallized quartz grain growth preserved in mylonitic quartz-rich rock. The long axes of quartz subgrains (S_b) are oriented at about 50° to the shear foliation (S_s). Note that some of the quartz grains are "pinned" by the mica. Photo is looking southeast in the plane of the stretching lineation and perpendicular to the foliation. This fabric is interpreted to indicate that the upper member of the shear couple moved to the northeast. Sample from the southwestern flank of Thor-Odin.

"fish" to the next.

Strain-insensitive foliations

In highly strained mylonites, compositional layering and monomineralic, polycrystalline ribbons lie parallel to the shear plane (described above). Within a polycrystalline quartz ribbon, the quartz grains occasionally are all aligned, defining a penetrative shape fabric.

Oblique grain-shape foliations occur rarely in the mylonites studied; however, in thin sections containing this fabric, the long axes of the dynamically recrystallized grains, best seen with the lambda plate inserted, are generally oriented at 30-50° to the shear foliation within the quartz aggregates.

This type of fabric was first described by Means (1981) as a strain-insensitive foliation because the angle between the shape fabric (S_b) and the shear foliation (S_s) does not decrease with progressive deformation. In response to an increase in internal strain energy as a result of tracking the finite strain ellipsoid of the deformation, large quartz grains break down into small new subgrains such that continuous dynamic recrystallization takes place. As a result of recrystallization in a strain field, the new crystals are aligned, marking the instantaneous elongation direction of the strain ellipse with respect to the shear plane of the deformation (White et al., 1980; Simpson and Schmid, 1983; Lister and Snoke, 1984). The attitude of the oblique foliation depends on the shear strain

accumulated since the particular volume of rock last recrystallized.

Plate 9D shows typical dynamically recrystallized quartz grain growth preserved in a mylonitic quartz-rich rock. The long axes of quartz subgrains are oriented at about 50° to the C foliation. The quartz fabric reveals the relationship between the instantaneous elongation direction of the strain ellipsoid (S_b) and the shear foliation (S_s), and therefore, a northeast-directed sense of shear.

CONCLUSIONS

The assemblage of shear asymmetry indicators described above shows remarkable consistency; in single outcrops, from outcrop to outcrop, and across 200 km of terrain. These mylonitic fabrics are considered to be reliable kinematic indicators, as independent structures have consistently recorded a northeast-directed sense of movement on the Monashee décollement.

Hundreds of structures were utilized to determine the shear sense along the length of the décollement. The most common and unambiguous kinematic indicators include C-S fabrics and asymmetrical extensional shears. Rotated asymmetric boudins and "pinch and swells" are less common along the length of the Monashee décollement, but are consistent structures where they

are observed. Rotated porphyroclasts are ubiquitous; however, determination of their shear sense is sometimes ambiguous so care must be taken in interpreting these structures. Mica "fish" and strain insensitive foliations are much less common, but very useful where they are preserved. It is important that these structures be recognized as parts of an assemblage, rather than as individual kinematic indicators, utilized to determine a northeast-directed sense of shear on the Monashe_e décollement.

APPENDIX 1: ANALYTICAL METHODS FOR GEOCHRONOLOGY STUDIES

Analytical methods used for the geochronological work are those outlined by Parrish et al. (1987). Minerals were separated from rock samples weighing about 20-25 kg using standard crushing, grinding, Rogers Gold table, heavy liquid, and Frantz magnetic separation techniques. Zircons and monazites were selected for analysis by sieving and handpicking in ethyl alcohol. The grains were picked to optimize clarity with care being taken to avoid cracked and cloudy grains in order to reduce radiation damage problems. Population sizes varied from 1 grain in the detrital study (VC-106) to up to 11 grains in deformed biotite-quartz-feldspar augen gneiss analyzed (VC-362). All zircon fractions were abraded following the method of Krogh (1982) to ensure that surface-correlated Pb loss would be removed if it were present. Very clear euhedral monazite fractions were chosen for analysis, but were not abraded.

The samples were spiked with a mixed ^{233}U - ^{235}U - ^{205}Pb 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 Parrish et al. (1987). Common Pb corrections were done assuming model Pb compositions derived from the growth curve of Stacey and Kramers (1975). Decay constants are from Steiger and Jager (1977).

Errors reflect one standard error, and error ellipses on concordia plots are 2 standard errors (see Roddick, 1987). An analysis is considered to be concordant if the ellipse overlaps concordia.

Thorium Corrections

All of the monazite fractions show "reverse discordance", plotting above the concordia curve. This is interpreted to be due to excess ^{230}Th incorporated during formation as a result of U and Th fractionation during crystal growth, as monazite favours Th relative to U (see Scharer, 1984; Parrish, 1990). ^{230}Th is an intermediate daughter product of the ^{238}U - ^{206}Pb decay chain. The enrichment of ^{230}Th upon crystal formation results in the production of ^{206}Pb in excess of what would be present if the ratios of Th/U in the monazite and the parent magma were the same. The presence of this "unsupported ^{206}Pb " contributes to the total amount of radiogenic ^{206}Pb , resulting in radiogenic $^{207}\text{Pb}/^{206}\text{Pb}$ ratios which are too low; therefore, $^{207}\text{Pb}/^{206}\text{Pb}$ ages are too low and may be strongly negative. As a result the monazite data plot above the concordia curve.

Fractionation of U over Th during zircon growth leaves zircon with a deficiency of Th relative to the magma. Although the effect is very slight, the result is a deficiency of daughter ^{206}Pb . Therefore the $^{207}\text{Pb}/^{206}\text{Pb}$ ratios are too high and the zircons plot below concordia.

Th-U fractionation in monazite and zircon has an important

effect in young rocks as the amount of radiogenic ^{206}Pb derived from ^{230}Th forms a significant percentage of the total radiogenic ^{206}Pb (see Parrish, 1990). This effect decreases with increasing age, becoming unimportant in rocks older than approximately 150 Ma, as the Pb/U analytical uncertainty is of similar or greater magnitude relative to the expected excess ^{206}Pb age (Parrish, 1990) (e.g. corrected and uncorrected zircon data for sample VC-106 are virtually identical).

For all zircon and monazite fractions, the $^{206}\text{Pb}/^{238}\text{U}$ ratios and the relevant age calculations were corrected for unsupported ^{206}Pb from ^{230}Th incorporated during crystallization. This was done using the procedures outlined by Scharer (1984) and Parrish (1990). It is assumed for these corrections that the Th/U ratio measured from the whole rock (Table 2) represents the Th/U ratio of the magma.

The amount of excess ^{206}Pb increases with decreasing Th/U ratio of the magma and with increasing Th/U ratio of the monazite. The corrected isotopic ratio from Scharer (1984) is

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

where $f = (\text{Th}/\text{U})_{\text{mineral}}/(\text{Th}/\text{U})_{\text{magma}}$, and L_{238} and L_{230} refer to the decay constants of ^{238}U and ^{230}Th , 1.55125×10^{-10} and 0.922×10^{-5} , respectively. The corrected $^{207}\text{Pb}/^{206}\text{Pb}$ ratio is

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

Uncorrected and thorium-corrected data are presented in Table 1. Some of the thorium corrections moved the monazite data points down towards concordia, but they undercorrect all of the monazite data (none of the data is concordant). For the reversely discordant monazites, the $^{207}\text{Pb}/^{238}\text{U}$ ages are interpreted in terms of the age or thermal significance. The thorium corrections result in some of the zircon data moving upward and almost plotting on concordia, in particular fraction B of VC-362 and fractions B,C of VC-363. The correction procedure is of questionable usefulness perhaps because of invalid assumptions about the Th/U available to monazites and zircons during their growth (Parrish, 1990). The assumption that the Th/U ratio measured from the whole rock represents the Th/U ratio of the magma may also not be valid.

TABLE 2: WHOLE ROCK THORIUM AND URANIUM ANALYSES

Sample number	Th (ppm)	U (ppm)	Th/U
VC-106	3.1	0.5	6.2
VC-362	7.9	0.7	11.2
VC-363	3.8	1.5	2.5

Notes: Analyses performed by ICPMS courtesy of the Geological Survey of Canada.

Detection limit is 0.1 ppm.

SAMPLE DESCRIPTIONS AND LOCALITIES

Lithologies and UTM coordinates of samples for U-Pb dating are as follows:

VC-88-106: well foliated sillimanite-bearing quartzite (layer approximately 5 m thick) with heavy mineral bands and annealed mylonitic fabrics in thin section; elevation 7450 ft. in Cariboo Alp above cliff at Gates Ledge overlooking Mt. Gunnarsen, UTM 11u, 4157000E-5597875N;

VC-362: deformed migmatitic sillimanite-biotite-quartz-feldspar paragneiss, with annealed mylonitic fabrics, within southernmost basement horse of the Cariboo duplex; elevation 7150 ft., central flat of Cariboo Alp between east and west ridges (82 L/9), UTM 11u, 415175E-5597025N;

VC-363: sillimanite-bearing 30 cm thick pegmatite folded by an F2 fold within the biotite-quartz-feldspar paragneiss described above (VC-362); elevation 7150 ft., central flat of Cariboo Alp between east and west ridges (82 L/9), UTM 11u, 415175E-5597025N.

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MAP I

STATION LOCATION MAP OF C SOUTHERN FLANK OF THOR-ODIN

● 438 STATION LOCATION AND NUM

◎ VC-363 GEOCHRONOLOGY SAMPLE L

Contours at 100 ft. intervals

Topography from maps: 82 L/8 Gates Creek
82 L/9 Mt. Fosthall

Surveys and Mapping Branch, Canadian Energy

Scale: 1:16 700

**OF CARIBOO ALP,
ODIN CULMINATION**

NUMBER

PLE LOCATION

**reek (1:50 000)
hall (1:50 000)**

Energy, Mines & Resources

MAP 2 STRATIGRAPHY OF SOUTHERN FLANK OF THE

STRATIGRAPHY:

THE SELKIRK ALLOCHTHON

3 FAWN LAKE ASSEMBLAGE

Rusty-weathering semipelitic schist and platy
minor pelitic schist, quartzite, marble and calc
amphibolite boudins and layers locally compo
composes up to ca. 40%

THE MONASHEE COMPLEX

2 COVER GNEISSES

2d Dominantly psammitic paragneiss with layers
rusty-weathering semipelitic and pelitic schist
and discontinuous layers; diopside-bearing c
of sequence

2c Quartzite interlayered with pelitic and semipe

2b Heterogeneous succession dominated by
semipelitic schist; calcsilicate gneiss with
psammitic gneiss; minor quartzite; amphiboli

2a Quartzite with pelitic partings; quartz pebble

1 BASEMENT GNEISSES

Undifferentiated orthogneisses and hetero
dominated by migmatitic biotite-quartz-fel
including semipelitic, pelitic, psammitic, calc
gneisses and schists

1C 'Clot' rock : diopside-hornblende-quartz cl
siliceous matrix

1G Gedrite +/- cordierite +/- kyanite +/- sillimanite
schist

Lithologic Contacts:

OF THE THOR-ODIN

and platey metasandstone with
and calcsilicate gneiss;
compose ca. 30%; pegmatite

layers of diopsidic quartzite;
schists; amphibolite boudins
ring calcsilicate gneiss at top

semipelitic schist

by interlayered pelitic and
with minor impure marble;
amphibolite boudins and layers

pebble conglomerate

heterogeneous paragneisses
quartz-feldspar paragneiss; also
calcsilicate, and amphibolite

quartz clasts in a calcareous to

granite +/- biotite +/- phlogopite

CARIBBO
MOUNTAIN

R K

Mikes Lake

Fawn
Lake

Peter's
Lake

Scale: 1:16 700

gneisses and schists

1C 'Clot' rock : diopside-hornblende-quartz class
siliceous matrix

1G Gedrite +/- cordierite +/- kyanite +/- sillimanite +/-
schist

Lithologic Contacts:

— Sharp - - - - Approximate

▲ THRUST FAULT MD= MONASHEE DEC

tz clasts in a calcareous to

anite +/- biotite +/- phlogopite

..... Assumed

EE DECOLLEMENT

DIV OF PALE LAR
KOOTENAI LAND DIST

P A R K

93

118° 10'

Resolution Test Chart Labels:

- 1.0
- 1.1
- 1.25
- 1.4
- 1.6
- 1.8
- 2.0
- 2.2
- 2.5
- 2.8
- 3.2
- 3.6
- 4.0

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

S-

STRUCTURAL MAP OF CMA

MAP OF CARIBOO ALP

STRUCTURES

THRUST FAULT

STRETCHING LINEATION

FOLIATION S_{0-1}

F1 FOLD HINGE, $Z = V$

F1 AXIAL PLANE

F2 FOLD HINGE, $S = V$

F2 AXIAL PLANE

F3 FOLD HINGE, $Z = V$

F3 AXIAL PLANE

F1 AXIAL SURFACE

F2 AXIAL SURFACE

S

EATION

Z = VERGENCE

S = VERGENCE

Z = VERGENCE

ACE TRACE - SYNCLINE

ACE TRACE - ANTICLINE

MAP 4

STATION LOCATION MAP OF THOR-ODIN CULM

● 458

STATION LOCATION AND NUMBER

Contours at 100 ft. intervals

Topography from maps: 82 L/9 Mt. Fosthall (1:50 000)
82 L/8 Gates Creek (1:50 000)
82 L/16 Revelstoke (1:50 000)
82 K/5 St Leon Creek (1:50 000)
82 K/12 Beaton (1:50 000)

Surveys and Mapping Branch, Canadian Energy, Mines & Res

Scale: 1:100 000

OR-ODIN CULMINATION

NUMBER

(1:50 000)
(1:50 000)
(1:50 000)
ek (1:50 000)
50 000)

rgy, Mines & Resources

F2 AXIAL SURFACE TR

SELKIRK ALLOCHTHON

COVER GNEISSES

BASEMENT GNEISSES

MD = MONASHEE DECOLLEMENT

CROSS-SECTION A-B IN

E TRACE - ANTICLINE

HTHON

S

SSES

OLLEMENT

B IN FIGURE 4

Scale: 1:100 000

V Colema

V Coleman '90

OFFICE OF THE
LAND DISTRICT

PARK

118°10'

PROVINCIAL

M O N A S H E E

C O L U M B I A

F O R E S T

P A R K
R A N G E

H I G H L A N D

1 G M G
1 F O R E S T

S H U S W A

A M I S S

M O N A S H E E

F O R E S T

M O N A S H E E

50°30'

118°30'

118°15'

15

RANGE

11800

Map 5

Geology of Thor -

r - Odin Culmination

STRATIGRAPHY

THE SELKIRK ALLOCHTHON

- 3b Dominantly graphite-bearing calcsilicate gneiss; white pure rusty-weathering semipelitic schist; banded amphibolite; pegmatite composes up to ca. 40%
- 3a Dominantly rusty-weathering semipelitic schist and metasandstone with minor pelitic schist, quartzite, mafic calcsilicate gneiss; amphibolite boudins and layers locally composed of 30%; pegmatite up to ca. 40%

THE MONASHEE COMPLEX

- 2 COVER GNEISSES
Heterogeneous succession of interlayered pelitic and semipelitic schist; quartzite; quartz-feldspathic paragneiss; calcsilicate gneiss; amphibolite boudins and layers; mafic gneiss; and amphibolite.
- 1 BASEMENT GNEISSES
Undifferentiated orthogneisses and heterogeneous paragneisses dominated by migmatitic biotite-quartz-feldspar paragneiss. Including semipelitic, pelitic, psammitic, calc-silicate, and amphibolite gneisses and schists.

STRUCTURE

- 48 Foliation (S_{0-1})
- 30 Stretching Lineation
- Lithologic Contacts (mapped, assumed)
- Lithologic contacts compiled from Read, 1980; Bosch, 1988; and references therein.
- Thrust Fault (mapped, inferred, assumed)
MD = MONASHEE DECOLLEMENT
- COLUMBIA RIVER FAULT (CRF): compiled from Parrish et al., 1988; and references therein.
- Brittle Fault

ing calcsilicate gneiss; white pure marble;
pelitic schist; banded amphibolite gneiss;
to ca. 40%

nering semipelitic schist and platy
nor pelitic schist, quartzite, marble and
bolite boudins and layers locally compose ca.
40%

on of interlayered pelitic and semipelitic
-feldspathic paragneiss; calcsilicate gneiss
e; amphibolite boudins and layers

neisses and heterogeneous paragneisses
biotite-quartz-feldspar paragneiss, and also
litic, psammitic, calc-silicate, and amphibolite

ion

cts (mapped, assumed)

cts compiled from Read, 1980; Bosdachin, 1989;
d references therein.

pped, inferred, assumed)

EE DECOLLEMENT

ER FAULT (CRF): compiled from Read, 1980;
88; and references therein.

PROVINCIAL
MONASHIEE
(COLUMBIA
FOREST

PARK
RANGE

SHUSWAP

LEG MO
LIM

50°30'

KM

118°30'

G O L D

118°15'

MONASHIEE PROVINCE

C O L

CRF

27

MG
MF

42

14

END

04.03.92

FIN