1

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

National Library
of Canada

Bibliothèque nationale
du Canada

Canadian Theses Service

Services des thèses canadiennes

Ottawa, Canada
K1A 0N4

CANADIAN THESES

NOTICE

The quality of this microfiche is heavily dependent upon the quality of the original thesis submitted for microfilming. Every effort has been made to ensure the highest quality of reproduction possible.

If pages are missing, contact the university which granted the degree.

Some pages may have indistinct prints, especially if the original pages were typed with a poor typewriter ribbon or if the university sent us an inferior photocopy.

Previously copyrighted materials (journal articles, published tests, etc.) are not filmed.

Reproduction in full or in part of this film is governed by the Canadian Copyright Act, R.S.C. 1970, c. C-30.

**THIS DISSERTATION
HAS BEEN MICROFILMED
EXACTLY AS RECEIVED**

THÈSES CANADIENNES

AVIS

La qualité de cette microfiche dépend grandement de la qualité de la thèse soumise au microfilmage. Nous avons tout fait pour assurer une qualité supérieure de reproduction.

S'il manque des pages, veuillez communiquer avec l'université qui a conféré le grade.

La qualité d'impression de certaines pages peut laisser à désirer, surtout si les pages originales ont été dactylographiées à l'aide d'un ruban usé ou si l'université nous a fait parvenir une photocopie de qualité inférieure.

Les documents qui font déjà l'objet d'un droit d'auteur (articles de revue, examens publiés, etc.) ne sont pas microfilmés.

La reproduction, même partielle, de ce microfilm est soumise à la Loi canadienne sur le droit d'auteur, SRC 1970, c. C-30.

**LA THÈSE A ÉTÉ
MICROFILMÉE TELLE QUE
NOUS L'AVONS REÇUE**

THE VALKYR SHEAR ZONE AND THE SLOCAN LAKE FAULT: EOCENE STRUCTURES
THAT BOUND THE VALHALLA COMPLEX, SOUTHEASTERN BRITISH COLUMBIA

by

SHARON D. CARR, B.Sc.

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

Carleton University

Ottawa, Ontario

January, 1986

© copyright

1986, Sharon D. Carr

Permission has been granted to the National Library of Canada to microfilm this thesis and to lend or sell copies of the film.

The author (copyright owner) has reserved other publication rights, and neither the thesis nor extensive extracts from it may be printed or otherwise reproduced without his/her written permission.

L'autorisation a été accordée à la Bibliothèque nationale du Canada de microfilmer cette thèse et de prêter ou de vendre des exemplaires du film.

L'auteur (titulaire du droit d'auteur) se réserve les autres droits de publication; ni la thèse ni de longs extraits de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation écrite.

ISBN 0-315-29884-7

The undersigned hereby recommend to the Faculty of Graduate

Studies and Research acceptance of the thesis

"The Valkyr Shear Zone and the Slocan Lake fault:

Eocene Structures That Bound the Valhalla Complex,

Southeastern British Columbia"

submitted by Sharon D. Carr, B.Sc.,

in partial fulfillment of the requirements for

the degree of Master of Science.

.....
Chairman, Department of Geology

.....
Thesis Supervisor

Randall A. Marsh
.....
Thesis Co-Supervisor

Carleton University

January 16, 1986

ABSTRACT

The Valhalla complex, a Cordilleran metamorphic core complex, lies in the Omineca belt of southeastern British Columbia. It comprises Mesozoic or older, polydeformed, high grade paragneiss and variably deformed Cretaceous to Eocene granitoid sheets. The complex has a protracted history that probably includes metamorphism and deformation during easterly-directed Mesozoic thrusting as well as extensive ductile deformation of Tertiary granites indicative of significant Eocene shearing. This study focuses on the structural, kinematic, and temporal relationships in Paleocene and Eocene granitoid sheets with respect to structures which bound the complex.

The asymmetry of mylonitic fabric elements in these granitoid sheets, and in overlying rocks, yield an easterly-directed shear sense on all flanks of the domal complex indicating the presence of a shear zone that is arched over the complex. This ductile zone, the Valkyr shear zone, separates the high grade, penetratively deformed Valhalla complex from surrounding lower grade rocks, thus the Valhalla complex is exposed in a tectonic window. The Valkyr shear zone was active between 58 Ma and 54 Ma under amphibolite facies metamorphic conditions. The displacement on this zone is uncertain and movement was, in part, concurrent with uplift and arching of the Valhalla complex. There is evidence to support an easterly rooting direction for the Valkyr shear zone indicating that it may be an extensional structure.

The eastern side of the complex is bounded by the Slocan Lake fault zone, a gently easterly-dipping and easterly-rooting normal fault. Ductile and brittle deformation in the Slocan Lake fault zone outlasted movement on the Valkyr shear zone. Deformation occurred at lower to middle greenschist facies. This structure is pinned at both ends and the maximum displacement occurs along the central section of the fault where there is at least 10 km of dip-slip displacement. The Slocan Lake fault truncates a 58 Ma granite (U-Pb), has 54 Ma synkinematic muscovite (Rb-Sr) in footwall fault rocks and is cross-cut by a basaltic dyke with an inferred age of 55 - 45 Ma. The Valkyr shear zone, arching of the Valhalla complex and movement on the Slocan Lake fault zone occurred in the early to middle Eocene.

This study is significant because it documents the presence of ductile shearing in the Omineca belt that is clearly early to middle Eocene in age and is, at least in part, extensional in origin. In many metamorphic core complexes, the relationship of lower plate mylonites to brittle structures which overprint them is unclear. In the Valhalla complex, structural and temporal data indicate that mylonites on the eastern margin of the complex, in the footwall of the Slocan Lake fault zone, were formed during movement on this fault.

ACKNOWLEDGEMENTS

This project was in part funded by National Research Council of Canada Operating Grant A6293 to R.L. Brown and by Carleton University.

I gratefully acknowledge the support of the Geological Survey of Canada under project number 830006. R.L. Brown and R. Parrish suggested the thesis topic and I appreciate their support and advice throughout the project. Many thanks to R. Parrish for sharing ideas and field data and for generously providing unpublished dates.

TABLE OF CONTENTS

	Page
ACCEPTANCE SHEET.....	ii
ABSTRACT.....	iii
ACKNOWLEDGEMENTS.....	iv
TABLE OF CONTENTS.....	v
LIST OF TABLES AND FIGURES.....	vi
CHAPTER 1: Introduction.....	1
CHAPTER 2: Geology of the Valhalla gneiss complex and the surrounding region.....	9
The Valhalla complex.....	11
The Valkyr shear zone - south of the Columbia River.....	20
Upper plate of the Valkyr shear zone.....	21
Upper plate of the Slocan Lake fault zone..	24
The northern end of the Slocan Lake fault..	26
K-Ar and Rb-Sr mineral dates.....	28
CHAPTER 3: Kinematic relationships and fabric variation in Paleocene and Eocene granitic rocks of the Valhalla complex.....	43
Kinematic indicators in units PEg and Pgm..	43
Fabric variation.....	48
Metamorphic grade of mylonites.....	52
Age of mylonite formation.....	54
Relationship of mylonitic fabrics to the Valkyr shear zone and the Slocan Lake fault.....	55
Discussion.....	57
CHAPTER 4: The Slocan Lake fault zone.....	67
Description of the fault zone.....	67
Displacement.....	75
Age of faulting.....	78
Summary.....	78
CHAPTER 5: Summary of conclusions.....	87
APPENDIX 1: Valhalla complex geology.....	89
APPENDIX 2: Upper plate geology of the Valkyr shear zone.....	91
APPENDIX 3: Upper plate geology of the Slocan Lake fault zone.....	92
APPENDIX 4: Petrography Unit PEg- Zone A.....	93
APPENDIX 5: Petrography Unit PEg- Zone B.....	95
APPENDIX 6: Petrography Unit PEg- Zone C.....	97
APPENDIX 7: Displacement Calculations.....	99
REFERENCES.....	101

LIST OF MAPS, TABLES AND FIGURES

MAP 1:	1:100,000 scale geology map of the Valhalla gneiss complex and the surrounding region.....	BACK POCKET
TABLE 1:	Common microstructures in amphibolite and greenschist grade mylonites.....	54
FIGURE 1:	Tectonic Map of Southern British Columbia.....	5
FIGURE 2:	Geology Map.....	7
FIGURE 3:	The Valkyr shear zone and Slocan Lake fault....	29
FIGURE 4:	Generalized east-west cross-sections.....	31
FIGURE 5:	Rocks of the Valhalla complex	33
FIGURE 6:	Rocks of the Valhalla complex	35
FIGURE 7:	Rocks of the Valhalla complex and the Rosebery stock.....	37
FIGURE 8:	Equal area plots of poles to foliation and lineations.....	39
FIGURE 9:	Compilation of K-Ar and Rb-Sr mineral ages.....	41
FIGURE 10:	Structure map	59
FIGURE 11:	Kinematic indicators in PEG.....	61
FIGURE 12:	Fabric variation map.....	63
FIGURE 13:	Fabric variation in unit PEG.....	65
FIGURE 14:	Unit PEG fault rocks - footwall of the Slocan Lake fault zone.....	81
FIGURE 15:	Cross-sections--Slocan Lake Fault zone.....	83
FIGURE 16:	Nelson batholith fault rocks - hanging wall of the Slocan Lake fault zone.....	85

CHAPTER 1 - INTRODUCTION

Tertiary normal faults associated with metamorphic core complexes are recognized in the Omineca belt of the Cordillera in southern British Columbia, Washington and Idaho (Price 1979, Ewing 1981, Armstrong 1982, see Figure 1). These faults, which bound the high grade core complex terranes, include the Slocan Lake fault zone (Reesor 1965, Parrish 1981, 1984), the Columbia River fault zone (Brown and Psutka 1979, Read 1979, Read and Brown 1981, Lane 1984), the Newport fault (Harms 1982), the Okanagan fault zone (Tempelman-Kluit 1984, Bardoux 1985, Parkinson 1985), the Kettle River fault and the Granby River fault (Little 1957, Preto 1970, Rhodes and Cheney, 1981). The Newport fault (Harms 1982), the Okanagan fault (Parkinson 1985) and the Slocan Lake fault (Parrish 1984) clearly have late Cretaceous and/or early Tertiary ductile shear zones associated with them, whereas mylonites in the footwall of the Columbia River fault zone, in the Revelstoke area, formed prior to the early Cretaceous (Lane 1984a) and in other core complexes the timing is uncertain. Controversies focus on: a) the tectonic significance of the extensional faults, b) the genetic and temporal relationship between faults and lower plate mylonites and c) the relative contribution of compressional and/or extensional deformation to the lower plate, high grade metamorphic terranes.

The Valhalla complex lies in the Valhalla Ranges northwest of Castlegar, British Columbia (Figure 1). It comprises Mesozoic or older polydeformed, high grade metasedimentary rocks and Cretaceous to Eocene granitoid sheets (Figure 2). The upper granitic sheets, of Paleocene and Eocene age (Parrish 1984, Parrish et al. 1985b), outcrop around the

periphery of the complex and have regionally extensive proto-mylonitic and mylonitic fabrics. The asymmetry of fabric elements consistently indicate an easterly-directed¹ sense of shear on all flanks of the domal complex. Mylonitic fabrics are also present in rocks which immediately overlie the northern, western and southern margins of the Valhalla complex. This zone of distributed strain is up to three kilometres thick and is interpreted as a ductile shear zone, here named the Valkyr shear zone. Granitoid, metamorphic, sedimentary and volcanic rocks in the upper plate of the Valkyr shear zone are at lower grade and preserve a different deformation history than gneisses in the higher grade, penetratively deformed Valhalla complex. The eastern margin of the Valhalla gneiss complex is bounded by the Slocan Lake fault zone (Parrish 1984). It is an easterly-dipping, easterly-rooting normal fault which juxtaposes relatively undeformed rocks of the Nelson batholith against early Tertiary, granitic mylonites of the Valhalla gneiss complex. The last movement on the Slocan Lake fault zone occurred in the brittle regime and postdates the Valkyr shear zone, although both were active in the early Eocene.

This paper documents mylonitic fabrics in the early Tertiary granites of Valhalla complex, and considers their relationship to bounding structures. The mylonites represent significant early to middle Eocene ductile shearing with an easterly-directed shear sense. Structural relationships indicate that the shear zones were active during uplift and arching of the Valhalla gneiss complex.

¹easterly-directed: indicates the direction of movement of the upper member of the shear couple and the hanging wall.

PREVIOUS WORK

Early geologic reconnaissance of the Valhalla and Slocan Ranges is included in Little's (1960) regional map of the Nelson west-half 1:250,000 map sheet. Little mapped the arched paragneiss and foliated granitic sheets in the Valhalla Ranges and noted mylonites east of Slocan Lake. He distinguished leucocratic, biotite bearing, granitoid rocks of the Valhalla series from porphyritic granite and granodiorite of the Nelson series, although he ascribed them a common magmatic origin. The Valhalla Ranges are the type area (McConnell and Brock, 1904) for leucocratic biotite granitic plutons of the Valhalla series which are extensive in southern British Columbia (Little 1957, Little 1960, 1961).

A detailed study of the Valhalla gneiss complex was completed by Reesor (1965). He established the major rock units in the complex and concluded that they were disposed in arched sheets up to 2 km thick. Reesor mapped a mylonitized and brecciated "crushed zone" between Valhalla gneiss complex and the Nelson batholith to the east, which he interpreted as a steep fault. This fault is now known to have a moderate easterly dip and has been named the Slocan Lake fault zone (Parrish 1981, 1984).

A mapping and geochronologic project designed to elucidate the age and tectonic history of the complex was initiated by R. Parrish of the Geological Survey of Canada in 1983. U-Pb zircon age determinations indicate that the granitoid sheets were emplaced in the Cretaceous, Paleocene and Eocene, thus the Valhalla complex is in large part a Tertiary structure (Parrish 1984, Parrish et al. 1985). Parrish (1984) also recognized mylonitic fabrics, with an easterly - directed shear

sense, in the immediate footwall of the Slocan Lake fault zone.

Field work for this study comprised the detailed examination of fabrics and structures along the eastern margin of the Valhalla complex and, where access permitted, across the southern end of the complex (see Map 1, back pocket). The discovery of mylonites with an easterly - directed shear sense in the Ladybird Creek area, on the west-dipping flank of the dome, indicated the existence of a shear zone that is arched over the complex. The upper contact, on the northern and western sides of the Valhalla complex, was examined jointly with R. Parrish in the 1985 field season and is inferred to be a shear zone that involves both upper and lower plate rocks. This tectonic contact, the Valkyr shear zone is characterized by S - C tectonites and by syn- and postkinematic granitic intrusions and pegmatites.

FIGURE 1: Tectonic Map of Southern British Columbia showing high grade gneiss terranes and their bounding faults (modified from Parrish et al. 1985a) VC = Valhalla Complex; MC = Monashee Complex; TOD = Thor Odin Dome; KD = Kettle dome - Grand Forks complex; OD = Okanogan Dome; OG = gneisses of Okanogan and Shuswap Highlands; SLFZ = Slocan Lake fault zone; VSZ = Valkyr shear zone; CRFZ = Columbia River fault zone; MD = Monashee decollement; NF = Newport fault; KRF = Kettle River fault; GRF = Granby River fault; OFZ = Okanogan fault zone.

LEGEND

MIDDLE EOCENE

- Coryell plutonic rocks
- Kamloops Group - volcanics, minor sediments

JURASSIC - EARLY EOCENE

- Granitic plutons
- Orthogneiss

EARLY JURASSIC

- 4 Rossland Group - volcanics, sediments of Quesnellia

MIDDLE PALEOZOIC - LATE TRIASSIC

- 3 Sedimentary, volcanic and ultramafic rocks of Quesnellia and/or other accreted terranes
- 3a Inferred or known metamorphic equivalents

LOWER OR MIDDLE PALEOZOIC

- Granitic orthogneiss, tectonically emplaced(?)

EOCAMBRIAN - PENNSYLVANIAN

- 2a Sediments and metasediments of the Kootenay Arc, of cratonic affinity
- 2 Inferred metamorphic equivalents

HADRYNIAN

- 1 Windermere Supergroup, cratonic affinity
- 1a Inferred metamorphic equivalents

HELIKIAN

- Purcell Supergroup, cratonic affinity

PROTEROZOIC

- Crystalline basement: probably part of North American craton

AGE UNCERTAIN

- A Paragneisses of Monashee Complex and Tenas Mary Creek Sequence
- B Paragneiss and orthogneiss of the Shuswap and Okanogan Highlands, Trail gneiss

- KNOWN OR INFERRED THRUST FAULT: tick on upper plate
- KNOWN OR INFERRED NORMAL FAULT: tick on upper plate
- VALKYR SHEAR ZONE: tick on upper plate

NOTE: RECTANGLE MARKS THE LOCATION OF FIGURE 2

FIGURE 2: Geology Map of Valhalla complex and the surrounding region.

LEGEND

EOCENE

CORYELL PLUTONIC ROCKS: Leucocratic hornblende syenite

Peg: Leucocratic biotite quartz monzonite to granite

PALEOCENE

Pgm: K-feldspar megacrystic biotite + hornblende quartz monzonite

CRETACEOUS

GRANITIC STOCKS: leucocratic biotite quartz monzonite: a) Cariboo Ck, b) Snowslide Ck, c) Wragge Ck, d) Rosebery, e) Mt. Carpenter

uKkgn KINNAIRD GNEISS: leucocratic hornblende + biotite orthogneiss; can have K-feldspar augen, leucocratic veins and pegmatite, quartz poor phases

uKgn: melanocratic biotite-hornblende augen granodioritic gneiss, intruded with leucocratic granitoid veins of uncertain age

CRETACEOUS AND/OR JURASSIC

GRANITIC PLUTONS: predominantly granodiorite and quartz diorite.

MIDDLE JURASSIC

NELSON BATHOLITH AND SATELLITES: granodiorite, quartz diorite, minor hornblende quartz syenite, and minor granite

MIDDLE AND LOWER JURASSIC

Jrg ROSSLAND GROUP: shale, volcano-clastics, augite porphyry

UPPER TRIASSIC

Tsg SLOCAN GROUP: slate, argillite phyllite, calcareous and arenaceous interbeds

PALEOZOIC AND TRIASSIC

P-Tms NEMO LAKES METASEDIMENTARY ROCKS: polydeformed semi-pelite and pelite, calcareous schist, amphibolite and ultramafic rock

PENNSYLVANIAN (?)

MOUNT ROBERTS FM: limestone, argillaceous quartzite and greenstone

PRE - MIDDLE JURASSIC (order does not imply relative age)

ms PARAGNEISS: polydeformed metasedimentary rocks intruded by leucocratic orthogneiss and pegmatite of uncertain age

cgn CASTLEGAR GNEISS: heterogeneous hornblende + biotite quartz-feldspathic paragneiss, amphibolite, calc-silicates, granitic layers

gn PARAGNEISS: heterogeneous sillimanite, garnet bearing gneiss and schist

tgn TRAIL GNEISS: heterogeneous para- and orthogneiss, amphibolite, quartz-feldspathic schist, pegmatite and aplite

VSZ VALKYR SHEAR ZONE

SLFZ SLOCAN LAKE FAULT ZONE

CLF CHAMPION LAKE FAULT

CHAPTER 2 - GEOLOGY OF THE VALHALLA GNEISS COMPLEX AND THE SURROUNDING REGION

The 30 km by 100 km Valhalla complex, lies in the mountainous Valhalla Ranges, bounded by the Slocan valley on the east and the Columbia River (Lower Arrow Lake) on the west (Figure 1). It is an elongate, north-trending, culmination in which thick gneissic and granitoid sheets, metamorphic layering and mylonitic foliation dip gently ($< 35^{\circ}$) outward. The complex has a protracted history that probably includes metamorphism and deformation during easterly-directed Mesozoic thrusting (discussed on page 16) as well as extensive ductile deformation of Tertiary granites indicative of significant Eocene shearing.

To the north, west and south, the complex is surrounded by 1) Jurassic and Cretaceous granodiorite and granite (the Nelson and Valhalla series of Little 1957, 1960, 1961) and syenite of the Eocene Coryell plutonic suite, 2) metasedimentary rocks of the Nemo Lakes belt and Slocan Group in the northern Valhalla Ranges (Little 1960, Read and Wheeler 1976, Parrish 1981), and 3) sedimentary and metasedimentary rocks, to the south and southwest, presumed to be correlative in part with the Pennsylvanian (?) Mount Roberts formation (Little 1957, 1960, 1982, see Figure 1 and Map 1).

The boundary that separates Valhalla complex from these rocks was mapped with Parrish in the 1985 season and is interpreted as a tectonic contact, thus the Valhalla complex is exposed as a tectonic window (Figure 2). Mylonites in the lower plate, described in detail in Chapter 3, occur over a three kilometre thick zone. Rocks in the upper plate (Figure 3a), are mylonitic within approximately 0.5 kilometres of the

contact (Figure 3b). The contact between upper and lower plate rocks is generally a strained zone, part of which is intruded by multiple phases of syn- and postkinematic granite and pegmatite (Figure 3c). The lower plate is characterized by high grade, penetratively deformed, sheetlike, intrusive rocks and gneisses, Eocene K-Ar mineral dates and a pervasive, ductile Tertiary (and possibly late Cretaceous) overprint. These characteristics are contrasted with upper plate rocks which are at lower metamorphic grade, the plutonic rocks are relatively undeformed, K-Ar mineral ages are generally Cretaceous or older, and Mesozoic or older structures are preserved. This shear zone, named the Valkyr shear zone, has not been studied in detail although it has been mapped or inferred around the perimeter of the Valhalla complex. The displacement is uncertain since there are no hanging wall/footwall cutoffs and the direction of rooting is not firmly established although there is evidence to suggest that it roots to the east (see page 58).

The eastern margin of the Valhalla complex is bounded by the Slocan Lake fault zone (Figure 3d). It roughly parallels the north trending Slocan valley for over 100 kilometres from Castlegar to north of Slocan Lake (Figure 2). On the basis of structural relations of adjoining rocks it is interpreted as a 20° to 40° easterly-dipping, normal fault (Parrish 1984). Between Silverton, on Slocan Lake, and Castlegar, the fault zone juxtaposes mylonitic rocks of the Valhalla complex in the footwall against the Nelson batholith in the hanging wall (Reesor 1965, Parrish 1984, Carr, 1985). North of the Valhalla complex, the Slocan Lake fault zone truncates the Nemo Lakes metasedimentary rocks, a west-trending belt that is present only on the west side of Slocan Lake (Parrish 1981). Displacement on the fault dies out northward; phyllites of the Slocan Group and granitic stocks outcrop north of Silverton in

both the hanging wall and footwall. South of Castlegar, the fault joins the Champion Lake fault which extends 30 km southward and terminates east of Trail (Corbett and Simony 1985, see Figure 2). In this area, the Rossland Group and Nelson batholith in the hanging wall are juxtaposed against the Trail and Castlegar gneisses.

This chapter presents descriptions of the lithologic units in the Valhalla complex and surrounding rocks (i.e. the upper plates of the Valkyr shear zone and the Slocan Lake fault) as well as their structure and tectonic inter-relationships. This is followed by a compilation of K-Ar and Rb-Sr mineral dates. Additional details of the geology are summarized in Appendices 1, 2 and 3.

THE VALHALLA COMPLEX

Within the Valhalla complex, the orientation of flat-lying and gently-dipping gneisses defines second order domes; the Valhalla dome centered west of Slocan Lake and the Passmore dome to the south (Map 1). The origin or structural significance of the two domes is not presently known. Four map units, originally defined by Reesor (1965), are distinguished in the Valhalla complex (units ~~ms~~, ~~uKgn~~, ~~Pgm~~, ~~PEG~~; Appendix 1, Figure 2). The core of the complex consists of sheets of high grade paragneiss, (unit ~~ms~~), interlayered with and overlain by upper Cretaceous granodiorite gneiss (~~uKgn~~), Paleocene biotite + hornblende quartz monzonite (~~Pgm~~) and Eocene biotite granite (~~PEG~~, see Figure 1). These granitic rocks have been dated by Parrish by U-Pb zircon methods (1984, 1985, see Appendix 1). They have a sheetlike configuration, contacts are concordant, the youngest sheets occur highest in the complex and their original intrusive geometry is unknown.

To the south, along the Columbia River, **PEg** intrudes and overlies the Castlegar gneiss (Simony 1979). In this area it is divided into two units; 1) a leucocratic K-feldspar megacrystic orthogneiss (formerly unit **cgna** of Parrish et al. (1985b) and Carr (1985), renamed the Kinnaird gneiss (unit **uKkgn**) by Halwas and Simony (1986); and 2) a heterogeneous paragneiss (unit **cg**). These gneisses have a similar tectonic history to upper Cretaceous - Eocene granitoid gneisses of the Valhalla complex.

Rock Descriptions

The rock units are described in ascending order through the culmination from oldest to youngest. This is followed by a description of the Castlegar gneiss, late intrusions and late stage structures in the complex.

The most extensive lithology, unit **ms**, consists of sheets of rusty weathering, upper amphibolite grade paragneisses of uncertain age and correlation. Unit **ms** occurs at three structural levels as shown in Figure 4, cross-section 4b. Common rock types in this heterogeneous gneiss include biotite-quartz-feldspathic gneiss, pelitic and semi-pelitic sillimanite schist, amphibolite, minor calc-silicate gneiss and minor quartzite. Leucocratic orthogneiss, migmatite and pegmatite, both concordant and discordant, comprise a minimum of 20% of the rock and as much as 80% in the north and northwest (Reesor 1965).

The lower two sheets of unit **ms** are exposed in Gwillim Creek, where in both cases, the upper boundaries are in sheared contact with unit **uKgn** (Map 1). A tentative easterly-directed sense of shear was assigned to the Gwillim Creek shear zones by Parrish and Carr during 1985 field

work, although this may only represent the last strain (Figure 5d). The extent and significance of these features is not presently known.

The uppermost sheet of unit **ms** is extensive and outcrops in Valhalla and Passmore domes. It is polydeformed; three phases of folding were identified in Gwillim basin (Parrish et al. 1985b) and folds have been reported throughout the complex by Reesor (Figure 5a). On the eastern margin of the complex these structures have been overprinted by an intense penetrative deformation. The upper sheet of unit **ms** has been thinned by up to 50% (as shown in Figure 4 cross-sections) and gneisses, which elsewhere preserve polyphase folds and cross-cutting relationships, are transposed into well layered gneisses. Sheath folds are present. The layering is concordant with overlying mylonites in units **Pgm** and **PEg** and parallel to the Slocan Lake fault zone.

Unit **uKgn** is a melanocratic, potassium feldspar augen biotite + hornblende granodioritic gneiss (Figure 5c) whose age is 89 ± 3 Ma (Parrish 1984). It occurs in the core of Valhalla dome and is interlayered and in sheared contact with unit **ms** (Figure 5d). The uppermost, 2 km thick sheet of **uKgn**, is resistant and forms many of the rugged peaks in the core of the complex. Unit **uKgn** is laced with both discordant and concordant leucocratic veins, 10 to 40 cm thick, which comprise about 30% of the rock (Reesor 1965). This gneiss has a strongly developed foliation and a less developed east or west plunging lineation defined by the orientation of feldspar and hornblende crystals, and biotite streaks. Feldspar augen, which can be up to 6 cm long, are not always parallel to this mineral lineation.

Unit **Pgm** overlies the upper sheet of unit **ms**. It is a 63 ± 1 Ma, Paleocene potassium feldspar megacrystic quartz monzonite (Parrish 1984) forming a two km thick sheet. **Pgm**, thickest in Passmore dome, thins and

pinches out to the north and south. The fabric is primarily igneous at locations on the west side of the complex (Figure 6a) but is highly strained on the east side where it contains a well developed mylonitic fabric with ultramylonite zones (Figure 6b).

Unit **PEg**, the structurally highest and most extensive granitoid sheet, outcrops around the periphery of the complex and lies in the immediate footwall of the Valkyr shear zone and the Slocan Lake fault zone (Figure 6c). It varies in thickness from 400 m on the east side of the complex to 3 km in the southwest Ladybird Mountain area. It is a biotite quartz monzonite which yields a 58 ± 1 Ma age from U-Pb zircon methods (Parrish unpub. data 1985). On the southwest flank of the complex along the Columbia River, **PEg** is crosscut by late discrete shear zones and basic dykes.

Unit **PEg** is variably strained throughout the complex. On the northern and western flanks, the upper boundary of **PEg** is strained in contact with granodiorite of Jurassic or Cretaceous age and the Nemo Lake belt metasedimentary rocks (Figure 2). The contact relationship is complicated by the intrusion of late phases of **PEg** and multiple generations of pegmatites but is very regular in map pattern. **PEg** exhibits the highest degree of strain on the eastern flank of the complex, in the footwall of the Slocan Lake fault zone where mylonites are pervasive. Within the fault zone, these mylonites are fractured, brecciated and have undergone retrograde metamorphism at greenschist grade. Unit **PEg**, which is extensive, lithologically homogeneous and has a well constrained isotopic age, provides an ideal setting to investigate the distribution of strain throughout the lower plate, particularly with respect to structures which bound the Valhalla

complex.

Unit uKkgn, the Kinnaird gneiss of Halwas and Simony (1986) was termed the Castlegar gneiss (cgn) by Parrish et al. (1985b) and Carr (1985). In the Columbia River area it is a leucocratic, quartz-poor, potassium-feldspar megacrystic hornblende gneiss (Figure 6d). Leucocratic pegmatite and fine-grained mafic rich layers are present. The gneiss has a strong foliation, minor small scale folds, small scale ductile shears with minor displacement and a moderately well-developed easterly-trending mineral lineation. Hornblende, feldspar aggregates and some potassium-feldspar augen lie in the lineation; however, large hornblende crystals and potassium-feldspar augen are often variably oriented. U-Pb dating work in progress indicates that the Kinnaird gneiss is late Cretaceous in age (Parrish unpub. data 1985). In the Columbia River area, uKkgn interdigitates with and overlies cgn.

Unit cgn is a heterogeneous, rusty weathering, layered hornblende-biotite-quartz-feldspathic paragneiss (Figure 7a), which outcrops east of Keenleyside dam on the Columbia River, and in Pass Creek valley 10 km north of Castlegar (Map 1). Granitic intrusions, leucocratic veins, amphibolite layers and calc-silicate layers within the gneiss are variably folded, boudinaged and transposed. The paragneiss has a well-developed foliation and easterly-trending stretching lineation in which hornblende is stable.

The Kinnaird gneiss (uKkgn) and Castlegar paragneiss (cgn) exhibit the same structural and metamorphic characteristics as the Valhalla complex (Simony 1979). Both are penetratively deformed at high metamorphic grade, have an east-west lineation, and are apparently sheetlike. For these reasons, these two gneiss units, uKkgn and cgn, are included in the Valhalla complex.

A suite of syenitic rocks which intrude the Valhalla complex near Deer Park on the Columbia River are correlative with Eocene Coryell intrusions (Parrish et al. 1985b, Map 1 & Figure 2). Unit **Ecsy**, a porphyritic syenite stock, outcrops along the Columbia River near Syringa Creek and is thought to have a faulted intrusive contact with **PEg**. It is coarse grained, quartz free and constituent mafic minerals include hornblende, biotite and clinopyroxene. This unit is 52 ± 1 Ma old (Parrish unpub. data 1985). Unit **Ecsy** is crosscut by north-trending, steeply-dipping basic dykes, foliated mafic dykes and pink syenitic veins and intrusions which are thought to be of Coryell affinity. This syenite is deformed by discrete minor ductile shears (Figure 7b). Elsewhere these syenitic rocks clearly intrude unit **PEg** west of Syringa Creek along the Deer Park road.

Comparison of structures on the eastern and western flanks of the, Valhalla complex

Structures preserved in the central and western areas of the Valhalla complex have different orientations and geometry than those on the east flank. On the basis of field relationships, Reesor (1965) concluded that folding throughout the complex was overprinted on the east side by shearing and flattening. These observations are corroborated by this study.

At least part of the deformation preserved on the west side of the complex is late Cretaceous or older. Reesor reports that recumbent folds in units **ms** and the melanocratic part of **uKgn** are crosscut by the leucocratic veins in unit **uKgn** and that the leucocratic veins predate the emplacement of Paleocene unit **Pgm**.

Three phases of deformation (of uncertain age) were identified in the

upper sheet of unit **ms** at the headwaters of Gwillim Creek by Parrish et al. (1985b). A large scale recumbant first phase fold trends northwest (Figure 4b) and S_2 crenulations and minor F_3 folds were observed. These structures are cross-cut by granitic gneiss and migmatites. This is in contrast to relationships observed in unit **ms** on the eastern flank of the complex where both granitic gneiss and paragneiss are generally concordant; all folds are recumbant and attenuated, and sheath folds are present. Reesor studied the relationship between the orientations of minor fold axes and mineral lineations throughout the complex. He noted that the intensity of the mineral lineation increased eastward across the complex. Reesor observed that folds in the western zone are variably oriented, but on the eastern flank of the complex, fold axes plunge eastward and parallel the mineral lineation (Reesor 1965, pp 55-56). He concluded that either the folds and lineation on the east side formed synchronously, or that the fold axes were rotated.

The rocks exposed along the eastern flank of the complex, (units **ms**, **cgn**, **Pgm**, and **PEg**), have undergone penetrative deformation and attenuation. Units **Pgm** and **PEg** exhibit mylonitic and ultramylonitic fabrics; and in both units the shear foliation dips eastward at $< 35^\circ$ and there is an easterly-plunging penetrative stretching lineation. In units **ms** and **cgn**, folds and leucocratic granitic veins are transposed into the gneissic layering. The layering is oriented parallel to the mylonitic shear foliation in overlying Tertiary granitoid rocks (units **Pgm** and **PEg**). The paragneisses dip eastward and have an easterly plunging lineation containing minerals which are stable in the upper amphibolite metamorphic facies (sillimanite, hornblende). Retrograde mineral assemblages are not present except as minor muscovite in pull-

aparts in the Slocan Lake fault zone. In unit **ms**, sillimanite, biotite, hornblende and garnet lie in the lineation. Quartz is annealed and in some thin sections feldspar and biotite are recrystallized. In unit **cgn**, the quartzo-feldspathic gneiss contains stable hornblende. Scapolite and diopside exhibit relict mylonitic shape fabrics in an annealed calc-silicate gneiss.

Mineral lineations in units **ms** and **cgn** at lower structural levels parallel the stretching lineation in overlying mylonitic units **PEg** and **Pgm**. Figure 8 is an equal area plot of poles to foliation and lineations measured 1) in paragneiss units **ms** and **cgn**, on the east flank of the complex and on the north flank of Passmore dome, and 2) in granitoid units **PEg** and **Pgm**, measured on the east side of the complex and throughout Passmore dome (see Map 1 for location of field stations). Mineral lineations in the paragneisses have the same orientation as stretching lineations in the mylonitic granitoid units.

The relationship of the high temperature fabric on the east flank in units **ms** and **cgn** with ductile shearing in Tertiary units **Pgm** and **PEg** will be discussed further in Chapter 3.

Late Dykes and Structures

Late steep dykes, discrete ductile shear zones and steep brittle faults crosscut the rock units of the Valhalla complex. The dykes intrude **PEg**, **Ecsy** and **cgn**, and are most common at the south end of the complex near the Columbia River, particularly on the west side of the culmination. All the dykes are Eocene or younger since they intrude units **PEg** (58 Ma) and **Ecsy** (52 Ma). There are four types; 1) recrystallized, sheared irregular basic dykes, 2) undeformed rhyolite dykes with chilled margins, 3) irregular, pink aplites and 4) late

basic dykes with chilled margins. The late basic dykes, which are the most common, consistently strike north, and dip 70° to the east, parallel to a prominent joint set (Figure 7c).

Discrete ductile shear zones with displacements of centimetres to metres occur in the Columbia River/Castlegar area (Bethune 1985, see Figure 7b). These shears are best developed and most common on the west side of the culmination in units **Ecsy**, **PEg** and **cgn**. Most of the shears dip 45° to 70° to the west with a westerly-directed sense of displacement. Approximately 20% of the shears dip eastward with the opposite sense of displacement. The shears are late features since they involve basic dykes which crosscut **PEg** and **Ecsy** and therefore postdate the pervasive regional mylonitic fabrics in unit **PEg**. Hornblende is stable in the shear zones indicating that high temperatures prevailed during this deformation.

Brittle faults of unknown but probably minor displacement, reported by Reesor (1965), were observed along the Columbia River and in Gwillim Creek. Fault gouge and highly fractured zones are less than 0.5 m thick and dip 65° to 85° to the east. Faults do not offset contacts mapped at the 1:50,000 scale. Brittle faults postdate the shears and often parallel the late basic dykes.

THE VALKYR SHEAR ZONE - SOUTH OF THE COLUMBIA RIVER

South of Castlegar, the geology has been mapped by Little (1960, 1982) Simony (1979), Crowe (1981), Corbett and Simony (1984) and Halwas and Simony (1986). The Castlegar gneiss (**uKkgn**), Trail gneiss (**tgn**) and paragneisses mapped as metamorphic Mount Roberts equivalents (**gn**), lie in the footwall of the Champion Lake fault and are inferred to lie in the footwall of the Valkyr shear zone (Figure 2). These gneisses have characteristics common to gneisses of the Valhalla complex. They are at high metamorphic grade (Simony 1979) with east-west oriented mineral and stretching lineations (Crowe 1981, Halwas and Simony 1986), late Cretaceous to Eocene K-Ar mineral ages (Figure 9), easterly-directed kinematic indicators (Halwas and Simony 1986), and are arched in an broad, upright antiform which is on strike with the Valhalla complex (Simony 1979). Granodiorite of the Mackie pluton, which overlies the Kinnaird gneiss and Trail gneiss, has a lineated and foliated zone at its base. This zone was mapped as an intrusive border phase of the pluton (Crowe 1981) and was reinterpreted by Halwas and Simony (1986) as a strained zone. The fabric elements parallel those in underlying gneisses, the rock has undergone a reduction in grain size and S - C mylonitic fabrics were observed, thus the writer interprets the lower contact of the Mackie pluton as a sheared tectonic contact. In this interpretation, the Mackie pluton occurs in the hanging wall of the Valkyr shear zone as shown on Figure 2. The shear zone is intruded by a postkinematic granite that was originally mapped as a late phase of the Mackie pluton. It is now known to be younger than the late Cretaceous Kinnaird gneiss based on cross-cutting relationships (Halwas and Simony 1986). South of the Mackie pluton, the Valkyr shear zone is inferred to

juxtapose the low grade Mount Roberts Formation and the Trail pluton in the upper plate against Trail gneiss in the lower plate. The trace of the shear zone wraps around the south end of the high grade gneiss terrane and is truncated by the Champion Lake fault.

UPPER PLATE OF THE VALKYR SHEAR ZONE

PLUTONIC ROCKS

Jurassic, Cretaceous and Eocene plutonic rocks extend from the Valhalla complex westward approximately 40 km to the Kettle River - Christina Lake valley (Tipper et al. 1981, see Figure 1). They are mapped as middle Jurassic, Nelson series granodiorite and Valhalla series biotite granite intruded by Eocene syenitic Coryell plutons (Little 1957, 1960). Hornblende bearing, "black and white" appearing granodiorite and quartz diorite that predominate on the western flank of the Valhalla complex (Figures 2 & 3) were mapped as Nelson series by Little; however, some phases may be Cretaceous or younger since they are similar to the Cariboo Creek stock and rocks on Arrow Lake dated as late Cretaceous (Parrish unpublished data 1985). South of the Valhalla complex, the Trail pluton and granodioritic phases of the Mackie pluton are correlative with the middle Jurassic Nelson batholith (Little 1960, 1982, Crowe 1981, Armstrong unpublished data file).

The plutonic rocks in the upper plate of the Valkyr shear zone generally have fresh igneous textures except near the lower contact where protomylonites and mylonites were observed (Ladybird Creek, Robson Ridge, the base of Mackie pluton and adjacent to the northwest part of the Valhalla complex, see Figure 12). Where present, the asymmetry of S - C mylonitic fabrics indicate an easterly-directed shear sense.

Plutons of the early to middle Eocene Coryell suite occur in the upper plate of the Valkyr shear zone near Lower Arrow Lake and west of Trail (Little 1960, 1982 see Figure 2), and smaller stocks are present in both the upper and lower plates near Deer Park and northwest of Trail (Parrish et al. 1985b, see Figure 2). Leuco- to melanocratic syenite is the predominate lithology with some quartz monzonite, quartz diorite, and granitic phases (Little 1960, 1982). Coryell rocks crosscut easterly-directed fabrics of the Valkyr shear zone in unit **PEg** and the Kinnaird gneiss as shown on (Figure 2) and are themselves crosscut by basaltic dykes.

THE MOUNT ROBERTS FORMATION

The Mount Roberts formation is part of the allochthonous Eastern Assemblage, interpreted as an obducted marginal basin (Monger 1972, Monger and Price 1979). It occurs in discontinuous belts between the Columbia River and the Kettle River (Little 1957, 1960) and consists of highly variable clastics with carbonates and volcanics, that have little stratigraphic continuity. The type section, located at Mount Roberts northwest of Trail, consists of siltstone, argillaceous quartzite, shale and limestone (Little 1960). The group is assigned a Pennsylvanian age on the basis of fossil evidence from unmetamorphosed rocks south of Trail but may be in part correlative with the Milford Formation and/or Slocan Group (Little 1960, 1982).

Rocks assigned to the Mount Roberts Formation occur at two localities in the hanging wall of the Valkyr shear zone (Map 1, Figure 2). Biotite and lower grade metasedimentary rocks located northwest of Trail, south of the Mackie pluton, are in sheared contact with the underlying Trail

gneiss (Little 1960, Simony 1979, see Figure 2). Sub-biotite grade limestone, argillaceous quartzite and greenstone northeast of Deer Park are tentatively correlated with the Mount Roberts Formation although the rocks have not been studied in detail (Little 1960). This east-west trending belt is truncated by the Valkyr shear zone (Figure 2). In the lower plate of the Valkyr shear zone, north of the Mackie pluton, heterogeneous sillimanite grade paragneisses were correlated with the Mount Roberts (Simony 1979, Little 1982); however, they are similar to other high grade paragneisses in the Valhalla complex (ms and cgn) of uncertain age and correlation.

NEMO LAKES BELT

The Nemo Lakes belt (Parrish 1981) of high grade metasedimentary rocks is exposed in the northern Valhalla Ranges west of Slocan Lake (Figure 2). It lies in the upper plate of the Valkyr shear zone and is truncated by the Slocan Lake fault zone. The juxtaposition of this amphibolite facies belt of rocks with Slocan group phyllites across Slocan Lake was the basis for postulating the existence of the Slocan Lake fault (Parrish 1981). The following description of the belt is summarized from Parrish (1981). A sillimanite grade sequence comprises pelitic, calcareous and semi-pelitic schists, quartzite, marble, ~~amphibolite and ultramafic rocks~~. Metamorphic isograds trend easterly and grade decreases northward into lower greenschist rocks of the Slocan Group (see page 32). The Nemo Lakes belt was tentatively correlated with the lower Paleozoic Lardeau group and the Triassic Kaslo-Slocan-Milford groups on the basis of lithology and Rb-Sr whole rock analyses (Parrish 1981); and was, in part, corroborated by more recent work (Parrish et al. 1985, Klepacki and Wheeler 1985). The boundary of these

two rock packages of different ages within the Nemo Lakes belt is characterized by lenses of ultramafic rocks, the base of which is interpreted as a suture.

Two phases of deformation are documented in the Nemo Lakes belt (Parrish 1981). Phase 1 isoclinal folds plunge westward and axial planes and associated cleavage parallel the layering. Ultramafic rocks and overlying Triassic rocks were emplaced during D_1 . Metamorphic mineral growth accompanied and outlasted D_1 . Phase 2 folds are predominant, large scale, upright, south-verging folds which fold the ultramafics and underlying suture. The early deformation in the Nemo Lakes belt is thought to be middle to late Jurassic in age. At the boundary with PEG, folds have been rotated and flattened into parallelism with the contact which dips 50° to the north.

UPPER PLATE OF THE SLOCAN LAKE FAULT ZONE

ROSSLAND GROUP

The Rossland Group is part of Quesnellia, an upper Paleozoic to lower Jurassic assemblage of volcanic, volcanoclastic and carbonate rocks interpreted as an obducted island arc terrane (Monger and Price 1979). It outcrops in an arcuate belt which extends from south of the Valhalla complex near Rossland to Nelson. It occurs regionally in the upper plate of the Valkyr shear zone and is locally in fault contact with the Trail and Castlegar gneisses across the Champion Lake fault (Figure 2). The group is early Jurassic based on fossil evidence from the Salmo and Rossland - Trail areas (Tipper 1984) and it conformably overlies the Slocan Group (see page 32). The Rossland Group comprises sedimentary and

volcaniclastic rocks and feldspar and augite porphyries (Little 1960, 1982) at biotite or lower metamorphic grade (Simony 1969). There is local contact metamorphism near Nelson intrusives (Little 1960). Structures reported by Little (1980) include folds (of uncertain age) and steeply dipping, Tertiary normal faults.

NELSON BATHOLITH

The heterogeneous, 35 by 50 km Nelson batholith lies in the Slocan Ranges, bounded by the Slocan valley to the west and Kootenay Lake to the east, and is entirely in the hanging wall of the Slocan Lake fault zone (Map 1 and Figure 2). The western edge of the intrusive complex, within the study area, includes massive porphyritic granodiorite (Slocan Lake, Sentinel Mountain), hornblende quartz syenite (Slocan Ridge, Sentinel Mountain, South Slocan), and granite (Lemon Creek, see Map 1). Crystal sizes and textures in the Nelson batholith are variable, but in contrast to rocks in the Valhalla complex, primary igneous fabrics are unmodified by ductile deformation on a regional scale.

Different lithologies, from quartz syenite to diorite to granite, suggest a composite origin. The batholith is predominantly middle Jurassic, approximately 165 Ma old, (Nguyen et al. 1968, Duncan et al. 1979, Duncan and Parrish 1979, Archibald et al. 1983), however, various parts of the batholith near Nelson, have been isotopically disturbed, yielding K-Ar dates as young as early Tertiary (Duncan and Parrish 1979, Harrison 1985, see Figure 9). The Nelson, Bonnington and Kuskanax batholiths and related stocks crosscut structural trends and isograds in the late Proterozoic to early Jurassic formations of the Kootenay Arc which they intrude (Little 1960, Read and Wheeler 1976, Duncan et al.

1979), except for the eastern margin and southeast "tail" of the Nelson batholith which may be late synkinematic (Archibald et al. 1983), or deformed after intrusion.

A leucocratic hornblende bearing quartz syenite phase, dated at approximately 171 Ma (U-Pb zircon, Parrish unpub. data 1985) occurs in the hanging wall of the Slocan Lake fault south of Slocan (Map 1). This quartz syenite, though finer grained, is similar in lithology and appearance to quartz syenites of the Eocene Coryell plutonic suite which predominantly occurs west of the Valhalla complex, but locally intrudes the southwest flank.

THE NORTHERN END OF THE SLOCAN LAKE FAULT ZONE

SLOCAN GROUP

The Slocan group is a thick recessive assemblage comprised of predominantly shale, argillite and phyllite. The age of the group is Triassic based on fossil evidence (Little 1960, Klepacki and Wheeler 1985, Orchard 1985). It occurs in a broad, northwesterly-trending belt north of the Nelson batholith and Valhalla complex, and is present in both the hanging wall and footwall of the Slocan Lake fault zone (Figure 2). The Slocan group has polyphase folds and near New Denver is folded into a large scale northwest trending recumbent syncline (Hedley 1952). Regional deformation and metamorphism predates intrusion of Nelson intrusives (Read and Wheeler 1976).

Outcrops in the Slocan lake area comprise massive to finely bedded, brown weathering shale and phyllite with arenaceous and calcareous interbeds. Phyllites are polydeformed with complex folds and axial

planar cleavage. In less deformed outcrops, the primary sedimentary structures are preserved.

GRANITIC STOCKS

A suite of calc-alkaline rocks occurs in a westerly trending belt in the northern Walhalla ranges and intrudes the Slocan group and the Nemo Lakes belt (Figure 2). Stocks truncated by the Slocan Lake fault zone include the Rosebery and Mount Carpenter stocks on the east side of Slocan Lake in the hanging wall, and the footwall Wragge Creek stock on the west shore. The buff to brown-grey weathering, biotite + hornblende + epidote quartz monzonites are generally porphyritic with variable crystal size and igneous textures. They are thought to be Cretaceous (Read and Wheeler 1976), and they crosscut structural and metamorphic trends (Parrish 1981). The Snowslide Creek stock (Figure 2) has a late Cretaceous U-Pb zircon date (Parrish unpub. data 1984).

Brittle deformation fabrics and retrograde alteration were observed in lakeshore outcrops of the Rosebery, Mount Carpenter and Wragge Creek stocks (Figure 7d). The rocks are green weathering with closely spaced fractures (< 2 cm apart), quartz and chlorite slickensides, gouge zones and pervasive chlorite and epidote alteration. In the Rosebery and Mount Carpenter stocks the intensity of the fabric and alteration decreases eastward; the Wragge Creek stock was not mapped away from the lakeshore. These fabrics and associated alteration are attributed to the Slocan Lake fault zone.

K-Ar AND Rb-Sr MINERAL DATES

Figure 8 is a compilation of published and unpublished mineral ages determined by K-Ar and Rb-Sr methods for the Nelson batholith and satellites, Valhalla complex and the surrounding region. With a few exceptions (discussed below), hornblende and biotite ages in the hanging wall of the Slocan Lake fault zone range from middle Jurassic to early Cretaceous, and those in the footwall are latest Cretaceous to early Tertiary. The occurrence of older mineral ages in the upper plate is characteristic of metamorphic core complexes throughout western North America (Coney 1980, Davis 1980, Armstrong 1982).

In general, K-Ar biotite ages in the hanging wall of the Slocan Lake fault zone range from 124 - 164 Ma and hornblende from 102 - 181 Ma. Exceptions are: 1) Eocene intrusions east of the Bonnington pluton yield 52 and 53 Ma K-Ar biotite ages (Archibald et al. 1983); and 2) 61 and 62 Ma K-Ar biotite ages near Nelson reflect a Tertiary isotopic disturbance (Duncan and Parrish 1979, Harrison 1985).

In footwall rocks, the K-Ar biotite ages range from 48 - 52 Ma except for 91 and 92 Ma ages in the Rossland monzonite at the southwest end of the Champion Lake fault (Fyles 1984). Four K-Ar hornblende ages are 55 to 70 Ma and the youngest hornblende age lies in the center of the Valhalla complex.

Muscovite porphyroclasts from two locations of **PEg** in the immediate footwall of the Slocan Lake fault zone, are 54 ± 1 Ma determined by Rb-Sr methods (Parrish unpub. data 1985). This retrograde synkinematic muscovite is confined to the fault zone and occurred late in the ductile deformation of unit **PEg**.

FIGURE 3: The Valkyr shear zone and the Sločan Lakè fault. NOTE: field station numbers in parentheses in this and subsequent figure captions are located on Map 1, back pocket. 3 a) granodiorite in upper plate of the Valkyr shear zone from west of Ladybird Creek is thought to be correlative with the middle Jurassic Nelson batholith (PCA 106, west of Koch Creek); b) C-S tectonite in the upper plate of the Valkyr shear zone near the contact with Valhalla complex is the deformed equivalent of 3a (PCA 90, Ladybird Creek area); c) north-dipping schists and gneisses of the Nemo Lakes belt at the contact with the Valhalla complex are cross-cut by post-kinematic intrusives (PCA 225); and, d) photograph looking north along Sločan Lake from the ridge east of Sločan. Slopes on the west side of the lake are gently easterly-dipping gneisses of the Valhalla complex in the footwall of the Sločan Lake fault zone. The trace of the fault, marked on the photograph, follows the break-in-slope on the east side of the lake and is overlain by the hanging wall Nelson batholith.

FIGURE 4: Generalized east-west cross-sections of the Valhalla complex, the Valkyr shear zone and the Slocan Lake fault zone. SLFZ = Slocan Lake fault zone; CLF = Champion Lake fault; VSZ = Valkyr shear zone; $\Rightarrow$ shear sense determined from the asymmetry of mylonitic fabrics.

4a) cross-section locations τ see Figure 2 for legend; b) section through Valhalla dome - brittle fault on the west side of the complex offsets the Valkyr shear zone; c) cross-section through Passmore dome - **Pgm** interdigitates with **ms** and pinches out eastward; and, d) cross-section along the Columbia River illustrates cross-cutting relationships - **Ecsy** (52 Ma) cuts pervasive, easterly - directed fabric in unit **PEg**. Discrete ductile shears (shown as bold west-dipping lines) are younger than **Ecsy**.

FIGURE 5: Rocks of the Valhalla complex. 5 a) Unit **ms**: First phase fold (PCA 144, Gwillim basin); b) unit **ms**: east-dipping quartzofeldspathic gneiss south of Winlaw is typical of paragneisses on the eastern margin of the Valhalla complex (SC 93); c) unit **uKgn** is a late-Cretaceous, melanocratic, K-feldspar augen granodioritic gneiss with leucocratic veins (PCA 103, Gwillim basin); and, d) the lower of the two Gwillim Creek shear zones (PCA 200). The view is to the northeast and is at an oblique angle to the sub-horizontal east-west stretching lineation. Unit **uKgn** is attenuated and grades downward from a granodioritic gneiss to a biotite schist at the sheared contact. Layering and amphibolite lenses in the underlying unit **ms** are clearly truncated. Late aplitic veins crosscut both units and are themselves deformed. A brittle fault offsets amphibolite layers in **ms** and apparently dies out into the sheared contact (right side of photograph).

FIGURE 6: Rocks of the Valhalla complex. 6 a) Unit **Pgm** protolith (SC 131, Koch Creek on west side of complex) is a K-feldspar megacrystic biotite-hornblende quartz monzonite which is Paleocene in age; b) unit **Pgm**, the deformed equivalent of 6a), is a highly strained S-C tectonite (SC 339, from Pass Valley; c) protomylonite from Eocene biotite quartz monzonite unit **Pgg** (SC 208, Ladybird Creek area); and, d) unit **uKkgd** - the Kinnaird gneiss (SC 254), a late Cretaceous, leucocratic hornblende, K-feldspar megacrystic orthogneiss.

FIGURE 7: Rocks of the Valhalla complex and the Roseberry Stock.

7a) Unit **cg** (Castlegar paragneiss) is a heterogeneous, quartzofeldspathic gneiss crosscut by granitic veins (SC 266, north side of the Columbia River); b) shear zone in leucocratic hornblende syenite (unit **Ecsy**) has a westerly-directed shear sense (SC 225); c) northward view of steep basaltic dykes cross-cutting unit **PEG** near Syringa on the Columbia River (SC 243); and, d) Lakeshore exposure of chlorite altered, fractured and brecciated biotite quartz monzonite of the Roseberry stock in the hanging wall of the Slocan-Lake fault zone (SC 327).

FIGURE 8: Equal area plots of poles to foliation and lineations. The mineral lineations in paragneiss units **ms** and **cgn** have the same orientation as stretching lineations in the overlying mylonitic granitoid units **PEG** and **Pgm**. The field stations on Map 1 show where measurements were taken. Units **ms** and **cgn** were examined on the eastern flank of the complex and on the northern flank of Passmore dome, and units **PEG** and **Pgm** were studied throughout Passmore dome and on the eastern flank of the complex. The foliations dip gently at $< 35^\circ$ and the lineations plunge east or west $+ 15^\circ$.

FIGURE 9: Compilation of K-Ar and Rb-Sr mineral dates; (• 50 = K-Ar biotite; • 55 h = K-Ar hornblende; and • 54 m = Rb-Sr muscovite) cooling ages for the Nelson batholith (and satellites), Valhalla gneiss complex and surrounding region. References are from Nguyen et al. 1968, Duncan and Parrish 1979, Archibald et al. 1983, Fyles 1984, Harrison 1985, Parrish pers. comm. 1985, and Armstrong (unpub data file). VSZ = Valkyr shear zone; SLFZ = Slocan Lake fault zone; CLF = Champion Lake fault.

CHAPTER 3 - KINEMATIC RELATIONSHIPS AND FABRIC VARIATION IN EOCENE AND PALEOCENE GRANITIC ROCKS OF THE VALHALLA COMPLEX

Tertiary granitoid units **PEg** and **Pgm**, which comprise the upper two sheets of Valhalla complex lie in the footwall of both the Valkyr shear zone and the Slocan Lake fault zone. They were examined in the field and in thin section with the following objectives: 1) to investigate kinematic relationships, and 2) to document the variation in strain fabrics and metamorphism throughout the complex, particularly with respect to bounding structures. Meso- and microscopic deformation fabrics in these units vary systematically: protomylonites with synkinematic biotite and hornblende occur throughout the complex and formed in the Valkyr shear zone; and more highly strained, hydrothermally altered, greenschist grade mylonites on the eastern margin of the complex were formed during movement on the Slocan Lake fault zone. **PEg** and **Pgm** contain asymmetric mylonitic fabric elements with an easterly-directed sense of shear throughout the complex as well as in the footwall of the Slocan Lake fault zone. These aspects of the fabrics in **PEg** and **Pgm** and timing constraints are described and interpreted in this chapter.

KINEMATIC INDICATORS IN UNITS **PEg** AND **Pgm**

The most useful kinematic indicators in **PEg** and **Pgm** are the asymmetry of penetrative C and S foliations (Berthe et al. 1979, Brown and Murphy 1981, Simpson and Schmidt 1983, Lister and Snoke 1984) and the orientation of shear bands (Platt and Vissers 1980, White et al. 1980). Unfortunately, other indicators are not present due to the homogeneous nature of the protoliths and the lack of inclusions or veins. Figure 10

shows the results of the kinematic study conducted in the field and confirmed in oriented thin sections from 21 locations. The irregular data distribution in Figure 10, particularly on the west side of the complex, reflects physical access in the Valhalla Ranges and not the distribution of strain in the rocks.

Where units **PEg** and **Pgm** are deformed, they are L-S tectonites. The lineation in **PEg** and **Pgm** is interpreted as a stretching lineation. The long axis of elongate feldspar aggregates, pressure shadows, ribbon shaped quartz grains, linear biotite streaks, and elongate feldspar porphyroclasts lie in the lineation. Extension fractures in pulled-apart porphyroclasts are perpendicular to the lineation. Mylonitic C and S foliations are present on rock faces and thin sections oriented parallel to the lineation and perpendicular to the foliation, whereas, irregular mineral cross-sections are observed perpendicular to the foliation and lineation, thus a progressive simple shear strain model is assumed although it is unlikely that the strain was ideal.

The orientations of the mylonitic shear foliation and stretching lineation in units **PEg** and **Pgm** are shown on the equal area plot of Figure 8. The foliation dips $< 35^\circ$ outward from the Valhalla and Passmore domes. Lineations on the eastern flank of the complex generally plunge $< 30^\circ$ to the east $\pm 15^\circ$, approximately down the dip of layering and the shear foliation. The lineation is horizontal and oriented east-west in layering which dips north, south or is flat-lying. On the western flank the lineation plunges down-dip to the west. The east-west trending stretching lineation is interpreted as the principle finite extension direction. The shear sense in all but a few cases is unambiguous; the upper member of the shear couple moved eastward. This was documented in west dipping layering on the west side of Passmore

dome, across the crest of the culmination, and in the footwall of the Slocan Lake fault on the eastern margin of the complex. This implies that the shear zone that generated the mylonitic fabrics is arched over Valhalla complex.

C AND S FABRIC

C and S foliations in mylonites form concurrently by predominantly ductile processes in response to an imposed strain, and may be used to determine the sense of displacement in a shear zone (Berthe et al. 1979, White et al. 1980, Brown and Murphy 1981, Simpson and Schmidt 1983, Lister and Snoke 1984). The C foliation, observed as compositional layering, has a constant orientation parallel to the walls of the shear zone and is therefore assumed to represent a plane of relative movement. The S foliation is made up of flattened grains, is oriented at $< 45^\circ$ to the C foliation and curves into it. Elongate and pulled apart minerals lie in the maximum extension direction contained within the flattening plane. The S foliation varies in orientation depending on the local finite strain. In an ideal simple shear model of progressive deformation, the finite strain axes rotate with respect to the shear plane and the first increment of strain oriented at 45° to the shear plane (Hobbs 1976). In this reference frame, the direction of rotation of the finite strain axes, the flow direction in the rock and the sense of displacement of the shear zone are indicated by the progressive decrease in the angle between the C and S foliations in the mylonite.

Fabric elements and interpretation of shear sense in units **PEg** and **Pgm** are shown in Figure 11. The C foliation in mylonitic samples appears as continuous and discontinuous domains of heterogeneous quartz and

feldspar porphyroclasts, and thin (<0.5mm), dark, very fine-grained, phyllosilicate-rich layers. In thin section, the dark layers are made up of recrystallized aggregates of biotite, feldspar, quartz and opaques. On surfaces oriented parallel to the lineation and perpendicular to the foliation, the traces of the S foliation and the extension lineation (measured in thin section) are inclined at 10° - 35° or less to the C foliation (Figure 11). The trace of the S foliation parallels the long axis of feldspar porphyroclasts (Figure 11a), sigmoidal quartz grains (Figure 11b), pulled-apart feldspar crystals (Figure 11c), muscovite "fish" (Figures 11b & 11d), and quartz subgrains (Figure 11d). Feldspar "tails" comprise recrystallized polymineralic aggregates preserved in the pressure shadow area at the ends of porphyroclasts. It can be shown that the C and S foliations developed more or less synchronously for the following reasons: 1) they both show the same variation throughout the complex (i.e., both C and S planes are moderately developed on the west flank and strongly developed on the east flank) and there is no indication that one truncates or postdates the other; and 2) the ends of feldspar tails, aggregates of matrix grains and elongate quartz aggregates in the S foliation are asymptotic to the C foliation. The asymmetry of the C and S fabrics at the meso- and microscopic scale indicates an easterly-directed sense of shear (see Figure 11).

SHEAR BANDS

Shear bands or extensional crenulation cleavages are discontinuous zones of concentrated strain (Platt and Vissers 1980, White 1980, Platt 1984). They occur in single, conjugate and multiple sets and in mylonites are oriented at an oblique angle to the C foliation and form after the C and S fabric has developed. Shear bands are thought to form

when the strain regime deviates from that of progressive simple shear (Platt and Vissers, 1980, Platt 1984). A component of coaxial strain at a high angle to the C foliation and thus a component of extension parallel to the C foliation results in the development of shear bands at $< 45^\circ$ to the C foliation (Platt and Vissers 1980). The orientation of the strain axes with respect to the existing foliations determines whether conjugates form or not. Single sets of shear bands are consistently oriented at an oblique angle to the C foliation, have a sense of shear which is synthetic to the bulk shear, and can be used to determine the sense of shear in a mylonitic tectonite (Platt and Vissers 1980, White et al. 1980) as shown on Figure 11a.

The traces of shear bands are observed on rock faces or thin sections oriented parallel to the stretching lineation and perpendicular to the shear foliation (Figure 11a). In units **PEg** and **Pgm**, shear bands are rare in the western and central areas of the Valhalla complex and very common on the eastern flank (This distribution may be a function of higher strain, lower metamorphic grade during deformation, or a late stage change in the strain regime). They occur as a single set, are very fine grained, dark colored, 1 to 3 cm long, discontinuous layers oriented at a 15° to 35° angle to the shear plane. In thin section, shear bands consist of thin zones of very fine grained recrystallized biotite, quartz and feldspar. They are generally sigmoidal and terminate at both ends at the grain boundaries of large porphyroclasts or die out into the C foliation. Feldspar tails, quartz grains and layers of matrix may be deflected into the shear bands and in a few cases can be traced through the shear band with offsets of 0.01 to 4.0 mm. Where present, the orientation of the shear bands supports the easterly-directed kinematic interpretation.

FABRIC VARIATION

A study of the degree of fabric development and type of crystal deformation within unit **PEg** demonstrates the strain variation across the complex, particularly with respect to the Slocan Lake fault zone. **PEg** is well suited for this study because it is extensive within the complex, and is homogeneous with apparently little primary variation in grain size and composition. A qualitative approach was used because there are no markers or cutoffs present which can be used to perform a more rigorous strain analysis.

Unit **PEg** was sampled and studied in detail where it is accessible along the entire eastern flank of the Valhalla complex, and on the south and western sides of Passmore dome (Russel Creek, Ladybird Creek and Ladybird Mountain, see Map 1). **PEg** was also examined for fabrics in the field at a few locations on the north and west flanks of the complex.

Rocks which have similar meso- and microscopic characteristics are grouped into three categories termed Zones A, B and C. Figure 12 shows the distribution of these zones and photographs in Figure 13 depict typical rock slabs and photomicrographs. Zone A rocks represent the protolith. **PEg** is relatively homogeneous, the igneous fabrics are preserved and microstructures indicate only minor ductile strain, primarily the development of a weak foliation. Zone B rocks are S - C tectonites (Lister and Snoke 1984), classified as protomylonites (Sibson 1977) and shear sense can be deduced from the mylonitic shape fabric. Zone C rocks are S - C tectonites (Lister and Snoke 1984) classified as mylonites (Sibson 1977). They have stronger fabrics and a finer grain size than Zone B tectonites and most Zone C mylonites have

undergone retrograde greenschist alteration. The fabric in Zone B developed during movement on the Valkyr shear zone whereas Zone C mylonites formed during motion on the Slocan Lake fault zone (this conclusion is discussed on page 55).

Zone A, includes areas along the north, west and south margins of the complex. Unit **PEg** exhibits a predominantly igneous texture modified by ductile strain. Mesoscopically, the rocks have a very weak foliation (Figure 13a) and a lineation present in discrete zones. Meso- and microscopic kinematic indicators are not present. Representative petrological data from samples collected at Russel Creek and the western end of Ladybird Creek are summarized in Appendix 4. Features such as deformed feldspar and quartz crystals and irregular crystal boundaries lined with recrystallized grains are visible in thin section (Figure 13b) and the volume of matrix varies from 10% to 20%. Some feldspar crystals exhibit deformation twins or undulose extinction. Subgrains and small neoblasts are present at feldspar boundaries. Orthoclase is myrmekitic with vermicular quartz. Quartz is present as irregular aggregates of crystals and some grains have undulose extinction, deformation bands and/or contain equant subgrains. Biotite appears unstrained and occurs as large equant subhedral crystals up to 1 mm in diameter. The overall texture is that of an equigranular igneous fabric that has been weakly deformed in the ductile regime.

Fabrics grouped in Zone B occur throughout the central part of Passmore dome and in sporadic zones on the western flank (Figure 12, Appendix 5). In these areas, **PEg** is an L-S tectonite with an asymmetric C and S fabric (Figure 13c) and rare shear bands. The quartz monzonite has 30% to 50% matrix which is present as layers up to 0.5 cm wide, in

pressure shadows and in the mantle zones of feldspar porphyroclasts.

Most feldspar crystals are fractured, irregular in shape with deformation twins, undulatory extinction or subgrains (Figure 13d).

Quartz crystals form elongate aggregates which are either sigmoidal with long axes parallel to the S foliation, or oriented parallel or subparallel to the C foliation. Subgrains in quartz grains are ubiquitous. In ribbon grains, the subgrains are commonly elongate and inclined to the C foliation. Fine grained euhedral biotite laths are oriented with their long axes parallel or sub-parallel to the C foliation. Synkinematic biotite, oligoclase and orthoclase occur in pressure shadows, in feldspar porphyroclast pulled-aparts and as fine grained recrystallized matrix.

Mylonitic fabrics in Zone C along the eastern flank of the complex are strongly developed (Figure 12 and Appendix 6) and well developed meso- and microscopic shape fabrics and shear bands are common (Figure 13e). The intensity of the fabric, studied in the Slocan Lake area, increases upwards with increasing proximity to the Slocan Lake fault zone. Microstructures visible in thin section are shown in Figure 13f. Matrix is generally greater than 50%. In feldspars, microstructures such as subgrains, undulose extinction and core and mantle structures are evident, and fractured crystals with pulled-apart or rotated fragments are very common. Quartz crystals and aggregates are elongate or ribbon shaped and contain subgrains. There is a preferred crystallographic orientation parallel to the lineation as determined petrographically with a lambda plate. Relict biotite crystals are kinked with sweeping extinction.

This zone also contains a lower to middle greenschist retrograde mineral assemblage in the immediate footwall of the Slocan Lake fault.

Synkinematic chlorite, muscovite, calcite, quartz and epidote occur in pulled-apart feldspar porphyroclasts and in pressure shadows. There is pervasive kaolinite and sericite alteration of feldspars. Biotite disappears upwards from the base of **PEg** and is rarely present in the fault zone itself. Feldspars do not occur in pull-aparts or in pressure shadows in Zone C. Some muscovite "fish" lie in the S foliation and others, which apparently occur as randomly oriented porphyroblasts, are kinked and have sweeping extinction. The muscovite occurs only in fractured and chloritic fault rocks and is interpreted as a retrograde reaction product in the breakdown of biotite.

Summary:

From Zone A to Zone C, the observed trends in microstructures are:

- 1). Increases in the strength of meso- and microscopic planar and linear fabrics (i.e., S - C foliation, extension lineation).
- 2). Increase in the percent of matrix.
- 3). Decrease in the average size of plagioclase, orthoclase and quartz grains.
- 3). Increase in the preferred shape-fabric of minerals.
- 4). Increase in the number and density of subgrains and corresponding decrease in the size of quartz subgrains.
- 5). Increase in the preferred crystallographic orientation of subgrains determined petrographically with a lambda plate.

Field oriented studies documenting microscopic changes with increasing deformation in mylonitic rocks have been discussed by Eisbacher (1970), Bell and Etheridge (1973), Sibson (1977), Berthe et al. (1979), White et al. (1980) and Brown and Murphy (1981). The fabric and microstructures that are preserved depend on the relative importance of recovery and recrystallization (Hobbs 1976, pp. 108-109), and the

post-deformation thermal history of the rock (Hobbs 1976, White et al. 1980). Some generalizations can be made about the changes in mylonitic fabrics with increasing strain. There is a decrease in grain size accompanied by recrystallization, and there is an increase in the volume of matrix, the intensity of fabrics and the degree of preferred shape-fabric and crystallographic orientation of crystals. These trends are present in unit **PEg** from Zone A through C, and are interpreted to represent an increase in strain.

This strain distribution is also reflected in unit **Pgm**. Fabrics were studied along an east/west transect across the central part of Passmore dome between Koch Creek and Slocan Ridge. Predominantly igneous fabrics are present on the west side of the complex and mylonitic fabrics are present across the crest of the dome. Strongly developed mylonitic and ultramylonitic fabrics occur on the southeast side of the complex.

In summary, in both **PEg** and **Pgm**, discontinuous zones of Zone B protomylonites were documented on the western, southern and central flanks of Passmore dome and on the north and northwest flanks of the Valhalla dome (Figure 12). Regionally penetrative, more highly strained mylonites of Zone C occur along the eastern margin of the Valhalla complex in the footwall of the Slocan Lake fault zone and are interpreted to have undergone more strain than the rocks in Zone B.

METAMORPHIC GRADE OF MYLONITES

Syn-kinematic mineral assemblages and microstructures in Zones A and B were stable in the amphibolite facies during shearing. Plagioclase, is An_{20-35} (determined optically and summarized from Reesor 1965), biotite is present and chlorite is absent. Biotite and oligoclase are synkinematic occurring in pressure shadows, pulled-apart porphyroclasts

and as dynamically recrystallized grains in the matrix. Hornblende in unit **Pgm**, stable during mylonite formation, occurs as euhedral crystals which have been passively rotated in the S foliation and are not recrystallized or altered. Unfortunately, the mineral assemblages do not allow tight temperature (or any pressure) constraints to be placed on the mylonite formation; however, the presence of hornblende necessitates a minimum temperature of 500°C; and biotite 400° - 440° (Winkler 1979).

In Zone C, the lack of biotite and synkinematic feldspar, and the presence of synkinematic chlorite, epidote, muscovite, calcite, quartz and pyrite indicate that the last ductile strain in the rocks occurred under lower to middle greenschist facies metamorphic conditions.

Simpson (1985) describes microscopic features in granitic rocks across the Eastern Peninsular Ranges Mylonite Zone of southern California. She documented the variation of microstructures of mylonites successively deformed at lower greenschist, middle - upper greenschist and amphibolite facies. The microstructures in the amphibolite facies are similar to those in Zones A and B in unit **PEg**, and those in greenschist facies mylonites are similar to Zone C minerals, as shown in Table 1. This corroborates the interpretation that mylonites in Zones A and B in Valhalla complex formed under amphibolite conditions and the microstructures that are preserved in Zone C were formed at greenschist grade.

TABLE 1: COMMON MICROSTRUCTURES IN AMPHIBOLITE AND GREENSCHIST GRADE MYLONITES

MICROSTRUCTURE	ZONE IN VALHALLA COMPLEX	METAMOPHIC FACIES IN SIMPSON 1985
recrystallized biotite	B	amphibolite
orthoclase myrmekites	A	amphibolite
dynamically recrystallized plagioclase	A & B	amphibolite
micro-cracking and micro-faulting of feldspars	C	lower greenschist
quartz ribbon structure	C	greenschist
kink bands in biotite	--	greenschist
kink bands in muscovite	C	(greenschist by analogy)

AGE OF MYLONITE FORMATION

The lower ages for shearing within units **PEg** (58 Ma) and **Pgm** (63 Ma) are constrained by their isotopic ages. Muscovite in unit **PEg** occurs only in the Slocan Lake fault zone and is a retrograde mineral which grew at the expense of biotite during easterly-directed shearing under lower to middle greenschist facies conditions. It occurs as "fish" (Figure 14d), in pulled-apart feldspar porphyroclasts and as kinked porphyroclasts indicating that it grew concurrently with mylonitization. It also occurs in brittle fractures and joints indicating that the

growth of muscovite outlasted ductile deformation. Rb-Sr determinations on muscovite from two locations in the Slocan Lake fault zone yield a 54 ± 1 Ma age (Parrish unpub. data 1985, see Figure 9). The age of the muscovite postdates amphibolite grade ductile deformation in **PEg** and is concurrent with the greenschist grade mylonitization in the Slocan Lake fault zone. Therefore, easterly-directed ductile shearing in **PEg** occurred during or immediately after emplacement, between 58 and 54 Ma.

RELATIONSHIP OF MYLONITIC FABRICS TO THE VALKYR SHEAR ZONE AND THE SLOCAN LAKE FAULT ZONE

There is a variation in strain across Valhalla complex in **PEg** and **Pgm** (Figure 12). These granitic sheets are weakly to moderately strained on the western, northern and southern margins and throughout the central part of the culmination (Zones A & B). Zone C mylonites on the eastern margin of the complex are more strained than rocks in Zone A & B and are inferred to have undergone strain for a longer period of time. Mylonites in **PEg** and **Pgm** formed under amphibolite facies conditions in western and central Valhalla complex (Zones A and B) and greenschist conditions were present during the last ductile deformation in Zone C on the eastern margin of the complex. In this interpretation, Zone B amphibolite grade protomylonites formed during movement on the Valkyr shear zone and Zone C, greenschist grade, more highly strained mylonites formed during movement on the Slocan Lake fault zone.

THE VALKYR SHEAR ZONE

Ductile strain in units **PEg** and **Pgm** on the crest and western margin of the complex is distributed over a 2 km to 3 km thick zone and has an

easterly-directed shear sense (Zone B, Figure 12). This strained zone, characterized by discontinuous zones of protomylonites, can be traced across the upper contact of **PEg** for a few hundred metres into overlying rocks (Figure 3c). It separates the lower plate Valhalla complex from an upper plate comprised of the middle Jurassic Nelson batholith and lithologically similar (Jura-Cretaceous ?) granitic rocks, and Paleozoic to Jurassic Nemo Lakes belt, probable Mount Roberts Formation (?), Slocan Group and Rossland Group. The name Valkyr shear is proposed for this ductile zone since the north trending Valkyr Ranges, which lie to the west of the Valhalla complex, are comprised exclusively of upper plate units. The displacement accommodated by ductile shearing is uncertain. The 54 ± 1 Ma age of synkinematic retrograde muscovite of Zone C mylonites in the Slocan Lake fault zone places an upper age on shearing in this zone.

THE SLOCAN LAKE FAULT

Zone C greenschist grade mylonites are confined to an east-dipping zone on the eastern flank of the Valhalla complex between Silverton and Pass valley (Figure 12). This zone parallels the Slocan Lake fault and does not arch over the complex or diverge from the fault zone. The fabrics indicate that 1) rocks on the east side of the complex in Zone C have experienced more strain than those of Zones A and B, on the crest of the culmination and on the west flank and 2) within Zone C the intensity of mylonitic fabric in the Slocan Lake area increases upsection with increasing proximity to the Slocan Lake fault zone. Based on these observations, the greenschist grade mylonites are inferred to have formed in response to movement on the Slocan Lake fault zone. The mylonites in the underlying unit **Pgm** are also more strained on the

eastern flank of the complex than on the west and, although they are not retrograded, they probably formed in response to movement on the Slocan Lake fault zone.

The Slocan Lake fault zone also involved units **ms**, **cgn** and **uKgn** and has overprinted and transposed older structures. On the eastern flank of the complex in units **ms** and **uKgn**, the east-west alignment of minerals, reorientation of fold axes into parallelism with the lineation, transposition of layering and intrusions, attenuation of the units and parallelism of fabric elements at all scales of observation with the mylonites in units **PEg** and **Pgm** supports this interpretation (see page 16).

DISCUSSION

1) Arching of the Valhalla complex could be synchronous with easterly-directed shearing on the Valkyr shear zone. The mylonitic fabrics are arched over the complex and have an easterly-directed shear sense throughout the domal culmination. If the shear zone postdated arching, one would expect the mylonitic fabric to diverge from the folded layering and parallel the superimposed shear zone. This is not what is observed in Passmore dome where the mylonitic S foliation is parallel to the gently folded layering. Stretching lineations are oriented east or west in Valhalla and Passmore domes, even where the layering dips north or south (Figure 8). This can be explained if at least part of the easterly-directed shearing and mylonitic fabric development occurred during arching, allowing for the reorientation of fabric elements dispersed during doming.

2). It is important to determine, if possible, the root direction of the shear zones: a westward root implies compressional thrusting whereas an eastward root indicates that the fault is extensional. The Slocan Lake fault zone roots to the east and is therefore extensional in origin (this is discussed further on page 78). An eastward root for the Valkyr shear zone is supported by the following observations. From west to east it truncates successively higher grade rocks in the upper plate. On the southwest margin of the complex near Deer Park, chlorite to sub-garnet grade greenstone, limestone and argillaceous quartzite (Mount Roberts Formation, Little 1960) are truncated by the shear zone (Figure 2). To the north of the complex, the Nemo Lakes belt is at sillimanite - muscovite grade (Parrish 1981). When projected into an east-west oriented cross-section, the Nemo Lakes belt lies approximately 10 km east of the Mount Roberts Formation. Assuming that regional geotherms were sub-horizontal during the early Tertiary, it is inferred that the Nemo Lakes belt was at a lower level in the upper plate than the Mount Roberts Formation and that the Valkyr shear zone cut downwards to the east. The Valkyr shear zone appears to cut structurally down section to the east. In the Nemo Lakes belt, the map pattern of the ultramafic rocks (which separate Paleozoic from Triassic rocks) diverges northeastward from the trace of the shear zone (Parrish 1981). The shear zone truncates structurally lower rocks on the lakeshore than it does 15 km west at Nemo Lakes, thus it cuts downwards to the east. This assumes that the Nemo Lakes belt was relatively flat lying prior to shearing. If the Valkyr shear zone roots to the east then it must outcrop west of the Valhalla complex and conversely, if it roots to the east, then it must re-emerge further east of complex.

FIGURE 10: Structure map of Valhalla gneiss complex and surrounding region showing the location and shear sense of kinematic indicators.

LEGEND

SLFZ SLOCAN LAKE FAULT ZONE: peg on upper plate

CLF CHAMPION LAKE FAULT ZONE: peg on upper plate

VSZ VALKYR SHEAR ZONE

Strike and dip of mylonitic foliation, trend and plunge of stretching lineation, arrow indicates direction of movement of the upper member of the shear couple.

Syncline

FIGURE 11: Examples of kinematic indicators in **peg**. Rock slab a) and photomicrographs b), c) and d), are oriented parallel to the lineation and perpendicular to the foliation. The closing direction of the angle between the S foliation and C foliation indicates an easterly-directed, dextral, shear sense; 11 a) mesoscopic shear sense indicated by the relationship between the S foliation, C foliation and shear bands (SC 38); b) horizontal, elongate quartz grains and phyllosilicates lie in the C foliation and sigmoidal quartz, muscovite fish and feldspar, pressure shadows lie in the S foliation (SC 77A); c) the foliation is defined by horizontal layers of fine grained matrix. A fractured feldspar porphyroblast lies in the S foliation (SC 57); and, d) compositional layering is interpreted as the C foliation and muscovite porphyroblast lies in the S foliation. Mylonitic fabric elements are crosscut by late fractures (SC 57).

FIGURE 12: Map of Valhalla complex shows fabric variation in units **PEg** and **Pgm**. Zone A = homogeneous protolith has weak foliation; Zone B = protomylonites; and Zone C = mylonites. VSZ = Valkyr shear zone; SLFZ = Slocan Lake fault zone; CLF = Champion Lake fault.

● ZONE A

□ ZONE B

▶ ZONE C

5

FIGURE 13: Fabric variation in unit **PEg**. Rock slabs and photomicrographs, oriented parallel to the lineation and perpendicular to the foliation, show fabric and microstructures in Zones A, B and C. 13 a) & b) Zone A - weakly deformed igneous protolith (SC 211 & SC 127); 13 c) & d) Zone B - protomylonites (SC 208 & SC 238); and, 13 e) & f) Zone C - mylonites, most have retrograde lower to middle greenschist facies overprint (SC 140). The spatial distribution of these zones is shown in Figure 12. Note the reduction in grain size from Zone A through C and the increase of S - C fabric intensity and colour change from Zone B to C.

CHAPTER 4 - THE SLOCAN LAKE FAULT ZONE

The Slocan Lake fault zone was studied in detail between Silverton and Castlegar where the Nelson batholith is juxtaposed against **PEg** and on Sentinel Mountain where **PEg** occurs in both the upper and lower plates (Figure 14a). In the footwall, brittle structures are superimposed on greenschist grade, Zone C mylonites (Figures 12 & 13) which formed during early stages in the movement history of the fault. The mylonites are described and analysed in Chapter 3, therefore the descriptive part of this Chapter is focused mainly on the brittle structures. The fault is not a discrete planar surface; rather it is a zone which ranges from 100 m to 800 m in thickness. The top and bottom of the fault zone are arbitrarily defined as the limit of closely spaced (< 20 cm) brittle fractures and faults and accompanying lower to middle greenschist retrograde alteration. The intensity of the brittle deformation and alteration decreases away from the fault surface and is transitional into unfractured, unaltered country rock in both hanging wall and footwall. The fault zone has complex geometry; it is crosscut by variably oriented, steep and shallow dipping faults which displace fault rocks (Figure 14b). The detailed geometry of the fault zone is not well known because the trace parallels the Slocan Valley and there is poor exposure across the strike of the fault.

The terminology used to classify fault rocks is from Sibson (1977).

DESCRIPTION OF THE FAULT ZONE

FOOTWALL ROCKS

Unit **PEg** fault rocks are exposed along the east side of the Slocan

Laké, in the Springer/Climax Creek area, on Perry Ridge, on Slocan Ridge, near Krestova and in Pass Valley (Map 1). The cataclastic fault zone in **PEg** varies in thickness along the trace of the fault. It is ~100 m thick at the tourist lookout at Slocan Lake, ~400 m in Slocan, ~600 m on Slocan Ridge and ~150 m on Sentinel Mountain, thus it appears to be widest in the middle section of the fault (see cross-sections in Figures 4 & 15). In the fault zone, **PEg** has a mottled, pink and green appearance and is crosscut by fractures spaced less than 3 cm apart (Figure 14c). It weathers into small angular fragments. Veins are generally absent except at Cape Horn where veins of pseudotachylite crosscut brittle structures as mylonites in **PEg** (Figure 14d). Relict mylonitic foliation and lineation are generally recognizable and have locally consistent orientations.

In thin section, porphyroclasts may be broken and offset by fractures and microfaults (Figure 14e) and zones of comminuted quartz and feldspar occur as planar zones or pods of cataclasite (Figure 14f). Relict mylonitic fabrics are clearly crosscut by these brittle features.

In the fault zone, **PEg** has been retrograded to chlorite grade. Chlorite is ubiquitous, feldspars are highly sausseritized and sericitized, and epidote, calcite, pyrite and quartz occur on joint and fracture surfaces. Rare quartz veins are present. Muscovite porphyroclasts (synkinematic with mylonitic fabric) and porphyroblasts, which apparently grew at the expense of biotite, are present within 50 m of the fault zone. Biotite, a constituent mineral in the protolith, is rarely present in the fault zone.

Joint sets and fractures were measured in the fault zone but no systematic orientations were observed. Faults are present at all scales of observation. They occur as 1) surfaces coated with chlorite, calcite

and quartz slickensides, 2) fault gouge zones 1 - 10 cm thick, 3) fault breccia up to 1 m thick or 4) mylonite zones 1 to 30 cm thick. No marker offsets were observed and displacements are unknown. Faults have variable orientations and both planar and curved faults are present. Steep faults are common and at Cape Horn (Slocan Lake), east-dipping faults terminate in thin ultra-mylonite zones (Sibson 1977) oriented parallel to the mylonitic foliation. The ultra mylonites are not crosscut by other ductile or brittle features.

HANGING WALL ROCKS

Nelson batholith fault rocks were observed in the Slocan Lake/Springer Creek area and on Slocan Ridge (Map 1). They comprise altered, cataclastic granodiorite and quartz syenite. The alteration zone varies from 50 - 200 m thick and is generally wider than the cataclastic zone. Alteration is most intense near the fault and is gradational upward into pristine country rock.

Fault rocks are fractured with protocataclastic and cataclastic textures but are generally coherent (Figures 16 a & b). Relict igneous textures are preserved; the granodiorite is porphyritic and euhedral phenocrysts are present. Near the fault surface itself, discontinuous lenses of crush breccia welded with quartz and calcite occur at the Slocan Lake tourist lookout and in Enterprise Creek (Map 1). Air photographs of the Nelson batholith were examined to identify structures in the hanging wall of the Slocan Lake fault zone. The only faults that were observed are within 2 km of the Slocan Lake fault, thus the Nelson batholith appears to have been faulted as a fairly coherent sheet.

Fractures are closely spaced (1 to 10 cm apart) and irregular in

orientation. Brittle faults are common and occur as thin layers of gouge and as brecciated zones associated with quartz and chlorite veins. Many have small displacements of the order of centimetres, but others have an unknown displacement. Faults and fractures have no apparent systematic orientation.

The Nelson batholith fault rocks are at lower to middle greenschist grade. Retrograde alteration minerals in the fault zone are chlorite, epidote, pyrite, hematite, sericite and kaolinite which give the rocks a chalky green and red stained appearance. Albite was observed in two thin sections. Feldspar crystals are highly sericitized and saussuritized. Primary igneous mafic minerals such as hornblende, pyroxene and biotite are not present.

Microstructures are predominantly brittle. Minor ductile strain features are present in quartz and some feldspar crystals, however, they are not significant compared to footwall rocks (Figures 16c & 16d). Feldspar crystals are characteristically fractured and broken and some exhibit undulose extinction, deformation twins and irregular grain boundaries. Microstructures in primary quartz include undulose extinction, deformation bands and subgrains. In the most highly strained samples, quartz crystals are flattened with subgrain development and have sutured grain boundaries. Fine grained (<0.1 mm diameter) matrix grains occur at grain boundaries and in isolated lenses; however, grain size reduction is not significant as matrix grains comprise less than 15% of the rock.

Microfractures and microfaults are ubiquitous, and three types were observed in thin section. The first consists of fractures and faults which crosscut feldspar crystals but do not truncate quartz grains. Where the two minerals are in contact, the fractures terminate at the

quartz grain boundary. A second type of fracture is through-going at the scale of a thin section (Figure 16c). Chlorite, quartz, pyrite, epidote and calcite occur in both of these fracture types. A third fracture set contains veins of unstrained, polygonal quartz and calcite crystals (Figure 16d). These crosscut all other fabrics. These relationships suggest that brittle deformation outlasted ductile strain in quartz crystals.

CONDITIONS OF FAULTING

The interpretation of mineral assemblages and textures allow some constraints to be placed on conditions during faulting. The chlorite-albite-quartz-epidote-calcite mineral assemblage and the total disappearance of biotite and hornblende in the fault zone, indicate that faulting took place under sub-biotite, middle to lower greenschist facies conditions. This places temperatures in the range of 250 - 400° (Winkler 1979).

Greenschist facies minerals are confined to the fault zone and probably represent local conditions caused by the introduction of fluids into the zone, rather than a regional drop in metamorphic grade. This is consistent with petrological and chemical studies which show that retrograde, more hydrated assemblages are commonly found in shear zones (Beach 1980, Brodie 1980).

DIP THE FAULT ZONE

The Slocan Lake fault zone strikes north-northeast and dips 20° - 40° to the east as determined by Parrish (1984) and confirmed in this study in the Slocan Lake, Perry Ridge and Slocan Ridge areas. The fault zone

was studied in detail in the Slocan area. Dips ranging from 20° - 35° were determined from 1:25,000 scale mapping, construction of cross-sections and "three point problem" calculations. The fault zone roughly parallels the mylonitic foliation in **PEg**.

Perry Ridge, located southwest of Slocan strikes 040° and its eastern flank dips 25° to the east (Map 1). At the northeastern flank of the ridge, chlorite grade, intensely fractured and brecciated **PEg** outcrops from the ridge crest at 1200 m (4000') to the river valley at 540 m (1800') and is interpreted as a dipslope exposure that roughly parallels the fault zone. Assuming that the cataclastic zone is 300 - 500 m thick, the dip must fall between 25° and 33° to expose fault rocks along the 1.5 km flank of the ridge.

On Slocan Ridge, stepped quartz and chlorite fiber growth on polished and grouved surfaces plunge eastward 22° to 39° . These slickensides probably formed during late movement on the Slocan Lake fault zone and give the orientation of the displacement vector.

KINEMATICS

The normal displacement was determined from the interpretation of mylonitic fabrics in the footwall of the fault zone (see page 43). It is also inferred from metamorphic relationships; the fault juxtaposes high grade rocks in the footwall (Valhalla complex, Nemo Lakes belt) against low grade rocks in the hangingwall (Slocan Group, Nelson batholith) indicating that the hanging wall moved down to the east (Parrish 1981, 1984). Stepped, east-trending mineral fibers also indicate that the hanging wall moved eastward relative to the footwall and that movement on the fault was dip-slip.

GEOMETRY OF THE FAULT ZONE

The Slocan Lake zone has a complex internal geometry as shown by irregularities in the fault surface that separates **PEg** from Nelson batholith brittle faults. North of Slocan, at Enterprise Creek, the Nelson batholith is in fault contact with paragneiss of unit **ms** for 2 km along strike (Map 1, Figure 4a). The Slocan Lake fault zone has cut down section removing unit **PEg**, (which is 400- 600 m thick to the north and south of Enterprise Creek), indicating that the fault is "scoop" shaped in this area.

West-dipping mylonitic foliation is often observed in the fault zone, as are east dipping faults which crosscut both ductile and brittle fabric. In the Springer Creek area, a 250 m thick block of **PEg** dips approximately 20° to the west (Map 1, Figure 15a). West of Winlaw, an outlier of Nelson batholith hornblende quartz syenite (**mJsy**) with west-dipping contact overlies unit **PEg** (Map 1, Figure 15b). In this locale, **PEg** is chloritic and fractured and the relict mylonitic foliation and lineation also dip west. On Slocan Ridge, a flat-lying fault in **PEg** separates west-dipping rocks in the hanging wall from easterly-dipping rocks in the footwall (Map 1, Figure 14b).

It is assumed that the layering and mylonitic foliation were subhorizontal or dipped eastward prior to faulting, based on the concordant relationship between the layering and mylonitic foliation (discussed in Chapter 3). Although the geometry of bounding faults was not observed, it is suggested that rotation about a north trending axis on east-dipping curved faults would account for the westward dips in the fault zone.

CONTINUATION OF THE FAULT

The Slocan Lake fault zone appears to die out at both the north and south ends. Near Silverton the trace of the fault enters Slocan Lake and is not exposed further north, although it may continue northwards in the valley approximately 20 to 25 kilometres for the following reasons. The presence of a fault is implied by structural and metamorphic discontinuities across Slocan Lake (Parrish 1981). Staurolite grade metasedimentary rocks of the Nemo Lakes belt on the western lakeshore are adjacent to low grade slates of the Slocan Group on the eastern shore. A large-scale, NW-trending syncline in slate of the Slocan Group on the northwest shore of Slocan Lake is not present along strike on the east shore of the lake (Map 1). The presence of chlorite grade cataclastic zones in lakeshore outcrops of the granitic Wragge Creek, Rosebery and Mount Carpenter stocks are evidence for a fault that continues the length of Slocan Lake (Figure 7d). Ten kilometres north of Slocan Lake, in Summit Lake area, the apparent continuity of the Slocan Group and stocks of the Kuskanax batholith across the river valley (Read and Wheeler 1976) implies that the fault must die out between Slocan Lake and Summit Lake, as suggested by Parrish (1981, 1984).

In the Castlegar area to the south, the displacement on the Slocan Lake fault zone appears to be taken up on the Champion Lake fault. The Champion Lake fault is on strike with the Slocan Lake fault zone. It outcrops southeast of Castlegar on the east side of the Columbia River valley, trends southward and terminates east of Trail. It dips 40° to 60° to the east and is interpreted as an Eocene brittle fault which has a displacement in the order of a few kilometres (Corbett and Simony 1984). The Slocan Lake fault cannot be unequivocally correlated with

the Champion Lake fault due to poor exposure and inadequate constraints on the timing of faulting. The two faults may be related because of similar hanging wall and footwall rocks. The Bonnington pluton, in the hanging wall of the Champion Lake fault, is equivalent to the Nelson batholith in age (~163 Rb-Sr whole rock age, Armstrong unpublished data file) and lithology (Vittie 1960, Corbett and Simony 1984). The Castlegar gneiss in the footwall of the Champion Lake fault has undergone complex high temperature ductile deformation, as have the rocks in the footwall of the Slocan Lake fault zone. Footwall rocks of both faults have an Eocene thermal history indicated by 48 to 59 Ma K-Ar biotite dates, whereas in all but one area, the Nelson batholith and the Bonnington pluton have late Jurassic and early Cretaceous K-Ar biotite dates (Figure 9).

DISPLACEMENT

The displacement on the Slocan Lake fault varies along its length. The metamorphic juxtaposition across the central part of the fault (which is discussed below) requires a minimum of 10 km to 20 km of dip slip movement. The displacement diminishes northward to zero at the end of the fault. The offset on the fault must also die out to the south since the Champion Lake fault terminates east of Trail (Corbett and Simony 1984) and there is a hanging wall/footwall cutoff in Peg in Sentinel Mountain (discussed below).

Precise calculations on the displacement on the Slocan Lake fault zone cannot be made as there are no piercing points. Estimates of the minimum displacement can be made by calculating the dip slip movement that is required to account for thermal juxtapositions across the fault.

This assumes that the same thermal gradient affected the hanging wall and footwall rocks. The details of the calculations are presented in Appendix 7.

The temperature of the hanging wall Nelson batholith has been less than 280° (the closing temperature of argon in biotite) since the late Cretaceous (Figure 9). Amphibolite facies minerals (hornblende, sillimanite-K-feldspar) require temperature conditions within the footwall to have been in excess of 500° and 600° . Calculations were made using data from Slocan Lake, Slocan Ridge and Pass Valley. The temperature juxtaposition across the fault varies from 160° to 310° and is generally 200° . Values were calculated over a range of dips (20° , 30° and 40°) using $25^{\circ}/\text{km}$, $30^{\circ}/\text{km}$ and $40^{\circ}/\text{km}$ geothermal gradients. Using these parameters, the minimum displacement ranges from 6 to 23 km. Assuming an average dip of 30° the range is 10 to 20 km depending upon the geothermal gradient.

There may be a hanging wall/footwall cutoff in unit **PEg**, northeast of Castlegar on Sentinel Mountain, which can be used to constrain the magnitude of displacement at the south end of the Slocan Lake fault (Figure 14 a). A leucocratic biotite quartz monzonite, similar in composition to unit **PEg**, overlies and is in fault contact with **PEg** low on the western flank of Sentinel Mountain (Map 1). Little (1960), mapped this quartz monzonite as part of the Valhalla plutonic series. It is heterogeneous in grain size and fabric. L - S tectonites, where present, are protomylonites (Zone B, Figure 12). They have a strong lineation and a less well developed east-dipping foliation. Both concordant and discordant pegmatites occur at the top of this granitic body. The age of this rock is uncertain. The upper contact with

granodiorite of the Nelson batholith, observed in one locale, is a discrete mylonite zone with an easterly-directed shear sense and along strike it is invaded by pegmatites. During mapping in the 1985 season, heterogeneous, pegmatitic phases of **PEg**, similar to the granitic rock on Sentinel Mountain, were observed in the western Valhalla Ranges. On the west side of the complex, relationships at the contact of **PEg** with the overlying Jura-Cretaceous granodiorite and quartz diorite are similar to those observed on Sentinel Mountain. If the quartz monzonite on Sentinel Mountain is a phase of **PEg**, then Slocan Lake fault zone low on the western flank of Sentinel Mountain juxtaposes **PEg** in both hanging wall and footwall. In this, the favored interpretation, the upper contact of **PEg** with the Nelson batholith is a sheared tectonic contact, similar to the one bounding the western margin of the Valhalla complex. Alternatively, the quartz monzonite may be a phase of the Nelson batholith and the juxtaposition of unit **PEg** against the Nelson batholith as proposed by Parrish (1984) is correct. In Carr (1985), the writer also suggested that the upper part of Sentinel Mountain could be a footwall horse of **PEg**. This interpretation is now rejected because a brittle fault is not observed at the top of the quartz monzonite.

If the interpretation of a hanging wall/footwall cutoff on Sentinel Mountain is correct, the maximum displacement at the south end of the fault is 6 km, assuming a dip of 30° on the fault. This assumes that **PEg** is sheetlike, approximately 3-km thick, and that the upper contact projects across the complex parallel to the foliation as shown in Figure 4c).

AGE OF FAULTING

The Slocan Lake fault was active in the early to middle Eocene. It postdates the emplacement of PEG (58 Ma) and may be concurrent or younger than 54 ± 1 Ma muscovite in the fault zone. The muscovite is synkinematic with greenschist grade Zone C mylonites which are inferred to have formed during movement along the Slocan Lake fault zone. At Cape Horn, on Slocan Lake, a vertical basalt dyke that strikes northwest crosscuts brittle fabrics in the fault zone. This is the only observed rock that clearly truncates and postdates the brittle deformation. The age of this dyke is presently uncertain, but is probably 55 Ma to 45 Ma as are most of the unmetamorphosed and generally undeformed basaltic dykes in southeastern British Columbia (Souther 1977).

SUMMARY

1). The Slocan Lake fault is a normal fault that dips 20° to 40° to the east. It extends both north and south of the Valhalla complex and diverges from the amphibolite grade ductile fabrics associated with the Valkyr shear zone, which arch over the complex. The displacement on the Slocan Lake fault zone dies out at both ends and the fault projects westwards as a relatively planar zone above the Valhalla complex, thus it must root to the east.

2). Since the Slocan Lake fault zone is pinned at both ends the maximum displacement occurs along the central section of the fault. Assuming the fault dips 30° , there is a maximum of 6 km dip slip movement at Sentinel Mountain near the south end. A minimum of 10 km of dip-slip movement in the central area between Silverton and Pass Valley is required to account for the thermal juxtaposition of $\sim 150^{\circ}$ to $\sim 250^{\circ}$.

across the fault. This part of the fault is adjacent to the area of highest structural and topographic relief in the Valhalla complex.

Movement on the fault probably accommodated uplift and/or arching of the Valhalla complex and the variation in displacement along the length of the fault can be related to the geometry of the north-south elongate complex.

3). Fault rocks along the northern lakeshore of Slocan Lake are cataclastic and penetrative ductile structures are not present, although the fault trace is in the lake and footwall fault rocks within 0.5 km of the fault were not observed. On Sentinel Mountain, amphibolite grade, protomylonitic fabrics thought to be related to movement on the Valkyr shear zone are crosscut by the Slocan Lake fault zone. Corbett and Simony (1984) report predominantly brittle structures in the Champion Lake fault. Thus, deformation at the north and south ends of the fault occurred predominantly in the brittle regime. This is in contrast to the central part of the fault zone, between Silverton and Pass valley, where highly strained, greenschist grade, unit PEG Zone C mylonites (Figure 12) in the footwall related to displacement on the fault, are overprinted by brittle structures. The presence of mylonites are indicative of higher temperatures at deeper levels during early movement on the fault, and their exposure in the middle section of the fault is consistent with the estimated displacement variation along the length of the fault. In this interpretation, the Zone C mylonites and underlying concordant amphibolite facies fabrics in Pgm, ms, uKgn and cgn are attributed to movement on the Slocan Lake fault zone, thus a brittle ductile transition is exposed along the length of the fault. More work

with the metamorphic assemblages in the paragneisses may show a systematic variation of displacement within the central part of the fault zone.

4). The fault is an early to middle Eocene structure since it truncates the 58 Ma unit **PEg**, has 54 Ma synkinematic muscovite in footwall fault rocks and is crosscut by a basaltic dyke with an inferred age of 45 - 55 Ma.

FIGURE 14: Unit **PEg** fault rocks - footwall of the Slocan Lake fault zone. 14 a) View looking south towards Sentinel Mountain. The trace of the Valkyr shear zone (**VSZ**) which juxtaposes upper plate middle Jurassic Nelson batholith (**mJgd**) and lower plate biotite granite (**PEg**) is below the ridge crest. The trace of the Slocan Lake fault (**SLFZ**) follows the break-in-slope along the lower slope of the ridge; b) a flat lying fault cross-cuts cataclastic **PEg** on Slocan Ridge (SC 289). The mylonitic foliation in the hanging wall dips westwards and was probably rotated into this orientation by movement on the fault; c) rock slab of **PEg** is crosscut by chlorite filled fractures (SC 217); d) late state pseudotachylite crosscuts the mylonitic fabric in **PEg** located in the Slocan Lake fault zone at Cape Horn north of Slocan (SC 86); e) photomicrograph of unit **PEg** fault rock (PCA 505). Elongate quartz aggregates, quartz subgrains and fine grained matrix are relict mylonitic features which are crosscut by quartz filled fractures. Feldspar crystals are altered to sericite; and, f) photomicrograph shows lense of cataclastite that truncates mylonitic fabric (SC 98).

FIGURE 15: Cross-sections of Slocan Lake fault show back-dips in fault zone. See Figure 2 for legend and Figure 4a for cross-section locations. The apparent trace of foliations (from this study and from Reesor, 1965) are projected into the sections 15 a) Springer Creek section (east of Slocan) shows back-dips in unit **PEg**; and, 15 b) Slocan Ridge-Winlaw section shows back-rotated outlier of hanging wall **mJsy**.

a)

W

E

0 1 km

SLOCAN LAKE - SPRINGER CREEK

b)

W

E

PERRY
RIDGE

SLOCAN
VALLEY

0 1 2 km

WINLAW - SLOCAN RIDGE

FIGURE 16: Nelson batholith fault rocks - hanging wall of the Slocan Lake fault zone. 16 a) brecciated and chloritized granodiorite and dyke (Springer Creek, SC 13); 16 b) granodiorite rock slab shows relict igneous texture crosscut by quartz and chlorite filled fractures and veins (SC 81); 16 c) photomicrograph shows broken feldspar crystals and fine grained matrix cross-cut by chlorite, quartz and carbonate filled fractures (SC 87); and, 16 d) fractured feldspar crystals and late quartz vein (SC 8).

CHAPTER 5 - SUMMARY OF CONCLUSIONS

This study has documented the ductile and brittle structures in the Valhalla complex, particularly the Paleocene (63 Ma) and Eocene (58 Ma) mylonitic granitoid rocks. The structural and kinematic relationships and timing of deformation clearly show that 1) there has been significant ductile shearing throughout the uppermost granitoid sheets of the Valhalla complex which is early Tertiary in age, 2) the Valhalla complex is bounded by the ductile Valkyr shear zone on the north, west and southern margins and the ductile/brittle Slocan Lake fault on the east side, thus the complex is exposed in a tectonic window, 3) arching of the complex occurred in the early Tertiary and was concurrent with ductile shearing, and 4) although mylonites on the eastern margin of the complex (in the footwall of the Slocan Lake fault zone) are overprinted by brittle structures, they were formed during movement on the fault. Tectonic models for the Valhalla complex and core complexes in southern British Columbia must accommodate these observations.

In summary, the metamorphic, kinematic, structural and temporal relationships indicate the following:

- 1). A zone of strain distributed throughout the upper 1 to 3 km of Valhalla complex and approximately 0.5 km of overlying rocks, named the Valkyr shear zone, was active in the early Eocene between 58 and 54 Ma and possibly earlier. It has an easterly-directed sense of shear, the displacement is uncertain and movement was, in part, concurrent with uplift and arching of the Valhalla complex. Geology of the lower plate is characterized by Eocene K-Ar mineral ages, high grade, polydeformed gneisses, penetratively deformed sheetlike intrusive rocks, and ductile

Tertiary (and possibly, late Cretaceous) penetrative deformation. Upper plate rocks have Cretaceous or older K-Ar mineral ages, are at lower metamorphic grade, the plutonic rocks are relatively undeformed, and Mesozoic and older structures are preserved.

2). Ductile and brittle deformation on the eastern side of the Valhalla complex, in the Slocan Lake fault zone, outlasted movement on the Valkyr shear zone. Exhumed footwall mylonites are overprinted by and juxtaposed against higher level brittle structures. Timing constraints indicate that the Valkyr shear zone, arching of the Valhalla complex and movement on the Slocan Lake fault zone occurred as a continuum in the early to middle Eocene. This is consistent with thermal data indicating that Valhalla complex stayed hot into the Eocene and was rapidly uplifted and quenched. K-Ar biotite mineral ages are Eocene in age and, excluding rocks in the Slocan Lake fault zone, high temperature upper amphibolite facies mineral assemblages (stable sillimanite - K-feldspar) have not been retrograded.

3). The Mesozoic and older history of the Valhalla complex is obscure. Older structures are invaded by migmatites and intrusions and are attenuated, transposed and overprinted by early Tertiary deformation. The metamorphic history, correlation and age of the paragneisses (ms) within the complex have not been studied in detail so that no Mesozoic structures can be clearly described. The Gwillim Creek shear zones postdate the 93 Ma granodiorite gneiss (uKgn) which they deform, and may be late Cretaceous, rather than Eocene in age (see Parrish et al. 1985b). The root direction and significance of the shear zones are uncertain at present.

2 OF/DE 2

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

APPENDIX 1: VALHALLA COMPLEX

UNIT	AGE (Ma)	DESCRIPTION	REGIONALLY EXTENSIVE MINERAL ASSEMBLAGES	REFERENCE
Ecsy	52 ± 1 (U-Pb Zrn data 1985)	coarse grained hornblende-biotite-clinopyroxene syenite	Kfs-Hbl-Bt-Cpx	Parrish et al. 1985b Carr 1985
Peg	58 ± 1 (U-Pb Zrn, Parrish unpub. data 1985)	leucocratic biotite quartz monzonite	Pl(An 20-35)-Or-Qtz-Bt (acc. Zrn, Mnz, Aln)	This study Unit 8, Reesor 1965
Pgm	63.5 ± 1 (U-Pb Zrn Parrish 1984).	K-feldspar megacrystic biotite + hornblende granodiorite gneiss	Pl(An20-45)-Or-Qtz-Bt-Hbl (acc. Zrn, Spn, Ap, Aln)	This study Unit 3, Reesor 1965
U ^K gn Kinnaid orthogneiss	late Cretaceous (U-Pb Zrn Parrish unpub. data 1985)	leucocratic K-feldspar megacrystic gneiss (amphibolite grade)	Kfs-Pl-Hbl-Qtz-Bt (acc. Zrn, Spn, Ap)	This study Simony 1979 Haltas and Simony 1986 Unit cnga, Carr 1985
U ^K gn	89 ± 3 (U-Pb Zrn Parrish, 1984)	melanocratic K-feldspar megacrystic biotite-hornblende granodioritic gneiss intruded by leucocratic granitoid veins (amphibolite grade)	Pl(An25-45)-Qtz-Or-Bt-Hbl (acc. Zrn, Ap, Aln, Spn)	Unit 2 (Veined gneiss) Reesor 1965 This study

APPENDIX 1 (CONTINUED):

ms	pre-middle Jurassic	quartzofeldspathic & pelitic schist and gneiss -amphibolite -calc-silicate -quartzite -leucocratic orthogneiss and pegmatite (upper amphibolite grade)	Pl-Qtz-Bt-Kfs-Grt-Sil-Qz -Kfs-Sil-Grt -Hbl-Pl(An30-80)-Qtz-Bt- -Di-Grt-Spr-Ilm Cal-Qtz-Pl-Di-Spr-Ilm Scp-Di-Cal-Qtz -Qtz-Sil-Bt-Grt-Kfs-Pl -Pl-Or-Qtz-minor Bt	This study Unit 1 (Hybrid gneiss) Reesor 1965
cg Castlegar paragneiss	pre-middle Jurassic	heterogeneous quartzofeldspathic paragneiss with amphibolite and calc-silicate layers (amphibolite grade)	Pl-Qtz-Kfs-Hbl-Bt	Little 1960 Parrish et al. 1985b Carr 1985

Mineral symbols from Kretz (1983): Aln = allanite; Anth = anthophyllite; Ap = apatite; Aug = augite; Bt = biotite; Cal = calcite; Cpx = clinopyroxene; Chl = chlorite; Czo = clinozoisite; Di = diopside; En = enstatite; Ep = epidote; Fo = forsterite; Gr = graphite; Grt = garnet; Hem = hematite; Hbl = hornblende; Ilm = ilmenite; Kfs = K-feldspar; Mnz = monazite; Ms = muscovite; Or = orthoclase; Opx = orthopyroxene; Pl = plagioclase; Py = pyrite; Qtz = quartz; Rt = rutile; Scp = scapolite; Sil = sillimanite; Spn = sphene; Tlc = talc; Tr = tremolite; Zrn = zircon.

APPENDIX 2: UPPER PLATE OF THE VALKYR SHEAR ZONE

UNIT	AGE (Ma)	DESCRIPTION	REGIONALLY EXTENSIVE MINERAL ASSEMBLAGES	REFERENCE
Coryell Intusives	Eocene	syenite		Little 1957, 1960, 19782
Wragge Ck Stock	age uncertain probably Cretaceous	biotite quartz monzonite	Pl-Or-Bt-Qtz+Ep	Read and Wheeler 1976
Cariboo Ck Stock	late Cretaceous (U-Pb Zrn, Parrish unpub. data 1985)	hornblende granite		Hyndman 1968 Read and Wheeler 1976
Snowslide Ck Stock	late Cretaceous (U-Pb Zrn, Parrish unpub. data 1985)	leucocratic biotite quartz monzonite	Pl-Or-Qtz-Bt	Parrish 1981
"Nelson series" Intusives	Jurassic and/or Cretaceous	granodiorite, hornblende quartz diorite, granite		Little 1957, 1960
Slocan Gp	Triassic (Little 1960, Orchard 1985, Klepacki 1985)	dark grey shale with calcareous and arenaceous interbeds (unmetamorphosed in north, grade increases southward to lower amphibolite grade)	Qtz-Cal-Gr-Ms	Little 1960 Parrish 1981 Klepacki 1985
Nemo Lakes belt	Paleozoic and Triassic (Parrish 1981, Parrish et al. 1985b)	-semi-pelite and pelite -calcareous schist -amphibolite -ultramafic rock (sillimanite grade; decreases northward)	-Sil-Bt-Gr-Ms-Pl -Di-Cal-Qtz-Scp-Pl-Tr -Hbl-Czo-Gr-Pl -Hbl-Pl-Qtz -En-Fo-Mg Chl Fo-Tlc-Tr Fo-En-Mg Chl	Parrish 1981
Mc Roberts	Pennsylvanian(?)	shale, siltstone, argillaceous quartzite, limestone, chert, volcanics and inferred metasedimentary equivalents		Little 1957, 1960, 1982, Simony 1979

Mineral symbols from Kretz (1983): Aln = allanite; Anth = anthophyllite; Ap = apatite; Aug = augite; Bt = biotite; Cal = calcite; Gpx = clinopyroxene; Chl = chlorite; Czo = clinzoisite; Di = diopside; En = enstatite; Ep = epidote; Fo = forsterite; Gr = graphite; Grt = garnet; Hem = hematite; Hbl = hornblende; Ilm = ilmenite; Kfs = K-feldspar; Mnz = monazite; Ms = muscovite; Or = orthoclase; Opx = orthopyroxene; Pl = plagioclase; Py = pyrite; Qtz = quartz; Rt = rutile; Scp = scapolite; Sil = sillimanite; Sph = sphene; Tlc = talc; Tr = tremolite; Zrn = zircon.

APPENDIX 3: HANGING WALL OF THE SLOCAN LAKE FAULT ZONE

UNIT	AGE (Ma)	DESCRIPTION	REGIONALLY EXTENSIVE MINERAL ASSEMBLAGES	REFERENCE
Roseberry stock	age uncertain probably Cretaceous	biotite quartz monzonite	Pl-Kfs-Qtz-Bt +Hbl+Ep	Read and Wheeler 1976
Mt Carpenter stock	age uncertain probably Cretaceous	biotite quartz monzonite	Pl-Kfs-Qtz-Bt +Hbl+Ep	Read and Wheeler 1976
Nelson batholith	Middle Jurassic (Nguyen et al. 1968, Duncan et al. 1979, Duncan and Parrish 1979, Archibald et al. 1983)	-massive porphyritic granodiorite -leucocratic hornblende quartz syenite granite	-Hbl-Pl(An20-40)-Kfs-Qtz-Bt-Opx -Pl(An22-50)-Hbl-Kfs Bt-Aug-Qtz (acc. Zrn, Rt).	This study Little 1960
Rosland Group	early Jurassic (Tipper 1984)	massive black shale, volcaniclastics, augite porphyry, shale, siltstone, sandstone (no regional metamorphism, contact metamorphism)		Little 1960 Tipper 1984
Slocan Group	Triassic (Little 1960, Orchard 1985, Klepacki 1985)	dark grey argillite, calcareous and arenaceous interbeds (unmetamorphosed and chlorite grade)	-Bt-Cal-Qtz-Tr-Alb -Cal-Qtz-Ms-Gr	Little 1960 Parrish 1981 Hedley 1952 Klepacki 1985

Mineral symbols from Kretz (1983); Aln = allanite; Anth = anthophyllite; Ap = apatite; Aug = augite; Bt = biotite; Cal = calcite; Cpx = clinopyroxene; Cl = chlorite; Czo = clinozoisite; Di = diopside; En = enstatite; Ep = epidote; Fo = forsterite; Gr = graphite; Grt = garnet; Hem = hematite; Hbl = hornblende; Ilm = ilmenite; Kfs = K-feldspar; Mnz = monazite; Ms = muscovite; Or = orthoclase; Opx = orthopyroxene; Pl = plagioclase; Py = pyrite; Qtz = quartz; Rt = rutile; Scp = scapolite; Sil = sillimanite; Spn = sphene; Tlc = talc; Tr = tremolite; Zrn = zircon.

APPENDIX 4: ZONE A - UNIT PEG

A. MESOSCOPIC FEATURES

-massive, light grey, weathers orange grey, equigranular, weak discontinuous foliation defined by flattened quartz crystals

B. MICROSCOPIC FEATURES

-no kinematic indicators

-weak foliation made up of flattened quartz grains and discontinuous lenses of recrystallized matrix

MINERAL	%	SIZE	CRYSTAL SHAPE	GRAIN BOUNDARIES	COMMENTS
PLAGIOCLASE	35	1 cm x 0.4 cm to 6 mm x 1 mm, commonly 2 mm x 2mm	subhedral, rectangular equant	straight curved	-zoned crystals, some albite twins, rare Carlsbad twins, An ₂₇ (oligoclase) -deformation twins, minor undulose extinction, minor core and mantle structure.
K-FELDSPAR	30	0.8 cm x 0.6 cm to 6 mm x 2 mm	subhedral, rectangular laths and equant crystals	straight curved	-poikilitic, perthites, myrmekites, microcline twins -minor undulose extinction, minor core and mantle structure
QUARTZ	30	highly variable 0.6 mm x 0.2 mm to 5 mm x 2 mm	irregular aggregates of blocky grains, elongate and equant crystals	scalloped curved lobate	-occurs interstitially between feldspar crystals, as single grains and as aggregates of crystals -no preferred crystallographic orientation -deformation bands, equant subgrains
BIOTITE	< 5	0.5 - 1.0 in length	euhedral- subhedral laths	straight, some crystals have ragged ends	-golden-brown, straight extinction

APPENDIX 4 (CONTINUED): ZONE A

<u>ACCESSORY MINERALS</u>	< %	zircon, allanite, monazite, pyrite
<u>MATRIX</u>	10-20% rings from .001 to 0.3 mm mode 0.1-0.2mm	occur as zones up to 1 to 2 mm wide at grain boundaries, mantling feldspars and as isolated lenses between grains

C. GENERAL COMMENTS

predominantly igneous texture modified by some ductile strain resulting in
sporadic development of weak foliation

APPENDIX 5: ZONE B - UNIT PEG

A. MESOSCOPIC FEATURES

- medium grey, weathers orange grey
- S-C tectonite - east over west sense of shear determined from the angular relationship of C and S foliations and shear bands

B. MICROSCOPIC FEATURES

MINERAL	%	SIZE	CRYSTAL SHAPE	GRAIN BOUNDARIES	COMMENTS
PLAGIOCLASE	35	porphyroclasts up to 4 to 8 mm long	irregular: wedge, rounded equant, rounded elongate, trapezoidal	curved embayed	-undulose extinction, deformation twins, pulled-apart grains present but uncommon, pressure shadows of matrix around porphyroclasts
K-FELDSPAR	30	porphyroclasts up to 4 - 8 mm long	irregular: rectangular, rounded equant, rounded elongate, subhedral	lobate curved straight	-perthites, myrmekites, Carlsbad twins -core and mantle subgrain development, undulose extinction, subgrains, deformation bands
QUARTZ	30	variable: -20 mm x < 1mm -3 mm x 1 mm	- elongate aggregates -irregular, blocky	straight and curved	-elongate aggregates and ribbon grains are oriented parallel to the C foliation, are sigmoidal or wrap around feldspar porphyroclasts -subgrains are blocky, 0.3 mm ² and have curved and lobate grain boundaries -weak 'c' axis fabric (lambda plate)
BIOTITE	< 5	< 1 mm long	-euhedral to subhedral laths -subhedral to anhedral	straight	golden-brown, straight extinction
		< 0.3 mm long		straight to curved	golden-brown, straight extinction

APPENDIX 5 (CONTINUED): ZONE B - UNIT PEG

<u>ACCESSORY MINERALS</u>	< 1 -zircon, apatite, allanite -opaques (pyrite, hematite)	-often concentrated in C foliation -disseminated along S foliation
<u>ALTERATION MINERALS</u>	< 1% rare chlorite and muscovite	
<u>MATRIX</u>	30-50% ranges from .001 to 0.2 mm mode .05 to 0.1 mm	-occur in discontinuous lenses and in layers zones up to 4 mm in width -matrix comprises anhedral quartz, feldspar and opaques and euhedral biotite

MICROSCOPIC FABRIC ELEMENTS AND KINEMATIC INDICATORS

C foliation - observed as the trace of matrix layers, elongate quartz grains and aggregates, concentrations of accessory minerals

S foliation - observed as elongate quartz inclined 30° to the C foliation, the long axis of feldspar porphyroclasts with 2:1 aspect ratio, pressure shadows, the perpendicular to extension fractures in plagioclase, the preferred orientation of elongate quartz subgrains in highly strained areas.

Shear bands - rare

-the sense of shear is east over west as indicated by the closing direction of the angle between C and S foliations

SYNKINEMATIC MINERALS

-biotite occurs in plagioclase pull-aparts and in feldspar pressure shadows

-orthoclase occurs in plagioclase pull-aparts and in pressure shadows (determined from stained thin sections)

C. GENERAL COMMENTS

-protonylonites after Sibson (1977)

-amphibolite facies minerals are stable

APPENDIX 6: ZONE C - UNIT PEG

A. MESOSCOPIC FEATURES

- medium to dark grey with dark grey fine grained layers, weathers green and pink in the Slocan Lake fault zone
- S-C tectonite -asymmetry of mylonitic fabric elements indicates east over west shear sense
- thin (~ 2 cm) ultramylonite zones
- "pseudotachylite" cross-outs mylonitic fabric at Cape Horn

B. MICROSCOPIC FEATURES

MINERAL	%	SIZE (mm)	CRYSTAL SHAPE	GRAIN BOUNDARIES	COMMENTS
PLAGIOCLASE	35	0.1 x 0.8 to 2 x 4mm	variable: trapezoidal elongate	straight, curved,	undulose extinction, rare deformation twins, core and mantle structure, pull-aparts, and fractured grains with rotated pieces are common, pressure shadows
K-FELDSPAR	30	0.8 x 0.4 to 2 x 4 mm	variable: trapezoidal elongate	straight	relict Carlsbad twins, undulose extinction, occurs in plagioclase pull-aparts, pressure shadows and matrix (from stained sections).
QUARTZ	30	0.1 x 0.2 to 2 x 6 mm	elongate ribbon grains anhedral (matrix)	straight curved seriate & lobate sub- grains	-elongate aggregates and ribbon grains are parallel to the C foliation, sigmoidal and wrapped around porphyroclasts -subgrains have a preferred 'c' axis fabric inclined to the C foliation (lambda plate) -subgrains are elongate (~ 0.1 mm long)
BIOTITE	< 5	.05 x .1 mm .01 x .01 and smaller 0.4 x 0.2	-aggregates of subhedral crystals -anhedral to subhedral -subhedral laths	ragged straight -straight sides ragged ends	sweeping extinction, kinks straight extinction occur in pressure shadows of porphyroclasts generally have straight extinction, some have sweeping extinction

APPENDIX 6 (CONTINUED): ZONE C - UNIT PEG

MUSCOVITE	< 2	0.5 x 0.2 cm and larger	euhedral laths equant	straight	"fish", sweeping extinction, some kink bands
ACCESSORY MINERALS	< 1		zircon, monazite, allanite, pyrite		
ALTERATION MINERALS	< 1		chlorite, muscovite, epidote, calcite, quartz, sericite, saussurite,		
MATRIX	> 50%	.015 - .050 diameter mode .025 - .050			

MICROSCOPIC FABRIC ELEMENTS AND KINEMATIC INDICATORS

C foliation - observed as the trace of compositional layers, concentrations of phyllosilicates and accessory minerals, quartz ribbons
 S foliation - the long axis of "mica fish", pulled apart feldspar porphyroclasts, sigmoidal quartz, pressure shadows, preferred orientation of quartz subgrains, and the perpendicular to feldspar pull-aparts oriented 33° to the S foliation
 Shear bands - common

the sense of shear is east over west as indicated by the closing direction of the angle between C and S foliations
 chlorite, quartz, epidote and calcite lined fractures crosscut the mylonitic fabric, no systematic orientations of fractures were observed

SYN-KINEMATIC MINERALS

chlorite, epidote, muscovite, calcite and quartz in pull-aparts and pressure shadows
 muscovite porphyroclasts and "fish"

C. GENERAL COMMENTS

mylonites after Sibson (1977)
 some of the ductile deformation occurred under middle greenschist or lower metamorphic conditions

APPENDIX 7 A : DISPLACEMENT CALCULATIONS - SLOCAN LAKE FAULT ZONE

LOCATION	FOOTWALL TEMPERATURE CONDITIONS	HANGING WALL TEMPERATURE CONDITIONS	TEMPERATURE DIFFERENCE	MINIMUM DISPLACEMENT
Nemo Lakes belt- lakeshore outcrop 1.5 km below the fault	Sil-St-Di ~ 565° C at the fault > 600° C	sub-Bt grade < 400° C	~ 160° C	~ 10 km
Unit ms Cape Horn, Slocan Lake 2.0 km below the fault	Sil-Kfs and migmatites > 650° C ~ 590° C at the fault	closing temperature argon in Bt < 280° C	~ 310° C	~ 20 km
Unit Pgm Slocan Ridge 1.8 km below the fault	Hbl > 500° C ~ 450° C at the fault	closing temperature argon in Bt < 280° C	~ 170° C	~ 10 km
Unit ms Passmore 4.2 km below the fault	Sil-Kfs and migmatite > 650° C ~ 525° C at the fault	closing temperature argon in Bt < 280° C	~ 240° C	~ 17 km
Unit cgn Pass Valley 2.0 km below the fault	Di-Scp ~ 500° C ~ 440° C at the fault	closing temperature argon in Bt < 280° C	~ 160° C	~ 10 km
Unit PEG Along trace of fault 0.5 km below the fault	Bt > 400 - 440° C ~ 400° C at the fault	closing temperature argon in Bt < 280° C	~ 160° C	~ 10 km

NOTE: The displacements presented are calculated based on a geothermal gradient of 30°/km, and a 30° fault dip.

Mineral symbols from Kretz (1983); Bt = biotite; Di = diopside; Hbl = hornblende; Kfs = K-feldspar; Scp = scapolite; Sil = sillimanite; St = staurolite.

APPENDIX 7 B: DISPLACEMENT TABLES

Geothermal Gradient	Temperature Difference			
	150° C	200° C	250° C	300° C
FAULT DIP = 20°				
25°/km	18 km	23 km	29 km	35 km
30°/km	15 km	20 km	24 km	29 km
40°/km	11 km	15 km	18 km	21 km
FAULT DIP = 30°				
25°/km	12 km	16 km	20 km	24 km
30°/km	10 km	13 km	17 km	20 km
40°/km	8 km	10 km	13 km	12 km
FAULT DIP = 40°				
25°/km	9 km	12 km	15 km	19 km
30°/km	8 km	10 km	13 km	16 km
40°/km	6 km	8 km	10 km	12 km

REFERENCES

- Archibald, D.A., Glover, J.K., Price R.A., Farrar, E., and Carmichael, D. M. 1983. Geochronology and tectonic implications of magmatism and metamorphism, southern Kootenay Arc and neighboring regions, southeastern British Columbia. Part I: Jurassic to Mid-Cretaceous. *Canadian Journal of Earth Sciences*, **20**, pp. 1891-1913.
- Armstrong, R.L. 1982. Cordilleran metamorphic core complexes - from Arizona to Southern Canada. *Annual Review of Earth and Planetary Sciences*, **10**, pp.129-154.
- Bardoux, M. 1985. The Kelowna detachment zone, Okanagan valley, south-central British Columbia. In, *Current Research, Part A, Geological Survey of Canada, Paper 85-1A*, pp. 333 - 339.
- Beach, A. 1980. Retrogressive metamorphic processes in shear zones with special reference to the Lewisian complex. *Journal of Structural Geology*, **2**, pp. 257-263.
- Bell, T.H. and Etheridge, M.A. 1973. Microstructures of mylonites and their descriptive terminology. *Lithos*, **6**, pp; 337-349.
- Berthe, D., Choukouné, P. and Jegouzo, P. 1979. Orthogneiss, mylonite and non coaxial deformation of granites: the example of the South American Shear-Zone. *Journal of Structural Geology*, **1**, pp. 31-42.
- Bethune, D.N. 1985. Strain analysis of discrete west-dipping, westerly-directed ductile shears on the southwest flank of the Valhalla gneiss complex, southeastern British Columbia, B.Sc. thesis (unpublished), Carleton University, 63 pp.
- Brodie, K.H. Variations in chemistry across a shear zone in phlogopite peridotite, *Journal of Structural Geology*, **2**, pp 265-272.
- Brown, R.L. and Psutka, J.F. 1979. Stratigraphy of the east flank of Frenchman Cap dome, Shuswap Complex. In, *Current Research, Part A, Geological Survey of Canada, Paper 79-1A*, pp. 35-36.
- Brown, R.L. and Murphy, D.C. 1981. Kinematic interpretation of mylonitic rocks in part of the Columbia River fault zone, Shuswap Terrane, British Columbia. *Canadian Journal of Earth Sciences*, **19**, pp. 456-465.
- Carr, S.D. 1985. Ductile shearing and brittle faulting in Valhalla gneiss complex, southeastern British Columbia. In, *Current Research, Part A. Geological Survey of Canada, Paper 85-1A*, pp. 89-96.
- Coney, P.J. 1980. Cordilleran metamorphic core complexes: An overview. *Geological Society of America, Memoir 153*, pp. 7-31.
- Corbett, C.R., and Simony, P.S. 1984. The Champion Lake Fault in

the Trail-Castlegar area of southeastern British Columbia. In Current Research, Part A. Geological Survey of Canada, Paper 84-1A, pp. 103-104.

Crowe, G.G. 1981. The structural evolution of the Mackie plutonic complex, southern British Columbia, M.Sc. thesis (unpublished), University of Calgary, 154 p.

Davis, G.A. 1980. Structural characteristics of metamorphic core complexes, southern Arizona. Geological Society of America, Memoir 153, pp. 543-569.

Duncan, I.J., Parrish, R.R. and Armstrong, R.L. 1979. Rb/Sr geochronology of the post-tectonic intrusive events in the Omineca Crystalline Belt, southeastern British Columbia. Cordilleran Section of the Geological Association of Canada, Vancouver B.C., Program and Abstracts, p. 15.

Duncan, I.J., and Parrish, R.R. 1979. Geochronology and Sr isotope geochemistry of the Nelson Batholith: a post tectonic intrusive complex in southeast British Columbia. Geological Society of America, Cordilleran Section, Program and Abstracts, 11, p. 76.

Ewing, T.E. 1981. Paleogene tectonic evolution of the Pacific Northwest. Journal of Geology, 88, pp. 619-638.

Eisbacher, G.H. 1970. Deformation mechanics of mylonite rocks and fractured granites in Cobequid Mountains, Nova Scotia, Canada. Bulletin of the Geological Society of America, 181, pp. 2009-2020.

Fyles, J.T. 1984. Geological setting of the Rossland Mining Camp. Province of British Columbia, Ministry of Energy Mines and Petroleum Resources, Bulletin 74, 56 p.

Halwas D. and Simony, P.S. 1986. The Castlegar Gneiss Complex, Southern British Columbia. In, Current Research, Part A, Geological Survey of Canada, Paper 86-1A, in press.

Harms, T. 1982. The Newport Fault: Low-angle normal faulting and Eocene extension, northeast Washington and northwest Idaho, M.Sc. thesis (unpublished), Queen's University, 157 p.

Harrison, T.M. 1985. Thermal history of the Nelson batholith, British Columbia. The Geological Society of America, Cordilleran Section, Abstracts with Programs, p. 260.

Hedley, M.S. 1952. Geology and Ore Deposits of the Sardon Area, Slocan Mining, British Columbia. British Columbia Department of Mines, Bulletin 29.

Hobbs, B.E., Means, W.D. and Williams, P.F. 1976. An outline of structural geology. John Wiley and Sons, Inc. Toronto, 571 pp.

- Klepacki, D.W. 1983. Stratigraphic and structural relations of the Milford, Kaslo and Slocan Groups, Rosebery Quadrangle, Lardeau map area, British Columbia. *In*, Current Research, Part A, Geological Survey of Canada, Paper 83-1A, pp. 229-233.
- Klepacki, D.W. and Wheeler, J.O. 1985. Stratigraphic and structural relations of the Milford, Kaslo and Slocan groups, Goat Range, Lardeau and Nelson map areas, British Columbia. *In*, Current Research, Part A, Geological Survey of Canada, Paper 85-1A, pp. 277-286.
- Lane, L.S. 1984a. Deformation history of the Monashee decollement and Columbia River fault zone, British Columbia. Ph.D. thesis (unpublished), Carleton University, 240 p.
- Lane, L.S. 1984b. Brittle deformation in the Columbia River fault zone near Revelstoke, southeastern British Columbia. *Canadian Journal of Earth Sciences*, 21, pp. 584-598.
- Lister, G.S. and Snoke, A.W. 1984. S - C Mylonites. *Journal of Structural Geology*, 6, pp. 617-638.
- Little, H.W. 1957. Kettle River, east half, British Columbia. Geological Survey of Canada, Map 6-1957.
- Little, H.W. 1960. Nelson map-area, west half, British Columbia. Geological Survey of Canada, Memoir 308, 205 p.
- Little, H.W. 1961. Kettle River, west half, British Columbia. Geological Survey of Canada, Map 15-1961.
- Little, H.W. 1962. Geology of the Rossland-Trail Map Area, British Columbia. Geological Survey of Canada, Paper 79-26, 38 p.
- Marjoribanks, R.W. 1976. The relation between microfabric and strain in a progressively deformed quartzite sequence from Central Australia. *Tectonophysics*, 32, pp. 269-293.
- McConnell, R.G. and Brock, R.W. 1904. West Kootenay Area, British Columbia. Geological Survey of Canada Map 792.
- Monger, J.W.H. 1977. Upper Paleozoic rocks of the western Canadian Cordillera and their bearing on Cordilleran evolution. *Canadian Journal of Earth Sciences*, 14, pp. 1832-1859.
- Monger, J.W.H., Souther, J.G., and Gabrielse, H. 1972. Evolution of the Canadian Cordillera: A plate tectonic model. *American Journal of Science*, 272, pp. 577-602.
- Monger, J.W.H., and Price, R.A. 1979. Geodynamic evolution of the Canadian Cordillera - progress and problems. *Canadian Journal of Earth Sciences*, 16, pp. 770-791.
- Monger, J.W.J. (Principal compiler), Woodsworth, G.J., Price, R.A., Clowes, R.N., Riddiough, R.P., Currie R., Hoy, T., Preto, V.A.G.,

- Simony, P.S., Snavely, P.D. and Yorath C.J. In press. Transect B2, Southern Canadian Cordillera, North American continent-ocean transects. Geological Society of America Decade of North American Geology Program.
- Nguyen, K.K., Sinclair, A.J. and Libby, W.G. 1968. Age of the northern part of the Nelson Batholith. Canadian Journal of Earth Sciences, 5, pp. 955-957.
- Orchard, M.S. 1985. Carboniferous, Permian and Triassic conodonts from the central Kootenay Arc, British Columbia. In, Current Research, Part A, Geological Survey of Canada, Paper 85-1A, pp. 277-286.
- Parkinson, D. 1985a. U-Pb geochronology and regional geology of the southern Okanagan valley, British Columbia: The western boundary of a metamorphic core complex. M.Sc. thesis, University of British Columbia, 149 p.
- Parrish, R.R. 1981. Geology of the Nemo Lakes Belt, northern Valhalla Range, southeast British Columbia. Canadian Journal of Earth Sciences, 18, pp. 944-958.
- Parrish, R.R. 1984. Slocan Lake Fault: a low angle fault zone bounding the Valhalla gneiss complex, Nelson map area, southern British Columbia. In Current Research, Part A, Geological Survey of Canada, Paper 84-1A, pp. 323-330.
- Parrish, R., Carr, S.D. and Parkinson, D. 1985a. Metamorphic Complexes and Extensional Tectonics, Southern Shuswap Complex, southeastern British Columbia. In, Field Guides to Geology and Mineral deposits in the Southern Canadian Cordillera, Geological Society of America, Cordilleran Section Meeting, pp. 12.1-12.15.
- Parrish, R., Carr, S.D. and Brown R.L. 1985b. Valhalla gneiss complex, southeast British Columbia: 1984 Fieldwork. In, Current Research, Part A, Geological Survey of Canada, Paper 85-1A, pp. 81-87.
- Platt, J.P. 1984. Secondary cleavages in ductile shear zones. Journal of Structural Geology, 6, pp. 439-442.
- Platt, J.P. and Vissers, R.L.M. 1980. Extensional structures in anisotropic rocks. Journal of Structural Geology, 2, pp. 397-410.
- Preto, V.A. 1970. Structure and petrology of the Grand Forks Group, British Columbia. Geological Survey of Canada, Paper 69-22, 80 p.
- Price, R.A. 1979. Intracontinental ductile crustal spreading linking the Fraser River and northern Rocky Mountain Trench transform fault zones, south-central British Columbia and northeast Washington. Geological Society of America, Abstracts with Programs, 11, 6:A-47.
- Price, R.A. 1981. Eocene stretching and necking of the crust and tectonic unroofing of the Cordilleran metamorphic infrastructure, southeastern British Columbia and adjacent Washington and Idaho.

Geological Association of Canada, Programme and Abstracts, p. A47.

Read, P.B. 1979. Relationship between the Shuswap Metamorphic Complex and Kootenay Arc, Vernon east-half, Southern British Columbia. In, Current Research, Part A, Geological Survey of Canada Paper 79-1A, pp. 37-40.

Read, P.B., and Wheeler, J.O. 1976. Geology of Lardeau west-half map area. Geological Survey of Canada, Open-File Map No. 432.

Read, P.B., and Brown, R.L. 1981. Columbia River fault zone: southeastern margin of the Shuswap and Monashee complexes, southern British Columbia. Canadian Journal of Earth Sciences, 18, pp. 1127-1145.

Reesor, J.E. 1965. Structural evolution and plutonism in Valhalla gneiss complex, British Columbia. Geological Survey of Canada, Bulletin 129, 128 p.

Rhodes, B.P. and Cheny, E.S. 1981. The low-angle Kettle River Fault: The eastern contact of Kettle Dome, northeast Washington. Geology, 9, pp. 366-369.

Sibson, R.J. 1977. Fault rocks and fault mechanisms. Journal of the Geological Society of London, 133, pp. 191-213.

Simony, P.S. 1979. Pre-Carboniferous basement near Trail, British Columbia. Canadian Journal of Earth Sciences, 16, pp. 1-11.

Simpson C. and Schmid, S.M. 1983. Microstructural indicators of sense of shear in shear-zones. Bulletin of the Geological Society of America, 94, pp.1281-1288.

Simpson, C. 1985. Deformation of granitic rocks across the brittle - ductile transition. Journal of Structural Geology, 7, pp. 503-511.

Tempelman-Kluit, D. 1984. Meteoric water model for gold veins in a detached terrane. Geological Society of America, Abstracts with Programs, p. 674.

Tipper, H.W. 1981. Offset of an upper Pliensbachian geographic zonation in the North American Cordillera by transcurrent movement. Canadian Journal of Earth Sciences, 18, pp. 1788-1792.

Tipper, H.W. 1984. The age of the Jurassic Rossland Group of Southeastern British Columbia. In, Current Research, Part A, Geological Survey of Canada, Paper 84-1A, pp. 631-632, 1984.

Tipper, H.W., Woodsworth, G.J., and Gabrielse, H. 1981. Tectonic Assemblage Map of the Canadian Cordillera and adjacent parts of the United States of America. Geological Survey of Canada, Map 1505A.

White, S.H. 1976. The effects of strain on the microstructures,

fabrics and deformation mechanisms in quartz. Philosophical Transactions of the Royal Society of London, Series A, 273, pp. 69-86.

White, S.H., Burrows, S.E., Carreras, J., Shaw, N.D., and Humphreys, F.J. 1980. On mylonites in ductile shear zones. Journal of Structural Geology, 2, pp. 175-187.

Winkler, H.G.F. 1979. Petrogenesis of Metamorphic Rocks. Springer-Verlag, New York, Fifth edition, 348 p.

1 OF/DE

MAP 1: GEOLOGY OF THE VALHALLA COMPLEX

2 OF/DE

3
F/DE

MIDDLE JURASSIC

mJgd NELSON BATHOLITH AND SATELLITES: GRANODIORITE (mJgd),
gabbro, and other rocks (gabbro)

5
OF/DE

SCALE = 1:25,000

INSET

SCALE = 1:25,000

INSET

8 OF/DE

S E L K I R K

I C O L U M B

LEGEND

EOCENE

Ecsy CORYELL PLUTONIC ROCKS: LEUCOCRATIC, COARSE GRAINED, HORNBLende SYENITE (52 Ma), WITH MINOR BIOTITE AND CLINOPYROXENE BEARING DIORITE

PEg LEUCOCRATIC BIOTITE QUARTZ MONZONITE TO GRANITE (58 Ma)

PALEOCENE

Pgm K-FELDSPAR MEGACRYSTIC BIOTITE + HORNBLende QUARTZ MONZONITE (63 Ma)

CRETACEOUS (ORDER DOES NOT IMPLY RELATIVE AGE)

qm, g GRANITIC STOCKS: LEUCOCRATIC BIOTITE QUARTZ MONZONITE TO GRANITE

uKgn KINNAIRD GNEISS: LEUCOCRATIC HORNBLende + BIOTITE ORTHOGNEISS; CAN HAVE K-FELDSPAR AUGEN, LEUCOCRATIC VEINS AND PEGMATITE, QUARTZ POOR PHASES (LATE CRETACEOUS)

uKgn MELANOCRATIC BIOTITE-HORNBLende AUGEN GRANODIORITIC GNEISS (90 Ma) WITH LEUCOCRATIC GRANITOID VEINS OF UNCERTAIN AGE

JURASSIC AND/OR CRETACEOUS

gd GRANITIC PLUTONS: PREDOMINANTLY GRANODIORITE, AND QUARTZ DIORITE

MIDDLE JURASSIC

mJgd NELSON BATHOLITH AND SATELLITES: GRANODIORITE (mJgd), HORNBLende QUARTZ SYENITE (mJsy), AND MINOR GRANITE (mJg)

UPPER TRIASSIC

Ksg SLOCAN GROUP: SLATE, ARGILLITE PHYLLITE, CALCAREOUS AND ARENACEOUS INTERBEDS

PALEOZOIC AND TRIASSIC

P-Tms NEMO LAKES BELT: POLYDEFORMED SEMI-PELITE AND PELITE, CALCAREOUS SCHIST, AMPHIBOLITE AND ULTRAMAFIC ROCKS

PENNSYLVANIAN (?)

22°15'

MAGNETIC NORTH

9

F/DE

MIDDLE JURASSIC

mJgd NELSON BATHOLITH AND SATELLITES: GRANODIORITE (mJgd),
HORNBLende QUARTZ SYENITE (mJgy), AND MINOR GRANITE (mJg)

UPPER TRIASSIC

Tsg SLOCAN GROUP: SLATE, ARGILLITE PHYLLITE, CALCAREOUS AND
ARENACEOUS INTERBEDS

PALEOZOIC AND TRIASSIC

P-Tms NEMO LAKES BELT: POLYDEFORMED SEMI-PELITE AND PELITE,
CALCAREOUS SCHIST, AMPHIBOLITE AND ULTRAMAFIC ROCKS

PENNSYLVANIAN (?)

Pmr MOUNT ROBERTS FORMATION: LIMESTONE, ARGILLACEOUS QUARTZITE AND
GREENSTONE

PRE - MIDDLE JURASSIC (ORDER DOES NOT IMPLY RELATIVE AGE)

ms PARAGNEISS: POLYDEFORMED METASEDIMENTARY ROCKS INTRUDED BY
LEUCOCRATIC ORTHOGNEISS AND PEGMATITE OF UNCERTAIN AGE

cgn CASTLEGAR GNEISS: HETEROGENEOUS HORNBLende ± BIOTITE QUARTZO-
FELDSPATHIC PARAGNEISS, AMPHIBOLITE, CALC-SILICATES, GRANITIC
LAYERS

GEOLOGIC CONTACTS: MAPPED, ASSUMED

FOLIATION AND DIP OF FOLIATION

92, 200 FIELD STATION LOCATIONS: (S. CARR; R. PARRISH AND S. CARR)

VALKYR SHEAR ZONE: HALF CIRCLE ON UPPER PLATE; MAPPED OR
ASSUMED, INFERRED

SLOCAN LAKE FAULT ZONE: MAPPED, ASSUMED, INFERRED

GWILLIM CREEK SHEAR ZONES:

BRITTLE FAULT: PEG ON UPPER PLATE

MAP IS MODIFIED FROM REESOR (1965), PARRISH (1981, 1984), LITTLE (1960)
AND READ AND WHEELER (1976). AGES IN BRACKETS ARE FROM PARRISH (1984)
PARRISH ET AL. (1985) AND PARRISH UNPUBLISHED DATA (1985), SEE
APPENDICES 1, 2, AND 3.

LOCATION OF MAP AREA

SCALE = 1:100,000

10 OF/DE 10

END

FIN

2 04 87