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LA THÈSE A ÉTÉ MICROFILMÉE TELLE QUE NOUS L'AVONS RECEUE
STRUCTURAL SETTING OF THE DOWNIE SLIDE,
NORTHEAST FLANK OF FRENCHMAN CAP GNEISS DOME,
SHUSWAP COMPLEX, SOUTHEASTERN BRITISH COLUMBIA

by

John Francis Pautke, B.Sc.

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

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ABSTRACT

The Downie Slide, a post-glacial rockslide on the west bank of the Columbia River 70 km north of Revelstoke, British Columbia, is geometrically controlled by the position and attitude of second and third generation structures developed on the north-east flank of Frenchman Cap gneiss dome. The early structural history of the region set the scene for future slope instability, when erosion exposed these structures to their present level.

Three phases of deformation are recognized in the Downie Slide area. No major first or second generation fold closures were encountered in the region, but structural and stratigraphic evidence indicate the stratigraphic succession lies on the overturned limb of a second phase antiformal syncline with limbs exceeding 15 km in length. The third phase of folding dominates the region west of the Downie Slide. Stratigraphy is carried over the northern culmination of Frenchman Cap dome by west dipping Phase 3 axial surfaces. These structures are common in the metasedimentary cover rocks that envelop the dome, but are also contained within rocks that have previously been mapped as core gneisses.

A stratabound zone of cataclastic deformation is exposed in the Columbia River valley. A preliminary examination of the nature of the deformation revealed that cataclasis occurred during the second phase of deformation.

The possibility of normal faulting immediately east of the cataclastic zone is proposed to explain the juxtaposition of lower greenschist rocks of the Selkirk Mountains against upper amphibolite facies rocks of the Shuswap Metamorphic Complex.
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I wish to extend my gratitude to all those members of British Columbia Hydro whom I have had the pleasure of coming into contact with throughout the course of this project. Especially, I am indebted to Dennis Moore and Peter Lang of Hydro for their unceasing cooperation and enlightening discussions on many aspects of the Downie Slide. Dr. R.L. Brown is gratefully acknowledged for his patient guidance and supervision over this study. I would like to thank Greg Crowe for his worthy assistance in the field, and Ross Taylor and Ron Conlon for the preparation of numerous thin sections.

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CHAPTER 1

INTRODUCTION

The eastern margin of the Shuswap Metamorphic Complex is characterized by three major domal complexes (Fig. 1); from south to north these are Valhalla (Reesor, 1965), Thor-Odin (Reesor and Moore, 1971) and Frenchman Cap (Fyles, 1970; McMillan, 1973, 1970). Other projects have been undertaken along the eastern margin of the complex by Ross (1968) and Little (1960) (Figs. 1, 2).

The area to be discussed in this study straddles the northeastern flank of Frenchman Cap gneiss dome (Fig. 2), the most northerly of the domal complexes. The dome is bounded on the east by lower Paleozoic to Windermere (Proterozoic) metasedimentary rocks and on the north, south and west flanks by as yet undivided paragneisses, granitic gneisses and siliceous and calcareous metasediments (Wheeler, 1965). The core gneisses of the dome are composed of mixed gneisses, homogeneous granite-gneiss and swirled gneissic granite and are enveloped by a thick succession of schists and paragneisses (Wheeler, 1965).

Recent work centred around Frenchman Cap dome (Fig. 2) includes regional mapping by Wheeler (1965) and detailed structural and stratigraphic studies by Ross (1968) in the Clachnacudainn Salient; Fyles (1970) on the south flank of the dome; McMillan (1973) on the west flank, and outside of Shuswap terrane by Lane (1977) in the Selkirk Mountains directly east of the present study area.

The Downie Slide (Plate 1a), a post-glacial rockslide on the west bank of the Columbia River 70 km north of Revelstoke,
Figure 1. Regional geological setting of the Shuswap Metamorphic Complex in southeastern British Columbia (from Reesor and Moore, 1971). Important studies have been carried out on the eastern margin of the complex by:

A - Wheeler (1965)
B - Ross (1968)
C - Reesor and Moore (1971)
D - Reesor (1965)
E - Little (1960)

Zones of cataclastic deformation are shown in wavy lines.
Figure 2. Local geological setting of Frenchman Cap gneiss dome. Recent studies conducted in the area are outlined. (G.R. = Goldstream River) (after Wheeler, 1965)
involved high grade pelitic and semipelitic schists of the Shuswap Metamorphic Complex. The prime objective of an extensive geological mapping program, conducted by the author in the Downie Slide area, was to obtain information concerning the regional structural and stratigraphic setting of the Downie Slide, in accordance with a research project proposed by British Columbia Hydro and Power Authority. Since about 1973, B.C. Hydro has been occupied with an extensive exploratory program dealing directly with the Downie Slide: collecting groundwater information, monitoring slope movements, defining sub-surface shear zones by seismic methods and undertaking remedial measures to stabilize the slope. The Authority requested that mapping be extended beyond the limits of the slide to assess the regional structural and stratigraphic relationships with respect to the slide.

The ridge mapped in this study contains a thick succession of paragneisses and metasediments which flank the northern culmination of Frenchman Cap gneiss dome about 6 km north of Pettipiece Pass (Fig. 2) and is informally referred to here as "Pettipiece Ridge" (Fig. 3).
CHAPTER 2

HISTORY OF THE DOWNIE SLIDE

The Downie Slide (Plate 1a) is a prehistoric rockslide situated on the west bank of the Columbia River 70 km north of Revelstoke, in southeastern British Columbia. It has been estimated to involve 750 million $m^3$ of material covering an area of about 10 $km^2$ and is ranked as one of, if not the largest, recorded rockslide in the world. It has a roughly lobate outline in plan, the toe of which extends 3.5 km along the west bank of the Columbia River. The slide mass extends from an elevation of 497 m (1630ft) at river level to a prominent Head scarp at about 1524 m (5000ft) elevation (Plate 1a).

The slide was first recognized by Jones (1952) during reconnaissance mapping of this section of the valley for a future damsite. Following recognition of the rockslide and the potential hazards it posed for future hydroelectric developments along the river, British Columbia Hydro initiated an extensive investigative program to monitor and provide information on the kinetics of the slide and ultimately to take remedial measures to stabilize it.

The slide is bounded on the west and south by nearly vertical escarpments reaching heights of more than 125 m (Fig. 3). The northern boundary is less prominent, defined by a low east trending ridge that dies out below about 1067 m (3500ft) elevation.

Early slide movements have caused the toe to deflect the river’s course eastward, where it has produced extensive undercutting of the east bank resulting in steep cliffs and talus slopes more than 200 m high. Buried river gravels encountered in at least
two drillholes (B.C. Hydro, 1976; 1974) near the toe indicate that a buried river channel exists west of the present course of the river. At present, downslope creep is in equilibrium with erosion of the toe by the river.

Drillhole and seismic data (B.C. Hydro, 1976; 1974) indicate the sliding surface is essentially restricted to a single gouge-bearing shear zone at a depth of 185-245 m below the surface, subparallel to the slope of the hillside. The main shear zone does not outcrop at the surface but is believed to toe-in below river level. An auxiliary shear zone lying above the principal shear zone has been encountered in several drillholes (B.C. Hydro, 1976; 1974). This zone is narrower and discontinuous and is believed to have contributed little to the total downslope displacement. Surface observations and drillhole information indicate that the slide was displaced primarily as a cohesive slab of rock rather than a rubble slide.

Assuming the slide mass advances as a rigid body, surface movements recorded on straight line surveys across the lower reaches of the slide indicate net downslope displacements ranging from 23-48 cm over a ten year period (Nov. 1965 to Oct. 1975, B.C. Hydro, 1976). Farther up the slope, triangulation surveys indicate about 15 cm of upslope movement where possibly a zone of backward rotation is in effect (Piteau, Mylrea and Blown, 1973).

The most accurate limits that can be placed on the age of the slide are bracketed by the last period of glaciation (23,000 yrs) and the Mazama volcanic event (6,600 yrs, Piteau, Mylrea and Blown, 1973). The 20,000 year lower limit is valid if it is assumed that the slide was not activated until after the
last period of glaciation which in this area commenced about
23,000 years ago. Dating of a volcanic ash layer found in the
soil on the slide establishes an upper age limit. The ash is
correlated with the Mazama ash fall, an event originating at
Crater Lake, Oregon 6,600 years ago.

It is quite probable that pore water pressure beneath
the lower shear zone has contributed to the instability of the
slide. Remedial measures to stabilize the slide have begun with
the construction of two drainage adits scheduled to penetrate
sound rock below the lower shear horizon. In 1974, construction
of Adit 1 (2,000 ft el., centre of the slide) was halted due to
unstable ground conditions before reaching the upper shear zone,
but water tests performed in 1974, 1975 and 1976 showed ground-
water levels decreased substantially in the area immediately
surrounding the adit. Success with Adit 1 led to proposals for
construction of another adit farther to the north. Construction
of Adit 2 commenced during the summer of 1977.
CHAPTER 3

STRATIGRAPHY

The rocks exposed in the ridge west of Downie Slide, informally referred to as "Pettipiece Ridge" (Fig. 3) (all informal geographical names coined by the author will hereafter be enclosed in quotation marks), can be divided into three major groups in order of decreasing relative age, established by reliable stratigraphic facing directions. From west to east these are:

1) Paragneisses
2) Metasedimentary cover rocks
3) Granitic intrusion

These have been further subdivided into eleven mappable units (Fig. 3). Field stratigraphic descriptions and measured thicknesses of individual beds comprising the major units are presented in Appendix 1. Regional stratigraphic correlations between Fyles (1970), McMillan (1970, 1973) and this work are discussed in Appendix 2.

Paragneisses

Introduction

The lowermost units in the stratigraphic succession are composed of alkali feldspar augen paragneisses and amphibolitic, semipelitic and psammitic paragneisses (Units 1 and 2). Both of these units display well defined bedding indicating that they are indeed of sedimentary origin. Viewed from a distance, the light, uniformly coloured paragneisses of Unit 1 lie in remarkable
contrast to the overlying rusty-brown weathering paragneissess (Unit 2) and laminated metasedimentary cover rocks (Plate 1b). Wheeler (1965) included these rocks in the core gneisses of Frenchman Cap gneiss dome, but they seem to differ significantly from descriptions given for exposures of migmatitic core gneisses to the south in the region of Frenchman Cap peak.

Unit 1 (1500+ m thick)

A thick package of alkali feldspar augen paragneissess is exposed to the extreme west of the map-area. Interbedded with these are inliers and interbeds of silvers to rusty-brown pelites, some of which reach thicknesses of 10 to 15 m. These pelitic layers display a strong foliation defined by biotite or muscovite, and contain quartz and plagioclase; kyanite and sillimanite commonly occur as accessories.

This unit is texturally distinct from all others in the map-area. In the field it is more homogeneous and contains large alkali feldspar augen ranging from 4×10× mm to 1.5×6 cm in cross-sectional dimensions (Plate 1c); on a microscopic scale it has myrmekitic intergrowths of quartz and feldspar. The augen are set in a foliated semipelitic groundmass composed of quartz, plagioclase, potassium feldspar, hornblende, biotite and subhedral garnets. Sphene and zircon are present as accessories. In some areas augen have bulbous to sinusoidal shapes with distinct tails, while in other areas they thin considerably at the ends but continue for 10 to 15 cm into the groundmass, suggesting they could have been generated by intense stretching of primary psammitic layering.
Sodium cobaltinitrite staining revealed compositional zoning in the more bulbous augen, with a thin (1–2 mm) plagioclase rim enclosing an alkali feldspar core. In areas where augen are poorly defined, there is a consistent pattern of alternating plagioclase and alkali feldspar layering separated by thin quartz laminations.

A 5x10 m ultramafic pod was observed on "Pettipiece Ridge" about 1000 m west of the contact between Units 1 and 2 (Fig. 3). It contains a massive hornblende-rich core with a 1 m wide garnet, biotite-rich rim. No other ultramafic bodies were observed in the area.

Pegmatite constitutes a very minor proportion of the unit and thin discontinuous amphibolite and psammitic layers are rare.

Unit 2

(estimated thickness - 1000 m)

Conformably overlying Unit 1 is a thick sequence of thinly bedded striped and banded amphibolites, psammites, semipelites and pelites. Near the base, interbedded amphibolites and psammites exhibit migmatitic layering (Plate 1d). These lithologies grade upward into continuously layered interbeds of rusty pelite and semipelite. Also near the base are a series of feldspar augen paragneisses and feldspathic grit horizons, which may be interpreted as metaconglomerates. No direct unconformable relationships were observed at the contact between Units 1 and 2.

To the south, McMillan (1970) describes equivalent stratigraphy on the west flank of Frenchman Cap dome, but in that
region they are highly migmatitic, and amphibitic mafic gneisses are cut extensively by pegmatite.

Metasedimentary Cover Rocks

Introduction

The metasedimentary cover rock sequence comprises a 2000 m thick succession of pelites, semipelites, calcsilicates, quartzites and marbles extending from Seymour Creek (Fig. 3) to the Columbia River. The contact with the underlying paragneisses is conformable. Several distinct quartzite and marble horizons exposed in "Pettipiece Ridge" serve as invaluable marker horizons that can be traced for several kilometres along strike and aid in measuring structural thicknesses of the major rock units.

Only one appreciable facies change is recognized in the area. This occurs in Unit 7c, a grey, calcsilicate-bearing marble on the east bank of the Columbia River which grades into a clean white marble in the vicinity of Fissure Creek (Fig. 3).

Amphibolites are extremely rare in the cover rocks.

Unit 3

(measured thickness: 300 m)

The lowermost contact of Unit 3 is marked by a 20 m thick psammite bed with minor black semipelite layers. Three distinct quartzite beds have been distinguished in the field and are referred to here as lower, middle and upper quartzites according to their relative stratigraphic position in Unit 3.

The lower quartzite (Unit 3c = top of Unit 2, Fig. 3)
is a 5 m thick white to pink weathering quartzite laminated on a few centimetres scale and immediately underlain by a 5 m thick foliated rusty-black pelite layer. Above the lower quartzite lies a package of thinly interbedded semipelites, psammites and biotite-rich calc-silicates locally containing 2 m wide black calc-silicate pods.

The middle quartzite (Unit 3b, Fig. 3) ranges from 50 m thick in the hinges of third phase synclines to as little as 5-10 m on the upper limbs of third phase anticlines. In some areas the quartzite pinches out completely and where this occurs stratigraphic control is maintained by tracing units that immediately lie above and below the quartzite. Much of the thickening in the hinge zones of third phase synclines is tectonic, controlled primarily by refolding of second phase structures. This has been clearly documented by overprinting relationships on all scales at several localities west of "Downie Knoll" (Fig. 3). One such structure exposed about 1200 m southeast of "Ptarmigan Peak" (Fig. 3) is illustrated in Plate 2f.

A few minor discordant amphibolite bands occur locally about 1000 m east of "Ptarmigan Peak".

Above the middle quartzite lies a succession of thinly laminated impure marbles, black, grey and silver semipelites, psammites, calc-silicates and a distinct plagioclase augen semipelite. These beds also vary in thickness according to their position on the megascopic folds.

The upper quartzite (Unit 3a, Fig. 3), a 3-4 m thick buff weathering quartzite marks the top of Unit 3.
Unit 4 (measured thickness: 370 m)

Unit 4 in general represents a graded sequence of rocks, marked at the base by quartzofeldspathic grit and psammitic layers which pass upwards through semipelites and pelites to quartzites and marbles.

The base of Unit 4 is composed primarily of calcareous psammitic and quartzofeldspathic grits that are thinly interbedded with semipelite, calcsilicate and minor impure calcsilicate-bearing marbles. A stratigraphic top determination made in graded grit beds near the base of the unit indicated that the succession is in a right-way-up position. These grits grade upward into a thick black to rusty biotite-rich pelite and semipelite succession interspersed with layers of calcsilicate, psammitic and thin quartzites. A distinct black magnetic calcsilicate occurs in this (lower) part of the unit.

Overlying the pelite, semipelite succession is a 30 m thick sequence of impure scapolite-bearing marbles locally containing thin pelite chip layers. Near the upper contact is a distinctive 4 m thick white calcareous marble immediately underlain by a 6 m thick buff weathering quartzite. The contact between the two lithologies is sharp and no pelitic material was found in either bed. Deep solution cavities have developed in the marble at one locality in particular, northwest of Watam Lake (Fig. 3), where the bed is tilted into a near vertical orientation (Plate 1e) on the limb of a synclinal structure. The marble band was traced from east of Watam Lake, across "Pettipiece Ridge" and down the south slope of Fissure Creek (Fig. 3). It crosses Fissure Creek
in the vicinity of Tufa Springs (Fig. 3) and can be traced west along the steep northern slopes of Fissure Creek.

Tufa Springs, an informal name assigned to a terraced tufa deposit by British Columbia Hydro, discharges into Fissure Creek at about 735 m (2300 ft) elevation (Plate 2a). The deposit appears to be relatively old because ancient tufa deposits are deeply buried under overburden and a tall mixed forest to the west. The deposit has become extremely porous as a result of dissolution of organic matter leaving leaf and twig casts, and 20 cm diameter solution channels are common in older terraces to the west.

Although the marble is not exposed at Tufa Springs due to heavy overburden, stratigraphy exposed directly above it at "Downie Knoll" was recognized both upslope of Tufa Springs and in a cliff face on the north slope of Fissure Creek about 800 m northeast of Tufa Springs (Station Pl81, Fig. 4). Stratigraphic information gained in the Tufa Springs area and structural evidence obtained from the South Scarp (Fig. 5) suggest the white marble is not significantly influenced by megascopic structures in this area, and therefore should lie at about the same elevation as the spring. Water entering the rocks via solution cavities in the Watam Lake region is presumably able to percolate downslope (eastward) through the marble, dissolving carbonate and depositing it where it emerges at Tufa Springs. Similar springs were observed flowing from the same white marble on the north slope of Fissure Creek (Peter Lang, pers. comm. 1977).

The upper contact of Unit 4 is marked by a white to pink weathering quartzite that is immediately underlain by a 3 m thick
non-magnetic calcsilicate bed and directly overlain by a strongly magnetic calcsilicate bed.

Unlike the sequence below the white marble (Unit 4b), the upper sequence consists of a rusty pelite and semipelite succession that contains abundant calcsilicate horizons and cleaner marbles.

Unit 5  
(measured thickness: 120 m)

Unit 5 is recognized as the thickest single succession of quartzofeldspathic grits in the area. Interbedded with the thick gritty layers are thin semipelite and pelite beds. The feldspathic grit fraction is composed solely of plagioclase. Quartz and plagioclase clasts are typically lensoidal, and flattened in the foliation plane. Stratigraphic facing directions determined from graded grits at two independent localities in this unit again indicate the succession is right way up (Plate 2b).

Unit 6  
(estimated thickness: 400 m)

Above the grit unit lies a thick monotonous succession of pelites, semipelites and psammites interbedded on a scale of centimetres to tens of metres, containing local occurrences of quartzite, graphitic marble and various calcsilicate layers near the upper contact. The unit rests on a dip slope of the eastern flank of "Pettipiece Ridge" in which the Downie Slide is involved (Fig. 3).

Exposures of Unit 6 outcrop on the east bank of the Columbia River, directly across from the South scarp (Fig. 6), on Fissure Creek from 595 m (1950 ft) elevation westward to near
Tufa Springs and from the west bank of the river to "Downie Knoll" (Fig. 3).

Where stratigraphic control was poor as in the tree covered region between Head scarp and "Downie Knoll", rock units were grouped into two broad categories, pelite and semipelite. Lithologic variations in Unit 6 could only be mapped in cliff exposures in the Head and South scarp region (Fig. 3). Exposed at the base of Head scarp and in the upper (western) part of South scarp is a 30 m thick black biotite-rich pelite. Above this is a 30 m thick bed of pelite with thin discontinuous psammite and semipelite interbeds 4-6 cm thick. Occupying the top of Head scarp for nearly its entire length is a thickly bedded psammite and semipelite unit.

An easterly younging stratigraphic sequence may be established by mapping down the South scarp to the river as bedding dips east, slightly steeper than the slope. Progressing up-section from Head scarp, the rocks grade from pelitic to siliceous, and drillhole data on the Downie Slide (B.C. Hydro, 1974) indicate that a number of thin calcsilicates, graphitic marble and quartzite layers exist near the upper contact of Unit 6.

Contacts between the following map units (7 - 11) cannot everywhere be accurately mapped in the field due to poor exposure in the valley bottom.

Unit 7

(estimated thickness: 110 m)

The upper siliceous sequence of Unit 6 passes upward
into a dominantly calcareous and quartzitic succession (Unit 7, Fig. 6). The contact between Units 6 and 7 in the southern part of the area trends north parallel to the river, but swings westward just upstream of Sentinel rock (Fig. 6). Sub-units 7c, 7d and 7e have distinct lithologies (Legend, Fig. 6) and thus serve as useful marker horizons which have been traced across the river to Adit 2 on the west bank (Fig. 6). From the adit, the three sub-units trend north again and have been traced as far north as Fissure Creek (Fig. 6). The contact between Units 6 and 7 has not been directly observed in the field, but exposures have been mapped to within about 5 m of the actual boundary, at Fissure Creek, approximately 800 m west of the Columbia River (Fig. 6). At this locality (Station PO91, Fig. 7) the lowest recognizable bed belonging to Unit 7 is a thin layer of graphitic marble, below which lies a semipelite, psammite and quartzite sequence belonging to the siliceous upper sequence of Unit 6. The contact lies unexposed in the bed of Fissure Creek. The graphitic marble is sheared, but this is generally the case in the valley because marbles lie in direct contact with more competent rocks, generally quartzite. A similar contact relationship may be observed at the base of the grey marble (7c) on the east bank of the Columbia River across from the toe of the Downie Slide (Plate 2c, Station PO11, Fig. 7). The lower contact of sub-unit 7c, a thick calc-silicate-bearing marble with a 2-3 m wide graphitic shear zone at the base, is in contact with quartzite and semipelite beds.

Above the marble is a thickly to thinly bedded white to rust coloured quartzite, containing discontinuous calc-silicate layers and boudins. The upper contact of Unit 7 is marked by a
distinctive silver-weathering semipelite containing 1-1.5 cm long kyanite porphyroblasts.

Unit 8  (estimated thickness: 200 m)

Unit 8 is a white to rusty weathering massive to foliated fine-grained (cataclastic) quartzite in the northern extremity of the unit, to semipelitic composition in the south. The base of the unit is occupied by hornblende-bearing calcisilicate gneisses. Interbedded with the quartzite are beds of white to light pink kyanite-bearing muscovite-rich semipelite up to 5+ m in thickness. Outcrops of these layers can be observed along the Old Big Bend highway (Fig. 6), directly across the river from the North scarp of Downie Slide.

Unit 9  (estimated thickness: 295 m)

Pink, blue-grey and green calcareous quartzofeldspathic grits and gneisses are exposed along a section of the New Big Bend highway across from the North scarp (Fig. 6). Compositional layering ranges in thickness from one to tens of metres. Gritty and brecciated serpentine-bearing rocks are abundant near the base of the unit and most exposures are cut by pegmatite dykes and contain pegmatite boudins.

Unit 10  (estimated thickness: 100 m)

Light grey semipelite interlayered with psammitic and quartzofeldspathic beds 1–3 m thick outcrop north of Unit 9 along
the New Big Bend highway (Fig. 6). The unit becomes more thickly bedded and more pelitic northward, towards the upper contact, where a number of granodiorite dykes intrude the semipelite. Dyke contacts occur at both high and low angles to the regional bedding attitudes. Mineral assemblages in this unit contain quartz, plagioclase, biotite, garnet - sillimanite.

Granitic Intrusion

Unit 11 (estimated thickness: 500+ m)

A white, foliated biotite granodiorite intrusion occupies the eastern margin of the map-area. Texturally it is homogeneous with at least a two-phase intrusive history. Foliation, defined by biotite flakes, becomes progressively stronger westward and a zone containing angular xenoliths of metasedimentary rock is present near the western contact (Fig. 8). Relative timing of intrusive events has been documented by direct observation of cross-cutting relationships in the field. They are as follows:

1a) Intrusion of strongly foliated (biotite-rich) granodiorite phase into calcsilicate and rusty semipelitic metasediments.

1b) Pegmatite dykes and dykelets cut strongly foliated granodiorite phase.

2a) Weakly foliated (biotite-poor) granodiorite phase intrudes strongly foliated granodiorite phase.

2b) Pegmatite dykes cut strongly and weakly foliated granodiorite phases.
Figure 8. Schematic plan view of the eastern margin of the map-area, showing the contact relationships between the granodiorite intrusion and the metasedimentary country rocks. Xenoliths at A were not directly observed in the field but can be inferred from the xenolith (B) in the weakly foliated phase (see Plate 2d).
Plate 2d illustrates a part (1a, 2a above) of the intrusive relationships of the granodiorite intrusion.

The nearest metasediments to the pluton lie just to the north and east of the map-area; their age is still uncertain but they have been tentatively assigned to the Lower Cambrian and later Lardeau Group (Wheeler, 1965) of the Selkirk Range. To the west, the nearest metasediments (muscovite-rich pelite) outcrop at about 700 m (2300 ft) elevation in the valley bottom (Station P055, Fig. 7) and they are thought by the author to belong to Shuswap stratigraphy.
CHAPTER 4

STRUCTURE

Introduction

Two prominent structural features exist in the region east of the northern culmination of Frenchman Cap gneiss dome:

1) A distinct overprinting of younger (Phase 3) structures over older structures (Phase 2) occurs in the area west of the Head scarp. Second phase structures dominate the area east of Head scarp, and the third phase of deformation governs the structural geometry west of Head scarp.

2) A stratabound cataclastic zone generated in association with the second phase of deformation occupies the eastern boundary of the Shuswap Complex, isolating these rocks from the quite different stratigraphy of the Selkirk Mountains to the east.

Cataclastic deformation can be traced south along the eastern flank of the Shuswap Complex from Goldstream River, about 10 km north of the thesis area, to Revelstoke (Wheeler, 1965; this work) and similar zones have been recorded in the same structural position at Thor-Odin gneiss dome (Reesor and Moore, 1971), Valhalla Gneiss Complex (Reesor, 1965) and in the Nelson map-area (Little, 1960) (all shown in Fig. 1). Also, mylonitic rocks mapped by Ross (1968) along Laforme Creek on the northeastern margin of the Clachnacudainn Salient northeast of Revelstoke (Fig. 2) may be an auxiliary branch off the main cataclastic zone in the Columbia River valleys. The cataclastic zone will be discussed in more detail at the end of this chapter.
Unit 1, as described earlier, is the lowermost stratigraphic unit exposed in the "Pettipiece Ridge" area (Fig. 3) but is not the lowest unit in the core of Frenchman Cap gneiss dome. True granitic core gneisses are exposed farther to the south in the area immediately southwest of Frenchman Cap peak (Wheeler, 1965; McMillan, 1970; Fig. 2). The metasedimentary cover rocks are carried over the dome by westward verging third phase structures controlled by west dipping axial surfaces.

The thesis area has been subdivided into six structural sub-areas according to variations in structural trends (Fig. 5, key to sub-areas). To prevent clutter, only representative trends are plotted on the map, but all structural measurements for the six sub-areas have been plotted on equal-area stereographic projections (Fig. 5).

Structural maps have been prepared on two scales to illustrate regional trends (Fig. 5) and local structural features around the toe of the Downie Slide (Fig. 9). A composite cross-section was constructed in four sections along "Pettipiece Ridge", South scarp and the east slope of the Columbia River valley (Fig. 5). Interpretation of segment F-G may be oversimplified due to a lack of exposure in this area.

Three phases of deformation are recognized in the Downie Slide area. McMillan (1973) and Fyles (1970) documented two major phases to the south, followed by a weak third phase that deformed second phase axial surfaces into open megascopic warps and generated kink bands on a microscopic scale. All three phases appear to have had a significant effect on the rocks of the study area, but any one particular area is dominated by a single phase
dominated by a single phase (Phase 2 or Phase 3).

Structural Geometry

Phase 1

Small-scale, first generation folds are most commonly observed east of "Downie Knoll" (Fig. 5). Primary bedding on the limbs of these folds is essentially parallel to first phase axial surfaces defined by a strong mica cleavage, except in the hinge areas where the cleavage transects bedding at a high angle. Folds are typically isoclinal, having attenuated limbs and substantially thickened hinges regardless of rock type (Plate 2e).

No large-scale folds related to the first phase of deformation have been recognized in the study area. Reliable stratigraphic top determinations in graded grit beds consistently indicate that the stratigraphic sequence is in a right-way-up position. Nowhere was a reversal in tops observed. Thus, if the region has been isoclinally folded, the rocks of the study area must lie on a right-way-up limb of a fold with limb lengths in excess of 15 km.

Phase 2

Phase 2 folds are recognized throughout the entire study area, but megascopic structures prevail east of Bead scarp. They are characterized by having more open limbs than Phase 1 structures, an axial plane cleavage ($S_2$) subparallel to $S_1$, and they fold pre-existing (Phase 1) structures (Plate 2e). There is moderate thickening in hinges and attenuation of the limbs in folds involving
Micaceous layers.

Megasopic second phase fold structures in the South scarp and around the lower reaches of Fissure Creek are generally recognized only through careful mapping of bedding/cleavage relationships rather than minor folds which are rare in these areas. In contrast to this, bedding/cleavage relationships west of Head scarp become obscure and second phase minor folds are common, especially in the hinges of younger third phase folds (Plate 2f). A strong colour streaking defined by $S_1/S_2$ intersections can be mapped westward from the saddle immediately west of "Downie Knoll".

The largest second phase closures mapped west of Head scarp are cored by the middle quartzite of Unit 3 (3b) below "Ptarmigan Peak" (Fig. 5) and just west of the headwaters of the Fortynine Creek. Here the second phase structures have the same general sense as the folds interpreted in the Columbia River valley and when used in conjunction with stratigraphic facing directions indicate that the rocks lie on the overturned limb of a westward closing antiform syncline.

Minor folds and bedding/cleavage intersections mapped along the east bank of the Columbia River indicate the rocks are still on the lower limb of a westerly closing antiform (primary structures were not available here). Second phase vergence changes across the river and four minor closures on the limb of the major second phase structure (antiform syncline) were mapped along the South scarp (cross-section, Fig. 5). What may not be readily apparent from the cross-section is that the second phase closures in the river valley do not represent a major closure but are minor folds on a larger scale fold with an overall 'Z' sense when viewed
down plunge. The long lower limb of the structure projects below the base of the cross-section.

Hinges and bedding/cleavage intersections have shallow to moderate plunges on the east bank of the river and plot along a northeast dipping axial surface (Sub-area 1, Fig. 9). Second phase hinge lines swing from a generally southeast and northeast plunge in the eastern part of the map-area, to an east-west trend west of the Head scarp (Sub-areas 5, 6; Fig. 5) and north of Fissure Creek (Sub-area 2, Figs. 4, 5). The absence of the structure interpreted in the river valley, west of the Head scarp, may be explained by this swing in second phase hinge lines into a westerly orientation. The structure in the valley plunges into the plane of the cross-section, whereas farther west it plunges nearly parallel to the profile. Wheeler (1965) documented a large recumbent west-plunging, north-closing synformal structure due west of the thesis area which could be related to the second phase of deformation in this study.

A strong $L_2$ stretching lineation defined by elongate feldspar augen parallels a pervasive colour streaking, defined by the intersection of $S_1$ and $S_2$, and they are believed to be of the same generation (Plate 3a).

Kyanite and sillimanite crystallized parallel to the hinge lines of second phase folds. Garnets generally have curved or straight inclusion trails continuous with the external ($S_2$) foliation. In a few cases straight inclusion trails in elongate garnets are at a high angle to the foliation suggesting a moderate pre-$D_2$ metamorphic event, which involved at least the growth of garnet (Plate 3b).
In the region of the Downie Slide, structural and stratigraphic evidence suggest the rocks are on the overturned limb of a westerly facing antiformal syncline. Lane (1977) documented a large westward facing second phase structure in the Keystone Peak area of the Selkirk Mountains (due east of the thesis area) with primary structures indicating it too is an antiformal syncline. If the field evidence in the Columbia River valley has been interpreted correctly, there is apparent structural continuity between Selkirk and Shuswap terrane, despite the presence of a major cataclastic zone between the two areas. However, a lack of stratigraphic continuity implies disruption across the cataclastic zone. The author's map-area, in the valley and on "Pettipiece Ridge", lies at a deep structural level such that only the lower limb of the structure is encountered.

Phase 3

Phase 3 deformation controls the structural geometry over much of the map-area (Fig. 5). Third phase structures progressively increase in intensity and amplitude from east to west, originating as crenulations in pelitic rocks and broad gentle warps in siliceous rocks near the New Big Bend highway and culminating in megascopic flexural flow folds at the headwaters of Seymour and The Fortynine Creeks (Plate 2f). As mentioned earlier in this chapter, second phase structures predominate in the eastern part of the area and third phase structures predominate in the west. A transition zone, where the younger phase overprints and interferes with the older phase, occurs between Head scarp and about halfway along South scarp. Plates 3c and 3d illustrate the transition from dominant
second phase to dominant third phase between these two areas. Plate 3e illustrates a complex folding pattern believed to have resulted from the interference of these two phases, and may also indicate the position where Phase 2 structures swing from a north-south trend to an east-west trend.

Because the topography remains at a nearly constant elevation along "Pettipiece Ridge" and the cover rocks verge west over the core zone of Frenchman Cap dome under the influence of third phase structures, deeper structural (and stratigraphic) levels are encountered westward. Between Head scarp and "Downie Knoll" monoclinal flexures represent a form of semi-brittle deformation; west of "Downie Knoll" third phase folds exhibit thickened hinges and slightly attenuated limbs indicative of flexural flow folding under more ductile conditions (Plate 2f). However, not all thickening in this particular structure is attributed to the third phase of deformation as earlier minor folds documented in the hinge area attest to structural thickening in these areas prior to phase three folding. Although flexural flow is the dominant mechanism of folding, large-scale crenulations tend to develop in the cores of these structures (Plate 3f).

Third phase folds deform pre-existing linear fabrics defined by kyanite, sillimanite (Plate 4a) and $S_1/S_2$ intersections. Stereographic plots of these lineations folded around phase 3 fold hinges generally inscribe partly small and great circles west of Head scarp. East of Head scarp, near the mouth of Fissure Creek, sillimanite fibres folded around a third phase fold hinge inscribe a small circle indicating the fold mechanism here was primarily of flexural slip. Examples of these folds and stereographic projections of folded lineations appear in Appendix 3.
Although third minor structures are sparse around Fissure Creek and on the east bank of the Columbia River, axial surfaces of the few observed swing from an east-west trend to a northwest trend west of the river (Fig. 9). Axial planes and hinge lines have variable orientations in the east (Sub-areas 1, 2, 3, 4; Fig. 5) but tend to stabilize in the Seymour Creek area (Sub-areas 5, 6; Fig. 5). It is not possible at this time to speculate on the attitude of third phase axial surfaces and hinge lines west of the dome as these structures were not traced across the axis of the dome (in Unit 1, west of the map-area). Because of the steepening of third phase axial planes from Head scarp to Seymour Creek, at least on the east flank of Frenchman Cap dome, the regional structures tend to die out upwards (Fig. 5, cross-section).

Rarely, all three phases of deformation are preserved in a single outcrop (Plate 2e).

Post-Phase 3 Structures

It is important to note that kink banding, minor faulting, brittle folding, fracturing and shearing are primarily restricted to a 2 km wide zone in the bottom of the Columbia River valley, in the vicinity of the Downie Slide.

Kink Banding

Kink bands were only observed at six localities in the valley bottom, on both macroscopic and microscopic scales. On the macroscopic scale, kink bands are tabular in form and range from 10-30 cm in width. On the microscopic scale they are generally tapered and deform muscovite and kyanite crystals.
Axial planes and hinges of macroscopic kinks have variable trends and plunges in the field. Kink banding in the valley east of Downie Slide probably occurred very late in terms of the regional deformational history but have not been directly observed to deform third phase structures; they have deformed the regional foliation.

Shearing

Probably the most significant post-Phase 3 event to occur in the river valley is intense shearing at ductile/competent lithologic interfaces, such as marble/quartzite contacts. Two classic examples where this occurs are at Station P011 on the east bank of the river (Plate 2c; Fig. 7) and at Station P090 on Fissure Creek (Fig. 7). Stresses were not transmitted through the interface to the competent rocks below (quartzite) but rather have been concentrated in a 3-4 m wide zone on the ductile (marble) side of the interface. The shear zone is extremely graphitic, probably due to the release of CO₂ from calcite during deformation, causing graphite to be localized in the zone of shearing.

Shearing post-dates Phases 2 and 3 and thin section observations revealed that at least two episodes of shearing have taken place. The first episode consisted of crushing and liberating calcite, tectonic rounding of quartz and feldspar and localization of graphite in the shear zone. The second episode was much weaker, accounting for shearing along thin (tenths of a millimetre) graphite-rich layers which displace coarse calcite-filled extension fractures that formed between the two episodes.

The results of a preliminary fracture and calcite fibre study undertaken to determine the nature of late tectonic activity
in the Columbia River valley are summarized in Appendix 4.

**Brittle Folding and Faulting**

Post-Phase 3 brittle folding and faulting were observed at only two localities in the river valley. Both late structures are exposed in a roadcut on the New Big Bend highway northeast of Adit 2 (Station P049, Fig. 7). A near vertical fault is exposed on the east bank of the river, north of Sentinel rock. Displacement on this structure is not believed to be substantial.

A sample taken from a granodiorite dyke exposed on the New Big Bend highway (Station P053, Fig. 7) shows signs of weak brittle, post-metamorphic deformation, possibly the result of late normal faulting (Plate 4b). Normal faulting, with no more than 6 m displacement, was observed north of Watakam Lake.
Columbia River Cataclastic Zone

A zone of cataclastic deformation, trending nearly due north, lies in the Columbia River valley across from the Downie Slide (Fig. 9) and has been observed in several roadcuts from Goldstream River to Revelstoke. In the vicinity of the slide, where it has been studied in some detail, it ranges in width from about 600 m in the south, to about 900 m near the mouth of Fissure Creek. The existence of a cataclastic zone need not imply loss of cohesion during deformation but does indicate that strain rate has exceeded the rate of recrystallization (Carter, Christie and Griggs, 1964; Brown, pers. comm. 1977).

The rocks involved in the cataclastic zone are quartzites, calcisilicates, amphibolites, pelites, semipelites, quartzofeldspathic rocks, marble and a part of a granodiorite intrusion. In Figure 6 these are units 11 to 7a and 7b and the uppermost 5 m of 7c. Only the western margin of Unit 11 (pluton) is involved in the deformation.

The zone appears to be essentially stratabound in the Downie Slide area since it swings west and crosses the river with the rest of the stratigraphy just upstream from Sentinel rock and can then be traced north to Fissure Creek (Fig. 9).

The lower (western) boundary of the cataclastic zone is readily defined in the field by the disappearance of cataclastic textures at the upper contact of Unit 7c (marble). Here the deformed zone is marked by a massive, finely crushed zone that extends no further than 5 m into the marble. This feature is only exposed at one locality, but no cataclastic textures have been observed within the marble or in the rocks below the marble. The
marble may have behaved as a stress guide impeding transmission of the strain through the marble to the rocks below.

Unfortunately little confidence can be placed in the position of the eastern boundary due to poor bedrock exposure between the metasediments and the granodiorite intrusion. But the boundary may well be a gradational one, the deformation being expressed as a strong foliation near the western edge of the pluton and a progressively weaker foliation to the east.

Examination of thin sections revealed that the cataclastic fabric developed in a deep-seated metamorphic environment, and probably formed during the second phase of deformation. Minor folds in the cataclastic zone (Plate 4c) have comparable attitudes and trends as second phase folds outside the zone. The mylonitic foliation defined by micas and polygonized quartz grains is interpreted to be the dominant fabric in the cataclastic zone. Minor folds believed to have been generated during the second phase of deformation developed a strong axial planar polygonized quartz foliation (Plate 4d) resembling the dominant cataclastic foliation preserved in quartzites throughout the cataclastic zone. In thin section, the polygonized quartz foliation has been observed at a small angle to $S_2$ (Plate 4e) in a clean quartzite that bears a strong compositional layering in the field.

As will be discussed in the following chapter (Metamorphism), the peak of metamorphism occurred during the second phase of deformation with the first appearance of the aluminosilicates, kyanite and sillimanite along with garnet, biotite and muscovite. In some areas of the zone, these minerals crystallized concurrently with cataclasism (Plate 4f) while in
others, cataclasis definitely outlasted metamorphism. The cataclastic fabric predates phase three crenulation.

Deformation in the zone is primarily one of flattening. However, a weak lineation related to Phase 2 is developed in the rocks throughout the zone, but there is little microscopic evidence for a cataclastic lineation in thin sections cut parallel to the observed lineation.

According to Higgins' (1971) classification of cataclastic rocks, the rocks involved in the Columbia River cataclastic zone fall into four categories:

a) microbreccia (Plate 5a)
b) protomylonite (Plate 5b)
c) mylonite gneiss (mylonite schist) (Plate 5c)
d) blastomylonite (Plate 5d)

Definitions for the above terms are given in Appendix 5.

All of the above categories are characterized by a prominent fluxion structure (cataclastic foliation) except for microbreccia, and display a moderate to high degree of recrystallization concurrent with deformation. The most common cataclastic rock type exposed in the Downie Slide area is mylonite gneiss, composed primarily of quartz and plagioclase in quartzofeldspathic rocks, and biotite, quartz, feldspar, kyanite and garnet in rocks of pelitic to semipelitic affinity. Strained kyanite porphyroblasts are generally only partially annealed in the cataclastic zone.

Different minerals behave with different degrees of susceptibility or resistance to comminution (reduction in size of mineral grains due to cataclasis, from Higgins, 1971) during cataclasis.
Quartz is usually the first mineral to polygonize into sub-grains during cataclasis while the feldspars begin to fracture and polygonize after quartz. Feldspars are the most common porphyroclasts observed in the rocks of the Columbia River cataclastic zone. These porphyroclasts are usually composed of aggregates of sub-grains ranging in size from less than a millimetre to more than a centimetre in cross-section.

Garnet is capable of surviving cataclasis with little reduction in grain size. It is resistant to comminution on account of its equant habit and the micaceous groundmass with which it is most commonly associated. The equant habit allows the garnet to behave in a ball bearing fashion during deformation, while completely surrounded by a lubricating micaceous matrix (Plate 5e).

Cataclastic textures observed across the Columbia River cataclastic zone vary from one area to another and from one rock type to another. It is believed that this prominent structural feature is more complex than initially anticipated by Wheeler (1965), with considerable variations in strain across the belt, coupled with the possibility of large-scale displacements along it. Further speculation on the implications of the Columbia River cataclastic zone is beyond the scope of this study.

A summary of deformation, metamorphism and tectonism in the Downie Slide area is presented in Table 3.
<table>
<thead>
<tr>
<th>Deformation Event</th>
<th>Deformation and Metamorphism</th>
<th>Tectonism</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_1$</td>
<td>development of a strong biotite, muscovite foliation in axial planes of Phase 1 mesoscopic and mesoscopic isoclinal folds</td>
<td>stratigraphy inverted by a Phase 1 nappe structure with a limb length exceeding 15 km</td>
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<td>Post-$D_1$</td>
<td>- possible garnet growth</td>
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<tr>
<td>Pre-$D_2$</td>
<td>West of Cataclastic Zone</td>
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<td></td>
<td>- recrystallization of muscovite and biotite in the axial planes of tight Phase 2 folds</td>
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</tr>
<tr>
<td></td>
<td>- growth of kyanite and sillimanite in the axial planes of Phase 2 folds</td>
<td></td>
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<tr>
<td></td>
<td>- metamorphism outlasts deformation</td>
<td></td>
</tr>
<tr>
<td>$D_2$</td>
<td>Within Cataclastic Zone</td>
<td></td>
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<tr>
<td></td>
<td>- cataclastic foliation defined by polygonized quartz and micas axial planar to Phase 2 folds</td>
<td>- development of a Phase 2 antiformal syncline with limbs exceeding 15 km in length</td>
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<td>- kyanite oriented in axial planes of Phase 2 folds</td>
<td>- possible thrusting along a shallow east dipping cataclastic zone</td>
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<td>- locally cataclasis outlasts metamorphism</td>
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<td></td>
<td>D₃</td>
<td>Post-D₃</td>
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<tr>
<td></td>
<td>- generation of mesoscopic flexure (kinking) and flexural flow folds</td>
<td>- helicitic garnet growth over Phase 3 crenulations</td>
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<td>- metamorphic minerals annealed</td>
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<td></td>
<td>- cataclasis ceases</td>
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</table>
CHAPTER 5

METAMORPHISM

The rocks in the "Pettipiece Ridge" area of the Shuswap Metamorphic Complex have been subjected to upper amphibolite facies of regional metamorphism in early middle Jurassic times (Monger and Hutchison, 1972) but unlike stratigraphic equivalents to the south do not contain extensive exposures of pegmatite. No clearly defined isograds were mapped in the field as the area most likely to display a change in metamorphic grade is involved in a cataclastic zone, deep in the Columbia River valley.

Kyanite, sillimanite-bearing assemblages persist across most of the map-area, from Unit 1 near Seymour Creek (Fig. 3) east to the Columbia River. Kyanite–staurolite and kyanite–sillimanite assemblages are common on the east bank of the river and in the cataclastic zone, but they do not appear to define a metamorphic gradient. One exception to the regional metamorphic trend occurs along the New Big Bend highway (Station P053), where radial clusters of fibrous sillimanite crystallized in the presence of biotite and quartz. All of the above assemblages occur in the absence of alkali feldspar. East of the cataclastic zone and the granodioritic intrusion are the lower greenschist rocks of the Selkirk Mountains.

Pelites at river level, on the east bank of the Columbia River, contain kyanite, staurolite, garnet, quartz, biotite and plagioclase assemblages; kyanite + sillimanite, garnet, quartz, biotite and muscovite are common on "Pettipiece Ridge" from the Columbia River to Seymour Creek; kyanite, sillimanite, quartz,
plagioclase, muscovite - biotite occur in pelite layers in the
lowest exposed alkali feldspar augen paragneisses west of Seymour
Creek (Unit 1).

A steep metamorphic gradient exists between the eastern
boundary of the cataclastic zone (upper amphibolite) of Shuswap
terrane, and greenschist facies rocks of the western Selkirk
Mountains, in the Downie Peak area (Lane, 1977). A fundamental
feature of Frenchman Cap dome, and other related domes to the
south, is that stratigraphy which appears to encircle the dome,
appears to abut against or be truncated by the Columbia River
cataclastic zone on the eastern margin of the complex, between
A considerable thickness of stratigraphy (and possibly isograds)
may be absent from this (eastern) flank of the dome.

Evidence for an early metamorphic event can be seen in
garnets with straight inclusion trails normal to the external
foliation in garnets elongate parallel with the foliation
(Plate 3b). These garnets were observed in the South scarp.
On the lower reaches of the east bank of the river, post-tectonic
helicitic garnets overgrew the third phase fabric (Plate 5f).
In siliceous layers (psammitite) garnets are generally poikiloblastic,
containing from 50-80% quartz inclusions.

The bulk of the metamorphic mineral growth in the Downie
Slide area occurred during the first and second phases of
deformation. Growth of biotite, muscovite and possibly garnet,
parallel to axial planes of first phase folds, represents the
first metamorphic event; crystallization of garnets, aluminosilicates
(kyanite and sillimanite) and recrystallization of first phase
micas in axial planes of second phase folds are indicative of the second metamorphic event. Metamorphism peaked during this second phase. The assemblage sillimanite-alkali feldspar has not been observed anywhere in the "Pettipiece Ridge" area but pelitic layers in Unit 1 contain the assemblage sillimanite, kyanite, muscovite, quartz, garnet, plagioclase and biotite.

Marbles, amphibolites and calc-silicates can also be used to establish metamorphic grade. But again, no regional isograd could be delineated by them. Amphibolite and calc-silicate layers have assemblages containing hornblende, plagioclase, quartz, garnet and sphene + calcite, indicating a relatively high grade of metamorphism. An impure marble exposed on the west bank of the Columbia River (Station P110, Fig. 7), north of Fissure Creek, contains the assemblage diopside, calcite, forsterite, garnet, hornblende, biotite and quartz. West of "Downie Knoll", impure marbles commonly contain scapolite.

Equilibrium assemblages occurring in the rocks of the Downie Slide area do not readily permit accurate calculation of P-T conditions that prevailed at the peak of metamorphism. Rather, only a range of P-T conditions can be given. Utilizing one of the more common aluminosilicate assemblages over the "Pettipiece Ridge" area, coexisting kyanite-sillimanite, the metamorphic culmination occurred at a depth of between 17 and 23 km (P= 5.3 - 7.1 kb; T= 575°- 675°C, Carmichael, 1977).

A summary of deformation and metamorphic events in the Downie Slide area is presented in Table 3.
CHAPTER 6

STRUCTURAL SETTING OF THE DONWIE SLIDE

The purpose of this chapter is to demonstrate that the regional position and attitude of megascopic fold structures and their related fabrics, immediately surrounding the Downie Slide, have played an important role in controlling the slide geometry. As pointed out earlier, one of the dominant structural features on the east flank of "Pettipiece Ridge" is the first appearance and rapid increase in magnitude of third phase folds as the Head scarp is approached from the east. Before proceeding with the structural aspects, a brief outline of requirements necessary to render a slope unstable will be reviewed.

In order for a rock slope to fail, or become unstable, certain events must first occur to initiate sliding. The most important of these are development of tension cracks or fissures at the head of the slope, and formation of an incipient failure surface from the head to the toe of the slope (Hoek and Bray, 1974). The author believes that naturally occurring rockslides do not necessarily have to develop tension cracks behind the crest of the slope; rather that on a long slope, they can be generated at a pre-existing zone of weakness somewhere along the length of the slope. Other geometrical criteria that must be satisfied in order for a particular slope to become unstable are summarized by Hoek and Bray (1974);

a) The failure plane must strike within ± 20° of the trend of the slope face.
b) The dip of the failure plane must be less than the dip of the slope face (approx. coplanar at Downie Slide).

c) The dip of the failure plane must be greater than the angle of friction on this plane (the internal friction angle for the Downie Slide was calculated by the author to be 13°).

d) Release surfaces which provide little resistance to sliding must be available in the rock mass in order to define the lateral boundaries of the slide.

Though the above criteria (a-d) are satisfied by the Downie Slide, they are not sufficient to complete the requirements for failure. Other requirements which play a more direct role in contributing to slope instability, are those aspects such as:

i) physical characteristics of the incipient failure surface,

ii) reduction of cohesive strength along the length of the slope (generation of tension fractures), and

iii) removal of support from the base of the slope.

The first two requirements (i and ii) can be directly related to the early structural history of the region, and the last is associated with recent erosional processes.

The first requirement (i) is governed by the first and second phases of deformation. Foliation within Unit 6 of the Downie Slide area is defined primarily by the planar preferred orientation of mica flakes in the flattening plane of first and second generation folds. Axial surfaces of the two fold phases are essentially coplanar and dip about 20° towards the Columbia River, subparallel to the slope of the hillside. Recall that Unit 6 is a monotonous "layer cake" of interbedded pelites, semipelites and psammites and is therefore internally anisotropic. Pelitic This value has been more accurately calculated by B.C. Hydro (22°)–Patton, F.D. Summary of the Stability Analyses of the Downie Slide, British Columbia. April 10, 1975.
horizontal zones capable of sustaining low shearing stresses are considered to have acted as incipient failure surfaces within which the majority of downslope displacement has occurred. Once sliding was initiated in an incompetent micaceous zone, subsequent displacement would have continued preferentially within this horizon.

The second requirement (ii) involves reduction of cohesive strength at some point along the length of the slope. The Head scarp is situated at the hinge zone of the most easterly major monocline associated with the third phase of deformation. Steepening of bedding on the short limb of this anticlinal structure together with development of steeply dipping joints and extension fractures during semi-brittle deformation (in the Head scarp region, Phase 3) created a zone of potential weakness. Subsequent uplift exposed bedding, foliation and jointing to further weakening by surface processes. Water enters these upturned beds and jointed surfaces causing voids by solution and thus decreases the upslope cohesion of the rock mass. These openings may also facilitate water entry beneath the lower shear zone which could give rise to high pore water pressures. Water may also enter via solution cavities in similar structures found in Unit 4a (marble) northwest of Watam Lake (Plate 1a). This is a permeable calcareous marble that is immediately underlain by an impermeable quartzite layer. Thus, the marble is physically an ideal aquifer capable of generating a hydraulic head down dip to the east (cross-section, Fig. 5). Voluminous discharge of water at Tufa Springs may be a direct expression of this pore water pressure.

The final requirement (iii), that of removal of support
from the base of the slope occurred in recent times, well after the structural history was completed. If the slide is assumed to have been activated following the last period of glaciation, and presently there is no evidence to suggest otherwise, the final requirement for sliding was most likely achieved after glacial ice receded from the valley and erosion by the Columbia River removed support from the toe. Drillhole data from near the toe of the slide indicate the ancient river course (presumably that which followed the last period of glaciation) is buried beneath the toe of the slide, west of its present course.

A fracture study carried out by Blown (1966) showed that the most prominent joint set in the Downie Slide area has a 075°-095° trend and near vertical dip. This roughly coincides with the trend of the North and South scarps and could conceivably have played a major role as release surfaces controlling the northern and southern boundaries of the slide.

Mechanical crushing caused by shearing in weak pelitic horizons parallel to compositional layering and foliation is believed to be the mechanism that generated the soft material in the gouge zones within and at the very base of the slide. It has been previously suggested that the gouge material was produced by hydrothermal alteration because of the preponderance of kaolinite in the gouge (B.C. Hydro, 1974).

Because no large-scale third phase folds are visible in the South scarp below 825m (2700ft) elevation, the lower shear zone below this elevation is thought to be essentially planar. In contrast, the lower shear zone above this elevation probably bears numerous steps or undulations associated with the onset of
third phase folds.

Conclusions

The early structural history of the Downie Slide region created geometrical relationships favourable for future slope instability:

a) The lower shear zone was generated by slip along micaceous layers within a weak pelitic horizon. Displacements within this horizon were facilitated by the planar preferred orientation of micas that crystallized during the first and second phases of deformation.

b) The Head scarp is situated at the hinge zone of the most easterly major monocline associated with the ductile to semi-brittle third phase of deformation and thus represents a zone of potential weakness.

c) Steeply dipping joints associated, at least in part, with the third phase of deformation further reduced the cohesive strength of the slope in the region of the Head scarp.

d) The combination of upturned beds and extensive jointing above Head scarp, and downslope dipping strata on the east flank of "Pettipiece Ridge" created conditions capable of generating high pore water pressures beneath the west slope of the Columbia River valley.
CHAPTER 7

SUMMARY OF CONCLUSIONS

1. The geometry of the Downie Slide is structurally controlled by the position and attitude of second and third phase structures.

2. Structural and stratigraphic evidence indicates the stratigraphic succession exposed in the "Pettipiece Ridge" and Downie Slide area is on the overturned limb of a second phase, westerly facing antiformal syncline with limbs exceeding 15 km in length.

3. A zone of cataclastic deformation on the eastern margin of Frenchman Cap gneiss dome, possibly reflecting major thrusting, was initiated in a deep-seated metamorphic environment during Phase 2 deformation, but ceased before Phase 3 deformation.

4. Metamorphism culminated during the second phase of deformation.

5. There is some microscopic fabric evidence for a post-Phase 1, pre-Phase 2 metamorphic event.

6. There is a progressive change in third phase fold style, possibly related to depth in the stratigraphic succession, from flexural slip folds in the east (high level) to flexural flow and passive flow folding west of the Downie Slide (deep level).

7. The eastern extremity of the map-area is dominated by Phase 2 structures; the region west of the Head scarp is dominated by Phase 3 structures.
8. The possibility of normal faulting is proposed to explain the juxtaposition of high grade rocks of the Shuswap Metamorphic Complex against low grade rocks of the Selkirk Mountains.

9. Further field and laboratory work is necessary to gain a fuller appreciation of the regional structural implications of the Columbia River cataclastic zone.
CONCLUDING REMARK

It is hoped that the observations and results of this study may be utilized in other areas of the Columbia River valley, or elsewhere for that matter, in order to identify and possibly delimit areas of potential slope instability.
REFERENCES


Carmichael, D.M. 1977. P-T petrogenetic grid for part of the ideal pelitic system. Unpubl. figure only.


# Table 1: Detailed Stratigraphic Column

(see list of abbreviations following)

<table>
<thead>
<tr>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>11 Granodiorite (1500 m)</td>
<td>Light grey Bi-Qz granodiorite with 2-8 mm diameter Qz augen and thin platy aggregates of biotite and chlorite. Bi-Chl-Fspar-Mu-Qz</td>
</tr>
<tr>
<td>10 Semipelite (100 m)</td>
<td>Light grey semipelite interlayered with psammitic and quartzofeldspathic beds. Cut by medium-grained unfoliated felsic dykes. The unit becomes thickly bedded and more pelitic towards the top. Only exposed on the east side of the Columbia River. Displays cataclastic textures. Bi-Fspar-Ga-Si-Mu-Qz-Ky</td>
</tr>
<tr>
<td>9 Quartzofeldspathic Gneisses &amp; Grits (300m)</td>
<td>Pink, blue-green, green, calcareous quartzofeldspathic gneisses underlain by pink quartzofeldspathic grits. Compositional layering in the gneisses ranges in thickness from 1-10’s of metres. Cut by pegmatite dykes and contains pegmatite boudins. Serpentine-bearing rocks are abundant near the base of the unit. Only observed on the east side of the Columbia River. Displays cataclastic textures.</td>
</tr>
<tr>
<td>8 Quartzite (200 m)</td>
<td>White to rusty weathering, massive to foliated, fine-grained quartzite. Interbedded with white to light pink, kyanite-bearing muscovite-rich semipelite layers up to 5 m in thickness. Displays cataclastic textures.</td>
</tr>
<tr>
<td>7a Semipelite</td>
<td>15 m Medium-grained grey semipelite characterized by the presence of 2-10 mm long kyanite porphyroblasts.</td>
</tr>
<tr>
<td>7b Quartzite, Clcl</td>
<td>40m Clean, well-bedded quartzite interbedded with 1-5 m thick black Clcl layers and lenses. Clcl mineralogy Hb-Chl-Qz-Fspar-Cc and minor pegmatite.</td>
</tr>
<tr>
<td>7c Marble</td>
<td>21m Grey, micaceous, calcareous marble. Varies from massive, to thinly layered, to knotted with Clcl pods. Bi-Cc-Di-Qz</td>
</tr>
<tr>
<td>5m Sheared, graphitic, calcareous marble at the base.</td>
<td></td>
</tr>
<tr>
<td>7d</td>
<td>Quartzite</td>
</tr>
<tr>
<td>----</td>
<td>-----------</td>
</tr>
<tr>
<td>7d</td>
<td>Semipelite</td>
</tr>
<tr>
<td>7e</td>
<td>Clcl</td>
</tr>
</tbody>
</table>

| 6  | Pelite, Semipelite, Psammite (400m) | Undivided: pelite, semipelite, psammite all interbedded on centimetres to 10's of metres scale, with local occurrences of quartzite, graphitic marble and various Clcls near the top of the unit. The predominance of black pelite and dark grey semipelite over psammite, quartzite and Clcl characterize this unit. Bi-Ga-Mu-Qz-Ky-Si |

<table>
<thead>
<tr>
<th>5</th>
<th>Grits, Semipelite</th>
<th>20m</th>
<th>Interlayered quartzofeldspathic grits and semipelite layers 8-15 cm thick with minor pelite.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Semipelite</td>
<td>14m</td>
<td>Light grey, semipelite with minor pinkish coarse-grained quartzofeldspathic grits and pelite layers 5-10 cm in thickness. Bed thickness increases towards the top of the unit.</td>
</tr>
<tr>
<td>7m</td>
<td>Pelite</td>
<td></td>
<td>Silvery to rust coloured pelite with Bi-Ga-Mu-Qz-Ky</td>
</tr>
<tr>
<td>5</td>
<td>Grits</td>
<td>35m</td>
<td>Rusty, coarse- to fine-grained quartzofeldspathic grits interlayered with pelite, semipelite and psammite on 0.5 - 3 m scale.</td>
</tr>
<tr>
<td></td>
<td>Grits, Pelite</td>
<td>10m</td>
<td>Muscovite-rich pelite, quartzofeldspathic grits, semipelite</td>
</tr>
<tr>
<td></td>
<td>Grits</td>
<td>6m</td>
<td>Rusty to grey weathering fine-grained quartzofeldspathic grits.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2m</th>
<th>Black magnetic Clcl layered on scale of 4-15 mm. Feldspathic layers are continuous, mafic layers contain knots of diopside rimmed with hornblende. Di-Hb-Cc-Bi-Qz-Mag-Fspar</th>
</tr>
</thead>
<tbody>
<tr>
<td>4a</td>
<td>Quartzite</td>
</tr>
<tr>
<td></td>
<td>Clcl</td>
</tr>
</tbody>
</table>
Pelite, 10m Silvery interbedded pelite and semipelite beds 1-3 m thick. Grades to psammite at the top.

Semipelite

Marble 1m Yellowish, thinly layered calcareous marble.

Psammite

6m Calcareous "ribbon" psammite. Psammite inter-layered with 2-10 mm thick Clcl, pelitic and quartzitic layers. Qz-To-Bi-Ga-Hb-Cc

35m Distinct rusty weathering pelite and semipelite unit containing Si-Ky-Bi-Mu-Ga-Qz-Fspar.

Pelite, Semipelite

Generally bedding is present on a scale of metres but commonly have 3-5 mm laminations. On a gross scale lower half of unit is pelitic, upper half is semipelitic.

40m Dark grey weathering semipelite, similar to the previous semipelite but with a distinct lack of feldspar. 1-2 mm thick laminations wrap around garnet porphyroblasts. Bi-Mu-Ga-Qz

Semipelite

8m Medium-grained, pale green, friable impure marble. Clcl laminations produce a finely ribbed weathered surface. Bi-Qz-Di-Tr-Cc

Semipelite

31m Black to dark weathering semipelite. Garnets have a 0.5 mm thick quartz or feldspar reaction rim. Commonly layered on scale of 5-10 cm. Bi-Mu-Qz-Fspar-Ky-Ga

Clcl

2m Black Clcl

Marble 3m Medium to coarse-grained white calcareous marble. Bedded on 10-20 cm scale. Individual beds layered on 5-20 mm scale. Cc-Do-Tr-Ph?-Qz

Clcl 30cm Black calcisilicate

Quartzite

7m Clean thinly layered (4-10 cm) pink to light brown quartzite.

20m Slightly rusty weathering pelite interbedded with muscovite-rich semipelite layers averaging 10 cm in thickness. Alternating Mu-rich and Bi-rich laminations on a scale of 2-4 mm. Garnet porphyroblasts average 7 mm in diameter. Pelite contains Ky-Si-Ga-Mu-Bi-Qz

Pelite

4m Scapolite-bearing impure marble

3m Rusty pelite

10m Scapolite-bearing impure marble with shale chips (pelite)

3m Rounded weathering pale green marble
5m Thinly laminated impure marble
10m Rusty garnet-rich pelite with minor 0.5 m Clcl layers
10m Partly rusty pelite with semipelite laminations and beds 10-30 cm thick
5m Thinly layered semipelite and quartzite
3m Black magnetic Clcl
40m Rusty and non-rusty semipelite and pelite with minor quartzite layers
6m Impure marble and Clcl
6m Uniform silver weathering pelite
10m Thinly layered (1-5 cm) Bi-rich semipelite, psammite and minor Clcl bands 1-2 cm thick
5m pelite
30m Thinly layered semipelite, Clcl
20m Quartzofeldspathic grit layers interbedded with semipelite
25m Thinly laminated calcareous psammite, Clcl and impure marble
4m Silver weathering pelite with rusty patches

<table>
<thead>
<tr>
<th>3a</th>
<th>7m Buff weathering quartzite (upper quartzite)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8m</td>
<td>Calcareous psammite</td>
</tr>
<tr>
<td>15m</td>
<td>Interbedded black and grey semipelite and pelite</td>
</tr>
<tr>
<td>26m</td>
<td>Feldspar augen semipelite with 1-6 cm Clcl layers</td>
</tr>
<tr>
<td>10m</td>
<td>Thinly layered feldspar-bearing Clcl with Hb-Fspar knots</td>
</tr>
<tr>
<td>25m</td>
<td>Thinly bedded impure marbles</td>
</tr>
<tr>
<td>10m</td>
<td>Interbedded psammite (0.5 m) and Clcl (2-6 cm) with minor rusty semipelite beds 0.5 m thick</td>
</tr>
<tr>
<td>20m</td>
<td>Thinly laminated silvery semipelite, psammite with minor Clcl layers</td>
</tr>
<tr>
<td>5m</td>
<td>Thinly laminated impure marble with minor Clcl layers</td>
</tr>
<tr>
<td>4m</td>
<td>Yellowish marble</td>
</tr>
</tbody>
</table>
16m Impure carbonate layered on 0.5 m scale
5m Grey pelite

3b 1 - 50m White and pink clean quartzite (middle quartzite)

16m Light to dark grey semipelite and Mu-rich pelite with minor Clcl and Bi-rich pelite layers

35m Light green psammite, light grey semipelite and quartzite layers. All interbedded on a scale of 1-2 m.

40m Interbedded semipelite and Clcl with minor psammite and numerous quartz veins.

3c 7m White quartzite (lower quartzite)

5m Rusty-black pelite

4m Thinly layered semipelite and quartzite

20m Dominant psammite with minor black semipelite layers

35m Mixed unit of psammite, semipelite and Clcl layered on scale of 2-4-10 cm

20m Light grey to brown thinly layered semipelite

50m Interbedded semipelite and Clcl paragneiss

895m Interbedded amphibolite, semipelite, psammite, grits and alkali feldspar augen paragneisses near the base of the unit

1500+m Alkali feldspar augen paragneisses with inliers of pelite, amphibolite, psammite and an ultramafic pod. Minor pegmatite. Pelitic layers contain Ky-Si-Mu-Bi-Plag-Qz
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>Ac</td>
<td>actinolite</td>
</tr>
<tr>
<td>Bi</td>
<td>biotite</td>
</tr>
<tr>
<td>Cc</td>
<td>calcite</td>
</tr>
<tr>
<td>Chl</td>
<td>chlorite</td>
</tr>
<tr>
<td>Clcl</td>
<td>calcsilicate</td>
</tr>
<tr>
<td>Di</td>
<td>diopside</td>
</tr>
<tr>
<td>Do</td>
<td>dolomite</td>
</tr>
<tr>
<td>Fspar</td>
<td>feldspar</td>
</tr>
<tr>
<td>Fu</td>
<td>fuchsite</td>
</tr>
<tr>
<td>Ga</td>
<td>garnet</td>
</tr>
<tr>
<td>Hb</td>
<td>hornblende</td>
</tr>
<tr>
<td>Ky</td>
<td>kyanite</td>
</tr>
<tr>
<td>Mag</td>
<td>magnetite</td>
</tr>
<tr>
<td>Mu</td>
<td>muscovite</td>
</tr>
<tr>
<td>Ph</td>
<td>phlogopite</td>
</tr>
<tr>
<td>Qz</td>
<td>quartz</td>
</tr>
<tr>
<td>Si</td>
<td>sillimanite</td>
</tr>
<tr>
<td>Tr</td>
<td>tremolite</td>
</tr>
</tbody>
</table>
APPENDIX 2

A tentative regional stratigraphic correlation between Fyles (1970) and McMillan (1973) and this work is presented in Table 2. Quartzites and marbles of the metasedimentary sequence (Fig. 2 and Wheeler, 1965, map 12-1964) that outcrop on the south, west and north flanks of Frenchman Cap dome appear to lie at approximately the same stratigraphic level around the dome, i.e. directly above the core gneisses. Thus, lithologically distinct quartzite or marble horizons of this part of the succession may be correlated with reasonable confidence from one study area to another. McMillan (1973) proposed a correlation scheme between his area and Fyles' (1973) area on the south flank of the dome. A white coarse crystalline marble horizon associated with the Pb-Zn sequence in the Jordan River area (Riley, 1961; Fyles, 1970) was tentatively correlated with a white marble mapped by McMillan and (presumably) the same marble is used as a datum for the present correlation. No Pb-Zn mineralization is associated with the white marble in either the "Pettipiece Ridge" area, or on the west flank of the dome (McMillan, 1973). A comparison of Riley's (1961) geological maps and cross-sections of the River Jordan Mineral Property, with those of the present study, reveals a striking similarity to gneisses, quartzites and rusty schists of Unit 4 northeast of Watam Lake (Fig. 3).

Unit 6 of this work is tentatively correlated with the biotite- sillimanite- kyanite schists of Fyles (1970) and McMillan (1973); and the lowermost gneisses of all three workers are considered to be correlative.
Correlations are based primarily on lithologic similarities; little emphasis is placed on thicknesses which are largely structural and thus extremely variable from one area to another.
<table>
<thead>
<tr>
<th>Jordan River Area (Fyles, 1970) South Flank, Frenchman's Cap Dome</th>
<th>McMillan (1973) West Flank, Frenchman's Cap Dome</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lithology</strong></td>
<td><strong>Lithology</strong></td>
</tr>
<tr>
<td>Bi-Si schist, Bi-Fespar gneiss with gneissic quartzite layers</td>
<td>Bi-Si-Ky schist, Bi-Qz gneiss with Clcl gneiss, marble, and quartzite layers</td>
</tr>
<tr>
<td>White quartzite, rare Clcl gneiss, mica schist, Bi-Si gneiss layers</td>
<td>Quartzite with Bi schist, Bi-Si schist, and Bi-Qz gneiss layers</td>
</tr>
<tr>
<td>Clcl gneiss, marbles, mica schist</td>
<td>Clcl gneiss with Clcl gneiss and a quartzite layer</td>
</tr>
<tr>
<td>White quartzite, rare Clcl gneiss or mica schist layers</td>
<td>Carbonatite, Bi schist, Bi-Qz gneiss, marble</td>
</tr>
<tr>
<td>Qs-Bi-Rb gneiss with Clcl gneiss, mica schist, and quartzite layers</td>
<td>Bi schist, Bi-Si schist, Bi gneiss with quartzite, Clcl gneiss, and some marble layers</td>
</tr>
<tr>
<td>Quartzite in contact with 4, calcareous schist, Clcl gneiss; marble in contact with 6 (lead-zinc sequence)</td>
<td>Bi-Si schist, Bi-Si schist, and Bi-gneiss with quartzite and Clcl gneiss layers</td>
</tr>
<tr>
<td>Bi-Si schist</td>
<td></td>
</tr>
</tbody>
</table>

Above this point the correlation is less reliable

<table>
<thead>
<tr>
<th>Bews Creek Fault</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bi schist with quartzite and calcareous schist layers (thickness unknown)</td>
</tr>
<tr>
<td>Bi schist, Bi-Si schist, and Bi-gneiss with quartzite and Clcl gneiss layers</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Lithology</th>
<th>Unit</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartzite and conglomerate</td>
<td>2</td>
<td>4a</td>
</tr>
<tr>
<td>Heterogeneous gneissae</td>
<td>1</td>
<td>2,3</td>
</tr>
</tbody>
</table>

Migmatites and agmatitic migmatites

---

* The first two columns of the Table are reproduced from McMillan (1973)
** See list of abbreviations following Table 1
*** Units 7-11 of this study are presumed to lie above Fyles' and McMillan's stratigraphy
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Flank, Frenchman's Cap Dome</td>
<td>Northeast Flank, Frenchman Cap Dome</td>
<td></td>
</tr>
<tr>
<td>- Ky schist, Bi-Qz gneiss</td>
<td>Bi-Si-Ky pelite, semipelite and psammite***</td>
<td></td>
</tr>
<tr>
<td>Clcl gneiss, marble, and zite layers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>zite with Bi schist, Bi-Si st, and Bi-Qz gneiss layers</td>
<td>Quartzofeldspathic grits and semipelite</td>
<td></td>
</tr>
<tr>
<td>gneiss with Clcl gneiss</td>
<td></td>
<td></td>
</tr>
<tr>
<td>quartzite layer</td>
<td>Rusty pelite and semipelite, clean and impure marbles, minor psammite and Clcl, a distinct coarse crystalline white marble (tentatively correlated with the Pb-Zn sequence of the Jordan River area of Fyles (1970) and Riley (1961)).</td>
<td></td>
</tr>
<tr>
<td>matite, Bi schist, Bi-Qz is, marble</td>
<td></td>
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<tr>
<td>chist, Bi-Si schist, Bi is with quartzite, Clcl is, and some marble layers</td>
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<tr>
<td>chist, Bi-Si schist, and Bi is with quartzite and Clcl is layers</td>
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<tr>
<td>zite, some conglomerate</td>
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<tr>
<td>Citites and agmatitic Citites</td>
<td>Semipelite, psammite, impure marbles and Clcl with minor quartzite and pelite</td>
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</tr>
<tr>
<td></td>
<td>Alkali feldspar augen paragneisses; mixed paragneisses including amphibolites, psammites, semipelites, grits</td>
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</tr>
</tbody>
</table>

*Adapted from McMillan (1973)*

Above Fyles' and McMillan's
APPENDIX 3

Fold Mechanisms

Second phase linear elements deformed by phase three structures in the Downie Slide region support the field evidence for a change in fold style from east to west along "Petripiece Ridge". Stereographic projections of deformed lineations which inscribe a small circle on a stereonet were folded by flexural slip; a great circle, by passive flow and a combination of both great and small circles, by flexural flow (Ramsay, 1967). The following series of diagrams and associated stereographic projections (Fig. 10) illustrate a progression from a flexural slip mechanism at Fissure Creek (Station P086, Fig. 7) to flexural flow in the Head scarp region and near "Downie Knoll" (Stations P094, P106, P104 and P143, Fig. 4) to passive flow folding at the headwaters of The Fortynine Creek (Station P154, Fig. 4). In all cases, the orientation of sillimanite fibres (L2) were measured around the hinges of third phase folds in rocks of semipelitic to psammitic composition.
Figure 10. Fold mechanisms.  
- Phase 3 hinge line
- $L_2$ (sillimanite fibres)

Flexural flow

Flexural slip
**Figure 10. (cont'd)**

- **Phase 3 hinge line**
- **L₂ (sillimanite fibres)**

**Station 104**

- Flexural flow

**Station 106**

- Flexural flow
Flexural flow

Figure 10. (cont'd)

- Phase 3 hinge line
- $L_2$ (sillimanite fibres)

Passive flow
APPENDIX 4

Preliminary extension fracture and calcite fibre studies were conducted to determine the nature of recent tectonic activity in the Columbia River valley. The studies were restricted to the valley bottom where these structures were most commonly developed.

Shear Fractures and Calcite Fibres

Calcite fibres on shear fracture surfaces serve as useful strain markers indicating the direction of the last displacement between the two surfaces. Fibres can have a simple or compound history. If the history is simple, only one set of fibres will be present on the fracture surface. If it is compound, the fracture surface will contain several overlapping generations of fibres, with variable orientations. The fibres crystallize in a zone of shearing where calcite is available and crystallize preferentially in the elongation direction of the shear couple. Fibres found in the field are step-like and the direction of movement is determined by the asymmetry of the steps. Caution must be exercised in interpreting these fibres, as a single set of fibres does not necessarily mean one episode of displacement has occurred. Often, earlier fibres can be destroyed and new ones recrystallized during more recent shearing. Nowhere was there more than one set of fibres observed on a single shear surface but curved fibres were recorded, indicating a local rotational component of shearing.

Shear surfaces in the Columbia River valley do not assume completely random orientations. Figure 11a is a
Figure 11.  

A - Poles to shear fractures containing calcite fibres. Closed circles represent normal displacement; crosses represent reverse displacement.

B - Trends of calcite fibres. Symbols are the same as in A.
stereographic plot of poles to shear fractures with calcite fibres on their surfaces. A great circle may be drawn through the poles to these planes in the southern half of the stereonet, but there is an isolated grouping of poles in the northeast quadrant. Of 59 sets of fibres measured in the field, only 7 indicated reverse displacements (Fig. 11). Thus, in the valley, the last episode of post-Phase 3 shearing with concurrent calcite fibre growth, has had an overall normal component of displacement.

**Extension Fractures**

Extension fractures in the river valley showed no evidence of displacement either by offset of foliation or calcite fibre growth. Figure 12a shows the orientation of conjugate fractures in Sub-area 1 on the east bank of the Columbia River. Figure 12b shows the orientation of conjugate fracture sets on the west bank. There is a wider spread in data recorded on the west bank than that recorded on the east bank, but both areas maintain two distinct populations of extension fractures.

The mean intersection of conjugate fracture surfaces in Sub-area 1 plunges shallowly to the north with an acute angle of 58° (Fig. 12a). In Sub-areas 2 and 3 on the west bank, this intersection changes to a southerly plunge with an acute angle of 49° between the conjugate surfaces (Fig. 12b). For a detailed account of fracture patterns in and immediately surrounding the Downie Slide, the reader is advised to consult Blown (1966).

In general, extension fractures in the Columbia River valley north and east of the toe of the slide form a conjugate set, whose intersection trends north and plunges shallowly to
Figure 12. A - Poles to extension fractures recorded in Sub-area 1. Great circles represent average strike and dip of conjugate sets.

B - Poles to extension fractures recorded in the eastern parts of Sub-areas 2 and 3.
the north and south.
APPENDIX 5

Definitions of mylonitic textures (from Higgins, 1971)

Blastomylonite: A coherent rock intermediate between medium- to fine-grained mylonite or ultramylonite and a crystalline schist or gneiss because its texture is the result of combined cataclastic and crystalloblastic processes. It is not produced by later recrystallization or neomineralization of a previously mylonitized rock; cataclasis and neomineralization-recrystallization are concurrent, producing a rock in which crystalloblastic texture appears to have overprinted the basic mylonite texture. Porphyroclasts in blastomylonite are generally smaller than about 0.5 mm and may show recrystallization. They make up less than about 30% of the rock.

Microbreccia: An intensively fractured but unground (fragments have not rolled) cohesive breccia in which the grains and fragments are without form orientation. Fragments may range from megascopic to about 0.2 mm and are separated by finer grained material. Fragments larger than 0.2 mm make up more than about 30% of the rock.

Mylonite: A coherent microscopic pressure-breccia with fluxion structure which may be megascopic or visible only in thin section and with porphyroclasts generally larger than 0.2 mm. These porphyroclasts make up about 10 to 50% of the rock. Mylonites generally show recrystallization and even new mineral formation (neomineralization) to a limited degree, but the dominant texture is cataclastic.

Mylonite gneiss (mylonite schist): A coherent rock intermediate between a protomylonite or coarse mylonite and a crystalline gneiss or schist because its texture is the result of combined cataclastic and crystalloblastic processes. Augen structure is characteristic, the augen generally being porphyroclasts or crushed aggregates of felsic minerals. The augen,
although recrystallized, preserve evidence of cataclastic texture by their shapes and by the crush tails commonly associated with them; the surrounding groundmass has been recrystallized and/or neominalized, although it too may show palimpsest cataclastic texture. More of the porphyroclasts are larger than about 0.5 mm and they make up more than about 30% of the rock.

Protomylonite: A coherent crush-breccia composed of megascopically visible fragments which are generally lenticular and are separated by megascopic gliding surfaces filled with finely ground material. The fragments, or "megaporphyroclasts", make up more than about 50% of the rock. Protomylonite commonly resembles conglomerate or arkose on weathered surfaces. Features of the original rock, such as stratification and schistosity, may be preserved in the larger fragments.
PLATE 1

A. View looking due west towards the Downie Slide, showing the dominant physical features. The Columbia River lies in a gorge just above the base of the photograph.

B. View looking northwest of the dark metasedimentary cover rocks (background) overlying the light coloured paragneisses (foreground).

C. Close view of the alkali feldspar augen paragneisses, Unit 1. (Station P183)

D. Migmatitic amphibolite and psammite paragneisses, Unit 2. (Station P184)

E. Solution cavities in marble (Unit 4b) northwest of Watam Lake.
A. View looking east at Tufa Springs on Fissure Creek.

B. Two cycles of graded grits in Unit 5 near "Downie Knoll". Pencil points to top. (Station P131)

C. View west of graphitic shear zone on the Columbia River. Geological hammer for scale, right centre of photograph. (Station P011)

D. Xenolith in granodiorite pluton, Unit 11. Lens cap is 67 mm in diameter.
   A - rusty metasedimentary xenolith
   B - strongly foliated granodiorite
   C - weakly foliated granodiorite
   (Station P002)

E. View looking northwest at an outcrop containing Phase 1 ($P_1$), Phase 2 ($P_2$) and Phase 3 ($P_3$) folds. $P_3$ crenulates the second phase fabric. (Station P151)

F. View northwest of Phase 2 ($P_2$) fold refolded by a Phase 3 syncline, west of the headwaters of The Forty-nine Creek.
PLATE 3

A. View looking west, of $S_1/S_2$ intersection lineation ($L_2$) and a stretching lineation defined by elongate alkali feldspar augen (Station P183)

B. Pre-Phase 2 inclusion trail preserved in a garnet elongated in Phase 2 foliation. (Station P103) Crossed nicols.

C. View south of the South scarp where Phase 2 axial surfaces are subparallel to compositional layering (Station P102)

D. View south of upper reaches of the South scarp. Compositional layering is deformed into a Phase 3 monoclinal flexure. (cliff is about 50 m high; Station P103)

E. View east of an interference pattern thought to have been generated by overprinting of Phase 2 structures by Phase 3 structures near the western end of South scarp. At 'A', one hinge line ($H_2$?) trends east; at 'B', the hinge ($H_3$?) trends north. The hinge exposed at 'B' is about 2 m in length. (Station P105)

F. View north of megascopic crenulations in the hinge zone of a Phase 3 anticline in the saddle at the headwaters of The Fortynine Creek. (Station P139)
PLATE 4

A. View looking east at Phase 3 fold (H_3) in the South scarp. This fold deformed sillimanite fibres (L_2). (Station P104)

B. Photomicrograph of a fractured granodiorite dyke exposed on the New Big Bend highway. Only the quartz is fractured; feldspar is unstrained. Crossed nicols. (Station P053)

C. Photomicrograph of folds in a thin section from the Columbia River cataclastic zone. Area outlined is enlarged in Plate 4d. Uncrossed nicols. (Station P109)

D. Enlarged photomicrograph of fold hinge in Plate 4c, illustrating the axial planar polygonized quartz foliation (S_2). Crossed nicols. (Station P109)

E. Photomicrograph showing the polygonized quartz foliation (S_2) oriented at a small angle to compositional layering (S_0-1) (S_0-1 is parallel to the long dimension of the photomicrograph). The light band to the right is a microfault. Crossed nicols. (Station P074)

F. Photomicrograph of a kyanite porphyroclast surrounded by a polygonized quartz, muscovite groundmass. Sillimanite is nucleated on the upper surface of the kyanite. Kinks in the kyanite are the result of Phase 3 deformation. Crossed nicols. (Station P074)
A. Photomicrograph of unrecrystallised microbreccia. Angular fragments are suspended in a black, fine-grained matrix. Uncrossed nicols. (Station PO23)

B. Photomicrograph of protomylonite. Large pphyroclasts are feldspars, the fine-grained material surrounding the feldspars is quartz. Crossed nicols. (Station PO70)

C. Photomicrograph of mylonite gneiss. Large feldspar porphyroclast has well developed crush tails. Uncrossed nicols. (Station PO74)

D. Photomicrograph of blastomylonite. Feldspar porphyroclasts about 0.15 mm in diameter can be seen to the left, centre of the photomicrograph. Crossed nicols. (Station PO17)

E. Photomicrograph of rounded garnets (black) in a fine-grained pelitic matrix. Crossed nicols. (Station PO01)

F. Photomicrograph of a post-tectonic helicitic garnet that overgrew a Phase 3 crenulation. The axial trace of the crenulation can be seen in the upper right of the garnet. Uncrossed nicols. (Station PO05)
LEGEND

Lithologic contact: known

Bedding: strike, dip

Line of cross-section

Ice or snowfield

118°42' W

31°31'
FIGURE 3

STRATIGRAPHIC MAP OF

DOWNIE SLIDE AREA

SCALE 1:25,000

GENERALIZED STRATIGRA

Granodiorite pluton

Semi pelite with minor psammite and a

Quartzofeldspathic grits and gneisses
FIGURE 3

TRATIGRAPHIC MAP OF THE DOWNIE SLIDE AREA

SCALE 1:25,000

GENERALIZED STRATIGRAPHIC COLUMN

Granodiorite pluton

Semipelite with minor psammite and quartzofeldspathic beds

Quartzofeldspathic grits and gneisses
<table>
<thead>
<tr>
<th>Layer</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>Quartzite with muscovite-rich semipelite</td>
</tr>
<tr>
<td>7</td>
<td>Quartzite, calcilicate, grey marble and</td>
</tr>
<tr>
<td>6</td>
<td>Black pelite, semipelite, psammite</td>
</tr>
<tr>
<td>5</td>
<td>Quartzofeldspathic grits and semipelite</td>
</tr>
<tr>
<td>4</td>
<td>Rusty pelite and semipelite, clean and impu</td>
</tr>
<tr>
<td></td>
<td>minor psammite and calcilicate</td>
</tr>
<tr>
<td>3</td>
<td>Semipelite, psammite, impure marbles and cc</td>
</tr>
<tr>
<td></td>
<td>with minor pelite and quartzite</td>
</tr>
</tbody>
</table>
Quartzite with muscovite-rich semipelite

Quartzite, calcisilicate, grey marble and semipelite

Black pelite, semipelite, psammite

Quartzofeldspathic grits and semipelite

Rusty pelite and semipelite, clean and impure marbles, minor psammite and calcisilicate

Semipelite, psammite, impure marbles and calcisilicate, with minor pelite and quartzite
Mixed paragneisses including amphibolite grits and feldspar augen paragneiss

Feldspar augen gneisses

Vertical Scale
1 cm = 50 m
1 in = 413 ft

Biotite granodiorite pluton

Light grey semipelite interlayered with psammite and quartzofeldspathic beds. Cut by unfoliated, medium grained felsic dykes.
1. Mixed paraggresses including amphibolites, semipelites and felspar augen gneisses near the top of the pluton.

2. Feldspar augen gneisses.

3. Biotite granodiorite pluton.

4. Graded to semi-granule beds.

5. Granofels dykes cut by unfoliated, medium-grained grey semipelite.

6. Vertical Scale: 1 cm = 50 m, 1 m = 4.13 ft.
Mixed paragneisses including amphibolites, semipelites, psammites, grits and feldspar augen paragneiss near the base.

Feldspar augen gneisses

Vertical Scale
1 cm = 50 m
1 in = 413 ft

Biotite granodiorite pluton

Light grey semipelite interlayered with psammite and quartzofeldspathic beds. Cut by unfoliated, medium grained felsic dykes.
3a Buff weathering quartzite

- Dominantly feldspar augen-bearing semipelite interbedded with calc-silicate, psammite and pelite layers

- Thinly bedded impure marbles

- Psammite interbedded with calc-silicate and semipelite

- Impure marbles

- Buff weathering quartzite

3b Buff weathering quartzite

- Semipelite interbedded with pelite, psammite and calc-silicate

2 Interbedded amphibolites, semipelites, psammites, grits and feldspar augen paragneisses near the base.

1000m

2 Streaky and feldspar augen gneisses with inliers
Pelite, semipelite, psammite

Pink, grey and rust coloured quartzofeldspathic grits interbedded with muscovite-rich pelite and semipelite

Quartzite (4a), calcisilicate, semipelite, yellowish marble

Rusty weathering pelite and semipelite.

Pale green impure marble

Black semipelite, pelite, quartzite and a distinct 3m thick white marble band (4b)

Impure marbles, locally scapolite-bearing

Dominantly rusty pelite and semipelite interbedded with calcisilicates, and minor impure marbles, quartzites and psammmites

Thinly laminated calcareous psammite and quartzofeldspathic grits interbedded with semipelites, minor calcisilicates
Hornblende, plagioclase, calcite calcsilicate gneiss

Kyanite-bearing semipelite and pelite

Clean, thinly layered quartzite with minor pelite layers

White, massive to thinly bedded marble, sheared graphitic marble at the base

Dominant calcsilicate interlayered with psammite, quartzite and semipelite near the top of the unit

Semipelite and garnet-muscovite-bearing quartzites at the top, underlain by thick black kyanite-sillimanite-bearing pelite

Vertical Scale
1 cm = 20 m
1 in = 67 ft
Calcareous quartzofeldspathic gneisses and pink quartzofeldspathic grits. Locally serpentine-bearing. Contains boudins and pegmatite dykes.

White to rust coloured, massive and foliated quartzite, interbedded with kyanite-bearing muscovite semipelite.

Refer to FIGURE 6. Unit 7.

Pelite, semipelite, psammite, with minor quartzites, graphitic marble and calcisilicates.
Psammite interbedded with calcsilicate and semipelite

Impure marbles

Buff weathering quartzite

Semipelite interbedded with pelite, psammite and calcsilicate

Buff weathering quartzite

Psammite, pelite, minor quartzite and semipelite

Interbedded amphibolites, semipelites, psammites, grits and feldspar augen paragneisses near the base

Streaky and feldspar augen gneisses with inliers of pelite, amphibolite, psammite and ultramafics, minor pegmatite

Ptarmigan Peak
Quartzite (4a), calcisilicate, semipelite, yellowish marble

Rusty weathering pelite and semipelite

Pale green impure marble

Black semipelite, pelite, quartzite and a distinct
3m thick white marble band (4b)

Impure marbles, locally scapolite-bearing

Dominantly rusty pelite and semipelite interbedded
with calcisilicates, and minor impure marbles,
quartzites and psammites

Thinline laminated calcareous psammite and quartzofeldspathic
grits interbedded with semipelites, minor calcisilicates
and pelites
Hornblende, plagioclase, calcite calcsilicate gneiss

Kyanite-bearing semipelite and pelite

Clean, thinly layered quartzite with minor pelite layers

White, massive to thinly bedded marble; sheared graphitic marble at the base

Dominant calcsilicate interlayered with psammite, quartz and semipelite near the top of the unit

Semipelite and garnet-muscovite-bearing quartzites at underlain by thick black kyanite-sillimanite-bearing pelites
FIGURE 4

STATION LOCATION MAP OF THE
downie/slide area

scale 1:25,000

Contour Interval = 500 Feet

LEGEND

Δ APIs Station location

2000 Elevation contours (feet)

Lake, stream; intermittent

Boundaries of Downie Slide

Ice or snowfield
**LEGEND**

- **Station location**
- **Elevation contours (feet)**
- **Lake, stream; intermittent**
- **Boundaries of Downie Slide**
- **Ice or snowfield**

**Stations located outside the map-area:**

**UTM Coordinates**

<table>
<thead>
<tr>
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<th>E</th>
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</table>

Stations located around the toe of the Downie Slide appear in Figure 7.
SUB-AREA 2
FIGURE 5

STRUCTURE MAP OF THE DOWNIE SLIDE

SCALE 1:25,000
LEGEND

PHASE 1 STRUCTURES: Axial plane and plunge of fold hinge

PHASE 2 STRUCTURES: Axial plane cleavage and plunge of fold hinge
plunge of $S_0/S_1$, intersection lineation
($\sim$ Vergence)

PHASE 3 STRUCTURES: Axial plane and plunge of fold hinge
($\sim$ Vergence)

PHASE 2 AXIAL SURFACE TRACE: Antiform, synform known; projected

PHASE 3 AXIAL SURFACE TRACE: Anticline, syncline known; projected

LITHOLOGIC CONTACT: Known; projected

Lithologic units as in FIGURE 3
PHASE 1 STRUCTURES: Axial plane and plunge of fold hinge

PHASE 2 STRUCTURES: Axial plane cleavage and plunge of fold hinge, plunge of $S_2$ on $S_1$ intersection lineation (v. Vergence)

PHASE 3 STRUCTURES: Axial plane and plunge of fold hinge (v. Vergence)

PHASE 2 AXIAL SURFACE TRACE: Antiform, synform known; project

PHASE 3 AXIAL SURFACE TRACE: Anticline, syncline known; project

LITHOLOGIC CONTACT: Known; projected

Lithologic units as in FIGURE 3

CATACLASTIC ZONE
PHASE 2 AXIAL SURFACE TRACE: Antiform, synform

PHASE 3 AXIAL SURFACE TRACE: Anticline, syncline

LITHOLOGIC CONTACT: Known, projected
Lithologic units as in FIGURE 3

CATACLASTIC ZONE

LINE OF CROSS-SECTION

STRATIGRAPHIC FACING DIRECTION

ICE OR SNOWFIELD
SUB-AREA 4

STRUCTURAL CROSS-SECTION.
FIGURE 6

STRATIGRAPHIC MAP AROUND THE TOE OF THE DOWNIE SLIDE

SCALE 1: 4,800

[Map diagram with scale and measurements]
LEGEND

Biotite granodiorite pluton

Light grey semipelite interlayered with psammite and quartzofeldspathic beds

Calcareous quartzofeldspathic gneisses and pink quartzofeldspathic grits. Locally serpentine-bearing

White quartzite interbedded with kyanite-bearing muscovite semipelite
Calcareous quartzofeldspathic gneisses and pink quartzofeldspar grits. Locally serpentine-bearing.

White quartzite interbedded with kyanite-bearing muscovite semipelite

Grey semipelite

White to pink quartzite with thick calcisilicate layers and lenses

Grey micaceous marble; sheared graphitic marble at the base

White, fuchsite-bearing quartzite

Rusty semipelite

Knotted to thinly layered dark green calcisilicate

Pelite, semipelite, psammite, with minor quartzites, graphitic marble and calcisilicates
Lithologic contact

Bedding: strike, dip

Outline of bedrock outcrops

Forestry and access roads
FIGURE 7

STATION LOCATION MAP AROUND THE TOE OF THE DOWNIE SLIDE

SCALE 1:4,800

Contour Interval = 100 Feet
LEGEND

△ (P) 25

Station location

2000

Elevation contours (feet)

Forestry and access roads

Stream, major; intermittent

Boundaries of Downie Slide (in part)
FIGURE 9
STRUCTURE MAP AROUND
THE TOE OF THE DOWNIE SLIDE

SCALE 1:4,800

400 0 400 800 1200
Feet

0 100 200 300 400
Metres

34
$S_2 = \nabla (35)$
$L_2 = (57)$

$S_3 = \nabla (11)$
$L_3 = (34)$

SUB-AREA 1
KEY TO SUB-AREAS

LEGEND

PHASE 2 STRUCTURES  Axial plane cleavage and possibly S₀/S₁ intersection line

PHASE 3 STRUCTURES  Axial plane
LEGEND

PHASE 2 STRUCTURES  Axial plane cleavage and plunge of fold hinge or $S_0/S_2$ intersection lineation (vergence)

PHASE 3 STRUCTURES  Axial plane and plunge of fold hinge (verge) and plunge of crenulation lineation

PHASE 2 AXIAL SURFACE TRACE  Antiform, synform; approximate

COLUMBIA RIVER CATACLASTIC ZONE
LEGEND

PHASE 2 STRUCTURES  Axial plane cleavage and plunge of fold hinge or $S_0$/$S_2$ intersection lineation (vergence √)

PHASE 3 STRUCTURES  Axial plane and plunge of fold hinge (vergence √); plunge of crenulation lineation

PHASE 2 AXIAL SURFACE TRACE  Antiform, synform approximate

COLUMBIA RIVER CATACLASTIC ZONE
END
FIN