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Large lateral ramps in the Eocene Valkyr shear zone: extensional ductile faulting controlled by plutonism in southern British Columbia

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Abstract—A 2.5-km high, S-facing lateral ramp links northern and southern segments of the ductile Eocene Valkyr extensional shear zone which defines the upper and outer boundary of the Valhalla core complex in southern British Columbia, Canada. The evolution of the Valkyr shear zone and of the lateral ramp is strongly influenced by the setting and geometry of Middle Jurassic tonalitic plutons and of Paleocene–Eocene leucogranite, aplite and pegmatite

Middle Jurassic plutons were emplaced in the region of the Valhalla complex as a series of interconnected, flat-bottomed laccoliths with the basal surfaces of adjacent bodies at the same structural level; however, on a large scale the southern portion of the laccolithic complex is structurally 2.5 km lower than the northern portion. The lower surface of the laccolithic complex formed the upper limit of injection of gently-dipping Paleocene–Eocene leucogranite sheets. As a consequence the upper margin of leucogranite is 2.5 km structurally lower in the south than in the north.

During the Eocene, extensional shear zones propagated along the interface between the upper plate stiffened by the cool, strong Middle Jurassic tonalite, and the lower plate made weak and ductile by voluminous hot Paleocene–Eocene leucogranite sheets. The northern and southern segments of the Valkyr shear zone propagated at two different structural levels, and a lateral ramp formed in the intervening zone. The ramp was localized at a rheological change across a S-dipping boundary between hot ductile Paleocene–Eocene leucogranite and an adjacent strong Middle Jurassic pluton.

Maximum displacement of 15–20 km occurs in the central portion of the northern segment of the Valkyr shear zone. The southern segment has only 1–3 km of displacement. This has left the pre-Eocene geological relationships of the southern Valhalla complex and its surrounding rocks nearly intact, and it can be demonstrated that the Valkyr shear zone formed with a gentle original dip. © 1997 Elsevier Science Ltd

INTRODUCTION

Substantial progress has been made in the last three decades towards understanding ductile extensional shear zones and their association with Cordilleran metamorphic core complexes (Armstrong, 1972, 1982; Coney, 1980). Important insights have been gained in understanding the transitions between the ductile and brittle regimes of low-angle extensional faults, the geometric similarities between brittle and ductile faults, the relationship between structures in the hanging wall and footwall of master detachment faults, and the exhumation history of these faults (Wernicke, 1985; John, 1987; Buck, 1988; Davis and Lister, 1988; Parrish *et al.*, 1988; Wernicke and Axen, 1988; Lister and Davis, 1989, and references therein; Scott and Lister, 1992; Lister and Baldwin, 1993). However, there is still much to be done to document the three-dimensional propagation and geometry of extensional shear zones. Gibbs (1983) demonstrated that similarities between thrust and extensional fault geometries, and therefore large lateral ramps in extensional shear zones by analogy to lateral ramps in thrust fault systems (Dahlstrom, 1970; Boyer and Elliott, 1982), are to be expected.

This paper presents the first detailed documentation of lateral and frontal ramps in a ductile extensional shear zone, as well as controls on localization and propagation of the shear zone. The Valkyr shear zone (Carr *et al.*, 1987) is exposed over a 20 × 80 km area on the flanks of the Valhalla complex in southern British Columbia (Fig. 1). Generally sheet-like gneisses and granitic rocks are disposed in three gently-arched subsidiary domal culminations. The Valkyr shear zone has been described on the margins of Valhalla and Passmore domes in the northern part of Valhalla complex (Carr *et al.*, 1987); however, there was initially some difficulty in identifying the continuation of the Valkyr shear zone south of Lower Arrow Lake and Castlegar (Fig. 1). Remapping of ~600 km^2 of the southern Valhalla complex at a scale of 1:25,000, 1:10,000 and, locally, 1:2000 (Figs 2–4) resulted in the identification of a ~500 m thick zone of strained rocks, here termed the southern segment of the Valkyr shear zone. It lies at a structural level that is 2.5 km deeper than the northern segment. We have

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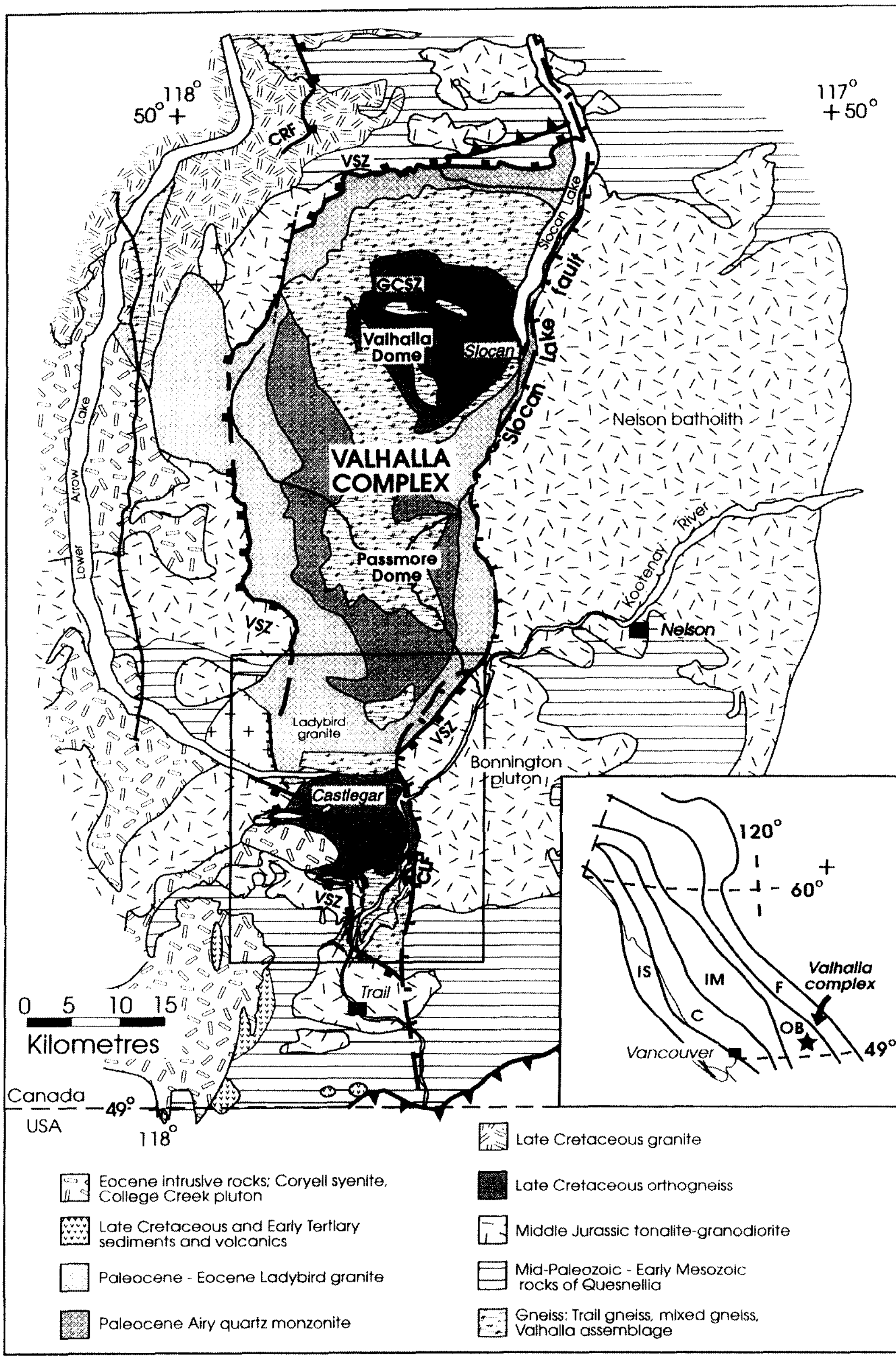


Fig. 1. Geological overview map of the Valhalla complex and surrounding area modified after Carr *et al.* (1987). Normal faults with top side down-to-the east displacement include: the brittle Champion Lakes fault (CLF); the ductile–brittle Columbia River (CRF) and Slocan Lake (SLF) fault zones; and the ductile Valkyr shear zone (VSZ). The Gwillim Creek shear zones (GCSZ) in the northern Valhalla complex are ductile thrust faults. The box in the southern area shows the location of Fig. 2, and the inset shows the location of the Valhalla complex within the morpho-geological belts of the Canadian Cordillera. (Inset: C, Coast belt; F, Foreland belt; IM, Intermontane belt; IS, Insular belt; OB, Omineca belt.)

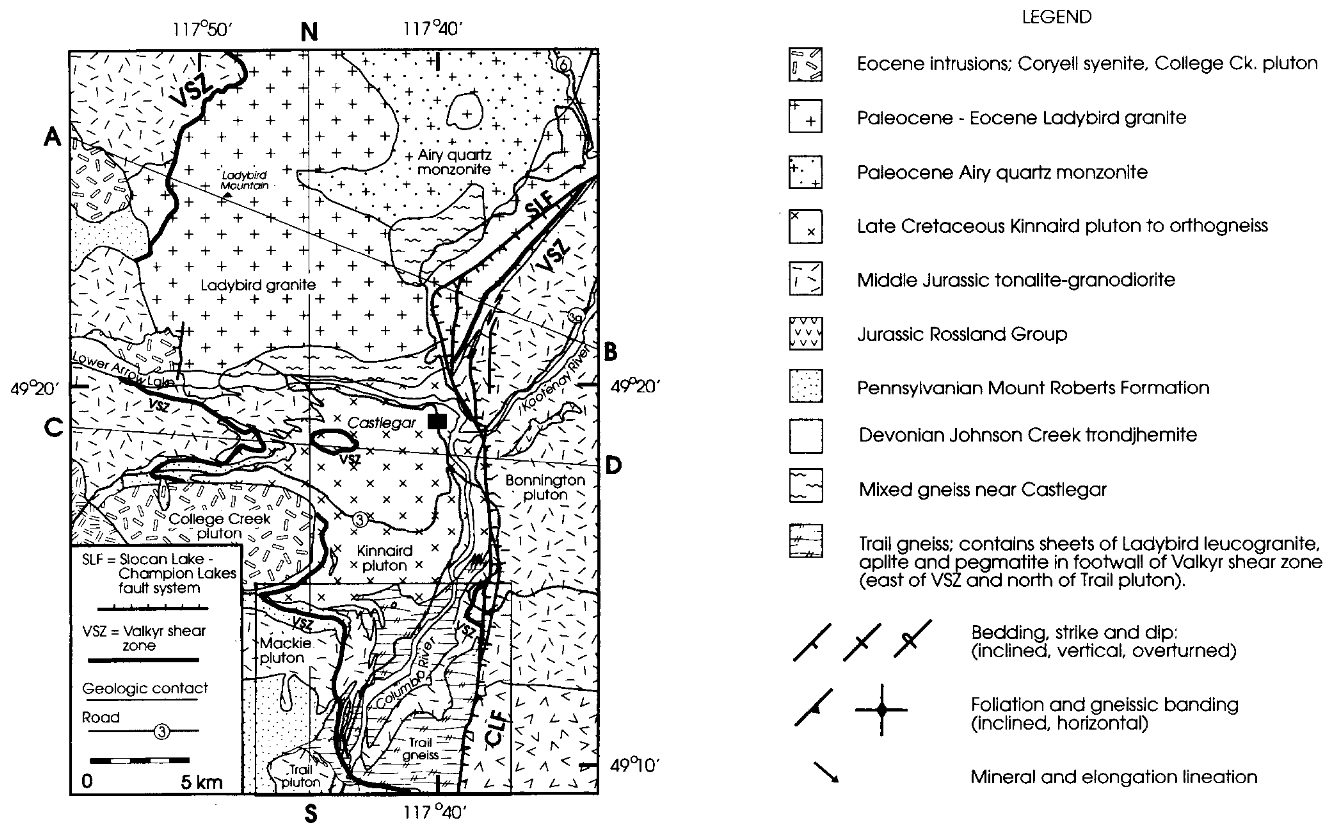


Fig. 2. Geological map of the southern Valhalla complex: A–B, C–D and N–S indicate the locations of three of the cross-sections shown in Fig. 4, and the box in the southern portion shows the location of Fig. 3. All rock units structurally below the Valkyr shear zone, that in map view lie between the traces of the Valkyr shear zone and the Slocan Lake–Champion Lakes fault zone, comprise significant proportions of Paleocene–Eocene leucogranite, pegmatite and aplite sheets.

documented the kinematics of this zone, the presence of frontal and lateral ramps, as well as the 2.5 km high S-facing Arrow Lake lateral ramp which connects the northern and southern segments of the Valkyr shear zone (cross-section N–S, Figs 4 & 5).

The displacement on the southern segment of the Valkyr shear zone, of less than 3 km, is accommodated on discontinuous strands, and pre-extensional geology is not entirely overprinted by extension. This setting allows us to document the orientation of the incipient Valkyr shear zone, and to examine the relationship between the shear zone and granitoid intrusions that play an important role in the evolution of the Valhalla complex. We propose the hypothesis that for core complexes with abundant young leucogranite, like the Valhalla complex, it is the emplacement of the leucogranite which defines the complex. Melts rise to some well-defined boundary and low-angle detachment takes place just below that boundary, in a manner predicted by the model of Melosh (1990).

GEOLOGICAL SETTING

The Valhalla complex, first recognized by Little (1960) and Reesor (1965), is a metamorphic core complex located to the west of the Rocky Mountain foreland fold and thrust belt. It occurs in the southeastern Omineca belt (Fig. 1) in the portion of Quesnel Terrane that overlaps rocks of North American affinity (Cook *et al.*, 1988). The ductile Valkyr shear zone formed during an Eocene episode of extension and metamorphic core complex development in southern British Columbia and adjacent portions of Washington and Idaho (Carr *et al.*, 1987; Parrish *et al.*, 1988). The Valhalla complex comprises high-grade ortho- and paragneisses that were intruded and ductilely deformed in the Paleocene–Eocene (Table 1). It constitutes the lower plate that lies beneath the Valkyr shear zone, which separates this lower plate from an upper plate that on the map surrounds the Valhalla complex, and comprises the southern portion of Quesnel Terrane (Fig. 1 and Table 1). The upper plate is characterized by Paleozoic, Triassic and Lower Jurassic assemblages, at chlorite, biotite and garnet grade, that have been deformed and intruded by Middle Jurassic, mid-Cretaceous and Middle Eocene plutons (Little, 1960, 1982; Parrish, 1995). In contrast to the lower plate, leucogranites of the Paleocene–Early Eocene Ladybird suite are absent from the upper plate.

The lower plate Valhalla complex comprises sheets of paragneiss and Late Cretaceous and Paleocene–Eocene orthogneiss (Table 1) and is characterized by amphibolite-facies metamorphism (Reesor, 1965; Simony, 1979; Halwas and Simony, 1986; Carr *et al.*, 1987). The

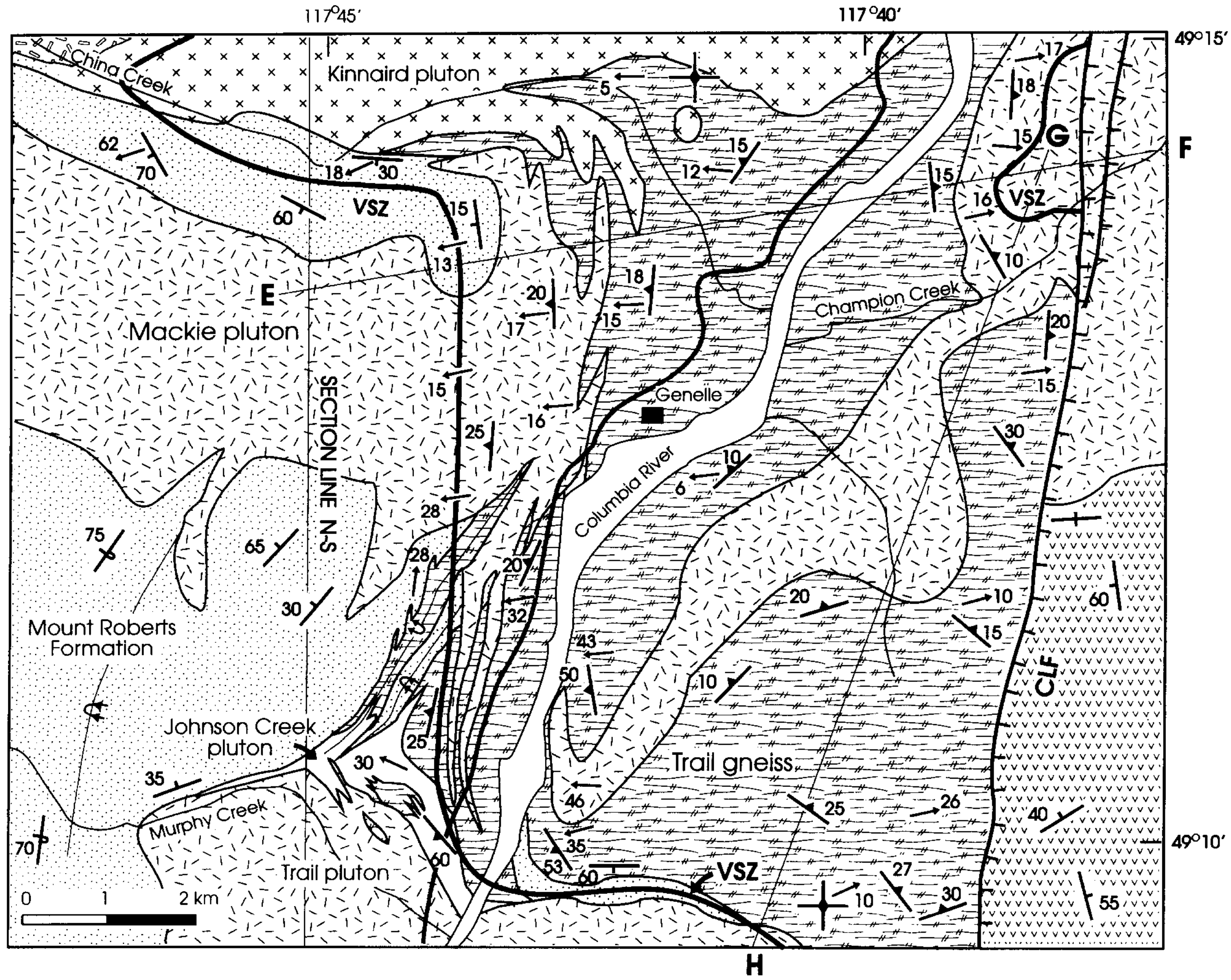
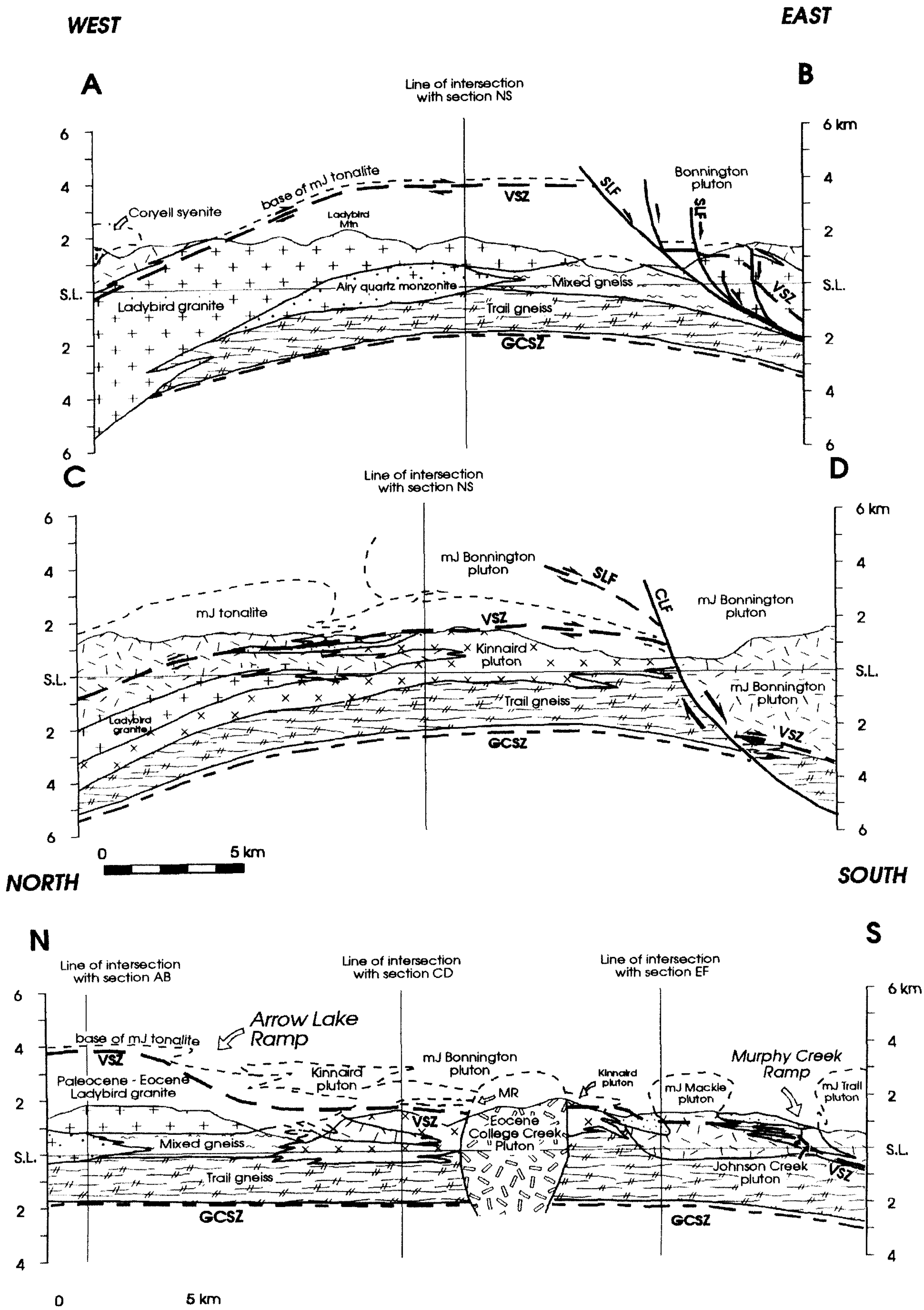


Fig. 3. Detailed map of the southernmost part of Valhalla complex showing the relationships between the Trail gneiss, Mount Roberts Formation, Mackie pluton and Eocene extensional structures. E–F and G–H indicate the location of cross-sections shown on Fig. 4. See Fig. 2 for location and legend. CLF, Champion Lakes fault zone; VSZ, Valkyr shear zone. All rock units structurally below the Valkyr shear zone, that in map view lie between the trace of the Valkyr shear zone and the Slocan Lake–Champion Lakes fault zone, comprise significant proportions of Paleocene–Eocene leucogranite, pegmatite and aplite sheets.

complex has undergone a long-lived pre-Tertiary deformation and thermal history (Simony *et al.*, 1990); however, for the purposes of this paper we focus on the Paleocene and Eocene history. The complex was injected by an abundance of Paleocene–Eocene leucogranite and pegmatite of the Ladybird suite. A composite leucogranite sheet up to 3 km thick forms the upper portion of the lower plate in the Passmore dome in the region north of Lower Arrow Lake (Figs 1, 2 & 4, cross-section A–B). In contrast, south of the lake in the area herein referred to as the southern Valhalla complex, the lower plate is invaded by innumerable sheets of leucogranite and associated garnet aplite and garnet pegmatite that are up to 100 m thick.

At the deepest exposed levels of the Valhalla dome (Fig. 1), well beneath the Valkyr shear zone, there are annealed mylonite zones with an apparent top-to-the-east shear sense. They are termed the Gwillim Creek

Fig. 4. Geological cross-sections of the southern Valhalla complex illustrating the relationships between plutons and the Valkyr shear zone (VSZ). CLF, Champion Lakes fault zone; SLF, Slocan Lake fault zone. Sections A–B, C–D and E–F are oriented east–west and are intersected by section N–S. Section G–H is oriented north–south and intersects E–F. Legend and location lines are shown on Fig. 2 except location lines for sections E–F and G–H which are shown on Fig. 3, and are at a larger scale. Balancing short sections in such a plutonic–gneissic complex is not possible; however, the intersecting sections provide some tests for internal consistency. The unpatterned region beneath the Gwillim Creek shear zones (GCSZ) represents unexposed rocks in the subsurface which probably include rocks of North American affinity and tectonic slices of Quesnel terrane. Important boundaries projected into the sections are the base of the Kinnaird pluton, base of the Middle Jurassic Mackie–Bonnington laccolithic complex, and top and base of a stack of isoclinal folds (section E–F). Section A–B illustrates the trace of the Arrow Lake ramp in the hanging wall of the Slocan Lake–Champion Lakes fault (SLF). Section C–D is south of Arrow Lake ramp and illustrates the trajectory of the Valkyr shear zone through the Kinnaird pluton. Section N–S illustrates the nature of the lateral ramps and how they cut across structural levels. Section E–F illustrates the manner in which the Valkyr shear zone cuts eastward and structurally downward through the plutonic and structural stack. MR, Mount Roberts Formation. Section G–H illustrates the Murphy Creek ramp in the footwall of the Champion Lakes fault. The apparent northward dip of the Valkyr shear zone is an artifact of the oblique angle between the section line and the E-facing frontal ramp.


WEST
EAST
A
B
Line of intersection with section NS
Coryell syenite
base of mJ tonalite
VSZ
SLF
Bonnington pluton
Ladybird Mtn
Ladybird granite
Airy quartz monzonite
Mixed gneiss
Trail gneiss
GCSZ
S.L.
6 km
C
D
Line of intersection with section NS
mJ Bonnington pluton
mJ tonalite
CLF
Kinnaird pluton
Ladybird granite
0 5 km
NORTH
SOUTH
N
S
Line of intersection with section AB
Line of intersection with section CD
Line of intersection with section EF
Arrow Lake Ramp
Murphy Creek Ramp
Paleocene - Eocene Ladybird granite
MR
Eocene College Creek Pluton
mJ Mackie pluton
mJ Trail pluton
Johnson Creek pluton

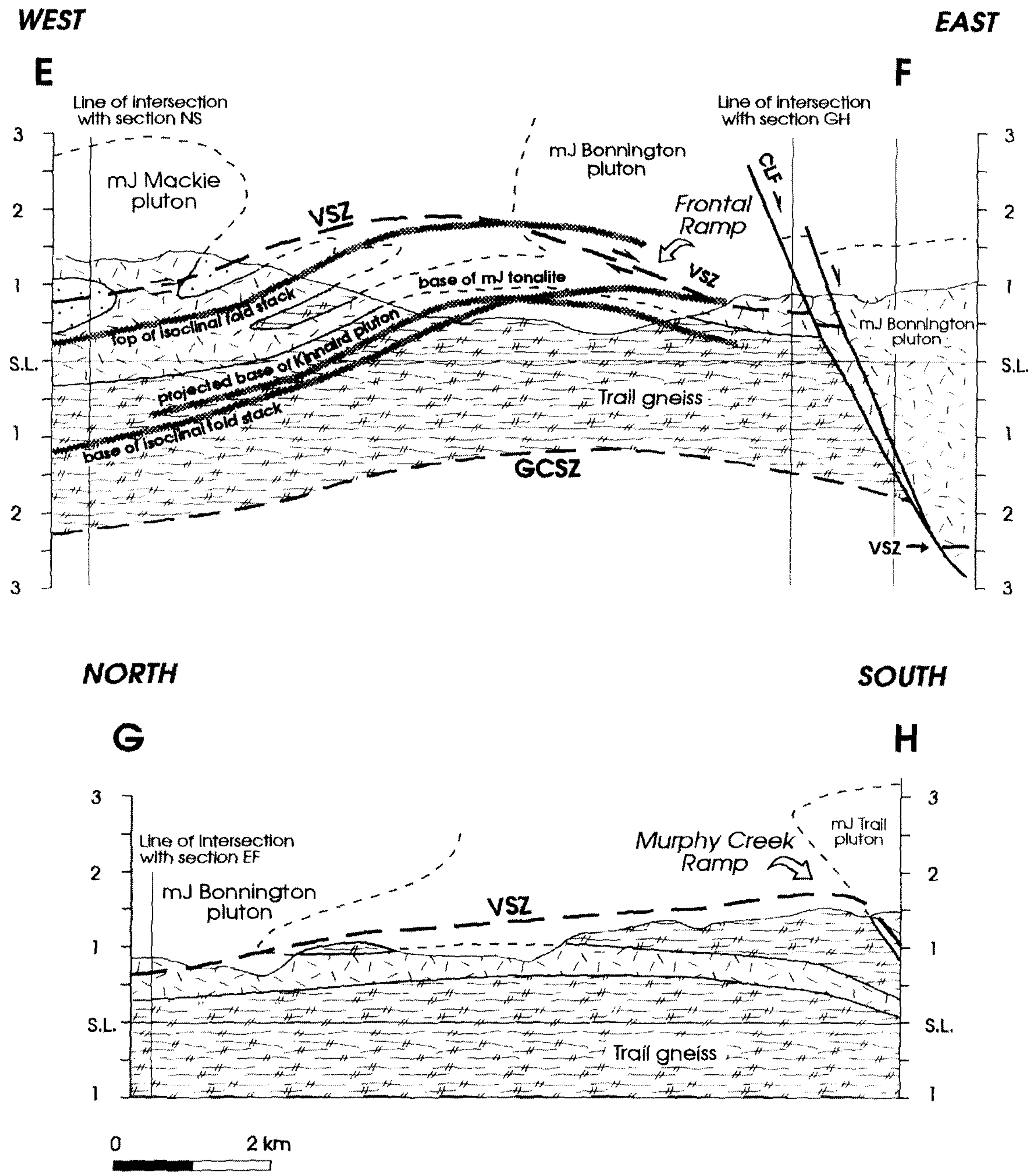


Fig. 4. (*continued*)

shear zones and are interpreted as Late Cretaceous thrust faults because they duplicate rock units (Parrish *et al.*, 1985, 1988; Heaman and Parrish, 1991; see also Cook *et al.*, 1988; Eaton and Cook, 1990). In the southern Valhalla complex, a zone of strained rocks can be delineated (Halwas and Simony, 1986) in which the fabric intensity increases downward. This fabric is older and unrelated to the Valkyr shear zone, and is likely to be correlative with the upper Gwillim Creek shear zone.

The Valhalla complex is bounded on the east side by the E-dipping Slocan Lake–Champion Lakes fault zone, an Eocene extensional fault system which is linked with, and outlasted motion on, the Valkyr shear zone (Corbett and Simony, 1984; Carr *et al.*, 1987; Parrish *et al.*, 1988; Cook *et al.*, 1988; Parrish, 1995). North of latitude 49°20′N, the Slocan Lake fault dips east at 30–40° and the fault zone consists of a lower ductile portion characterized by a distinct mylonite zone which is overprinted in the upper portion by cataclasite ranging from ultra-cataclasite to fault breccia. On the eastern margin of the Valhalla dome, the Slocan Lake fault merges down-dip with the Valkyr shear zone (Carr *et al.*, 1987; Brown *et al.*, 1992). South of latitude 49°20′N, the Champion Lakes fault, a southern, high-level strand of the Slocan Lake fault, dips east at 60–70° and cuts across gently-dipping mylonite zones of the Valkyr shear zone. The Champion Lakes fault is marked by a cataclastic zone. In its central portion, near latitude 49°45′N, the Slocan Lake

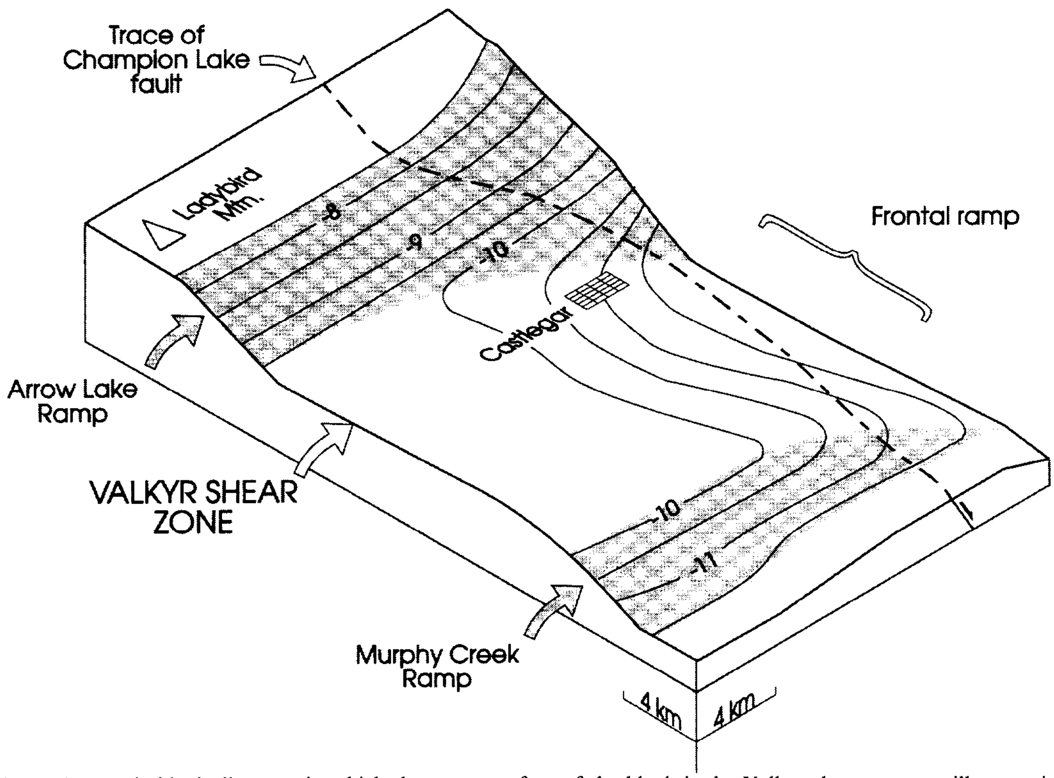


Fig. 5. Isometric block diagram, in which the upper surface of the block is the Valkyr shear zone, to illustrate in three dimensions the restored shape of the Valkyr shear zone with two S-facing lateral ramps and an E-facing frontal ramp in the southern Valhalla complex. The arching of Valhalla complex and motion on the Champion Lake fault have been removed. The flat, at the base of the Lower Arrow Lake ramp, is taken to have been at 10 km below Eocene sea level and the structure contours are at 0.5 km intervals. The view is to the NNE.

fault has approximately 10 km of down-to-the-east dip-slip (Carr *et al.*, 1987). The Champion Lakes fault has 4–6 km of dip-slip near latitude 49°20′N (Corbett and Simony, 1984) and the fault terminates near latitude 49°N.

THE VALKYR SHEAR ZONE

The Valkyr shear zone is a heterogeneous zone of ductile strain that is gently arched over the Valhalla complex, and is exposed on its northern, western and southern margins. It was active in the ductile regime and does not have an exposed brittle overprint. Mylonitic fabrics, where strongly enough developed, consistently yield a top-to-the-east shear sense (Halwas and Simony, 1986; Carr *et al.*, 1987). Carr *et al.* (1987) interpreted the Valkyr shear zone to be a normal fault because it apparently cut down-section in the direction of transport, and locally placed low-grade hanging wall rocks over high-grade footwall rocks. Based on field relationships indicating that the Valkyr shear zone re-emerges to the west of Valhalla complex, Parrish *et al.* (1988) interpreted the shear zone to root to the east. Detailed mapping in the southern Valhalla complex (Figs 3 & 4, cross-section E–F) supports this interpretation.

The Valkyr shear zone was first described and characterized on the margins of the Valhalla and Passmore domes (Carr *et al.*, 1987), and this will be referred to as the northern segment. In the upper plate Middle Jurassic plutons and metasedimetary rocks are mylonitic throughout a zone <200 m thick, whereas the lower plate strain zone is characterized by mylonites and protomylonites up to 2 km thick within the Paleocene–Eocene Ladybird granite. The strongest mylonitic fabrics coincide with the contact between Ladybird granite, which was hot at the time of motion on the shear zone, and the relatively cold and strong upper plate rocks. This boundary is locally partly obscured by medium-grained to pegmatitic sheets and stocks of Ladybird granite which were emplaced between 58 and 56 Ma (Parrish *et al.*, 1988), during and following the last motion on the Valkyr shear zone. Carr *et al.* (1987) gave a detailed description of the interpretation, and fabric, timing and kinematic studies of the northern segment of the Valkyr shear zone.

Southern segment of the Valkyr shear zone

South of Lower Arrow Lake, discontinuous mylonite bands occur in a diffuse zone 100–500 m thick at or near the upper limit of Ladybird leucogranite sheets and near the base of the Jurassic laccolithic bodies. The individual mylonite bands are 10–100 cm thick with a strong planar and linear fabric, and they are contained within moderately- to weakly-foliated rocks. The fabrics are comparable to those in the Ladybird granite of the northern Valhalla complex, documented by Carr *et al.* (1987) who categorized deformation fabrics into three zones. Fabrics

Table 1. Geology of the Valhalla complex and surrounding region

	Lithology	References
Lower plate Valhalla complex geology		
Eocene		
Dykes	Basaltic and gabbroic dykes	Souther, 1977; Little, 1982
Coryell intrusives	Syenite	Little, 1957, 1960; Parrish *et al.*, 1988; Stinson and Simony, 1994
Eocene–Paleocene		
Ladybird granite	Granite, aplite, granitic pegmatite	Little, 1960; Reesor, 1965; Halwas and Simony, 1986; Carr *et al.*, 1987; Parrish *et al.*, 1988; Carr, 1992;
Paleocene		
Airy quartz monzonite	K-feldspar megacrystic biotite $\pm$ hornblende quartz monzonite-granite	Reesor, 1965; Carr *et al.*, 1987
Late Cretaceous		
Kinnaird pluton	Porphyritic quartz monzonite-granite sheets	Simony, 1979; Halwas, 1986; Halwas and Simony, 1986; Parrish *et al.*, 1988
Mulvey gneiss	Melanocratic K-feldspar megacrystic biotite–hornblende granodioritic gneiss intruded by leucocratic grantioid veins	Reesor, 1965; Parrish, 1984; Carr *et al.*, 1987; Parrish *et al.*, 1988; Parrish, 1992
Middle Jurassic		
Base of Bonnington and Mackie plutons	Base of tonalitic and granodioritic laccoliths	Simony, 1979; Crowe, 1981; this contribution
Pennsylvanian		
Mount Roberts Formation equivalents	Semi-pelitic schists	Simony, 1979; Little, 1982; this contribution
Devonian		
Johnson Creek pluton	Leucotonalite	Simony *et al.*, 1990
Trail gneiss	Banded hornblende gneiss, biotite gneiss	Simony, 1979
Paleozoic (?)		
Valhalla assemblage	Quartzo-feldspathic schist, marble, calc-silicate gneiss, quartzite, minor pelite schists, amphibolite gneiss and ultramafics	Reesor, 1965; Parrish *et al.*, 1985; Schaubs and Carr, 1995
Age uncertain		
Paragneiss of Gwillim Creek area	Semi-pelite gneiss, quartzite, pelitic schists	Reesor, 1965; Parrish *et al.*, 1985
Mixed gneiss of Castlegar area	Heterogeneous quartzo-feldspathic paragneiss with amphibolite and calc-silicate layers	Little, 1960; Reesor, 1965; Simony, 1979
Upper plate geology surrounding the Valhalla complex		
Eocene		
Dykes	Basaltic and gabbroic dykes	Souther, 1977; Little, 1982
Coryell intrusives	Syenite	Little, 1957, 1960; Parrish *et al.*, 1988; Stinson and Simony, 1994
College Creek pluton	Granite	Halwas, 1986; Halwas and Simony, 1986; Parrish *et al.*, 1988
Marron volcanics	Intermediate tuff	Little, 1982; Fyles, 1984; Stinson and Simony, 1994
Late Cretaceous		
Sophie Mountain Formation	Conglomerate and sandstone	Little, 1982
Granite stocks	Porphyritic two-mica granite-quartz monzonite stocks	Read and Wheeler, 1976; Little, 1982; Archibald *et al.*, 1984; Halwas and Simony, 1986; Parrish, 1992
Middle Jurassic		
Nelson batholith, Bonnington and Mackie plutons, tonalite and granodiorite laccoliths and stocks	Massive porphyritic granodiorite, tonalite and granodiorite laccoliths, minor granite and syenite	Little, 1957,1960, 1982; Reesor, 1965; Nguyen *et al.*, 1968; Simony, 1979; Crowe, 1981; Archibald *et al.*, 1983; Corbett and Simony, 1984; Carr *et al.*, 1987; Parrish *et al.*, 1988; Ghent *et al.*, 1991; Parrish, 1992; Sevigny and Parrish, 1993
Early Jurassic		
Rossland Group	Massive black shale, volcaniclastic rocks, augite porphyry, siltstone, sandstone	Little, 1960, 1982; Tipper, 1984; Höy and Andrew, 1991
Triassic		
Slocan Group	Shale and phyllite with arenaceous and calcareous interbeds	Little, 1960, 1982: Tipper, 1984; Höy and Andrew, 1991; Roback and Walker, 1995
Paleozoic and Triassic		
Nemo Lakes belt	Semi-pelitic and pelitic schist, calcareous schist, amphibolite and ultramafics	Read and Wheeler, 1976; Parrish, 1981
Pennsylvanian (?)		
Mount Roberts Formation	Siltstone, shale, sandstone, congromerate, limestone	Little, 1957,1960, 1982; Simony, 1979; Roback and Walker, 1995

in the southern segment of the Valkyr shear zone consist of bands of Zone B protomylonites and Zone C mylonites. Mylonitic lineations are oriented E–W (Fig. 3).

Mylonitic fabrics within widespread granitic and granodioritic rocks are characterized by elongate quartz grains flattened in the foliation, and feldspars that are disrupted and pulled apart with bent and broken twin lamellae. On the west side of the Columbia River, σ-porphyroclasts are abundant in the mylonitic zones seen in granite of the Kinnaird pluton and in sheets of pegmatite and Ladybird granite in upper China Creek. These are best seen in E-striking vertical faces and they indicate top-to-the-east motion. The fabrics and kinematic sense are the same as those documented by Carr *et al.* (1987) in the northern segment, particularly those that they designated as Zone B.

In metasedimetary schists, microscopic examination reveals mylonitic zones with intensely strained quartz grains between foliae of well-formed reddish-brown biotite and muscovite. Shear is concentrated at the margins of the schist layers and *S–C* fabrics indicate a top-to-the-east sense of motion. At the outcrop scale, quartz veinlets and pods are offset across mylonite zones with the same sense of shear. This is seen, for example, in the narrow strip of Mount Roberts schist and granofels at the north margin of the Trail pluton, east of the Columbia River (Fig. 3).

The upper boundary of mylonitic fabric related to the Valkyr shear zone broadly coincides with the upper limit to which sheets of leucogranite, aplite and pegmatite of the Ladybird suite have been injected, and the map trace of the southern segment can be taken to represent both the upper limit of Valkyr shear zone fabrics and the top of the leucogranite zone (Figs 2 & 3). In detail, however, the upper limit of the Ladybird leucogranite is a surface with steps and re-entrants on a scale of tens and hundreds of metres rather than a smooth surface as our generalized map would suggest. This close association between the Valkyr shear zone and the presence of Ladybird leucogranite suggests that the ductile detachment was localized into the upper margin of the zone heated and rendered ductile by leucogranite injection.

In the southern segment, the Valkyr shear zone also approximately coincides with the upper limit of significant penetrative pre-Eocene fabrics. This relationship is not seen in the northern segment where the Gwillim Creek shear zones are well below the Valkyr shear zone, and is simply due to the fact that the upper margin of leucogranite injection is stucturally lower in the south than in the north.

In general, the steep Champion Lake fault juxtaposes upper-plate rocks against lower-plate Valhalla complex gneisses with the ubiquitous granite, pegmatite and aplite of the Ladybird suite. However, there is one place south of Castlegar, on the east side of the Columbia River at 760 m elevation near Champion Creek (Figs 3 & 4, cross-section E–F), where the Valkyr shear zone and the rocks in its immediate hanging wall are preserved in the footwall of the Champion Lakes fault. There we see the upper limit of leucogranite interleaved with Middle Jurassic tonalite, and mylonitic foliations of the Valkyr shear zone dipping 10–30° eastward. It is clear that the Valkyr shear zone is arched over the domal structure of the southern Valhalla complex. This is similar to the geometry observed at the northern margin of Valhalla dome (Reesor, 1965; Carr *et al.*, 1987) (Fig. 1).

The depth at which the southern Valkyr shear zone was active is difficult to determine. The shear zone is partly superimposed on rocks that had previously undergone Jurassic and Cretaceous shear, and the metamorphic mineral assemblages are in part of Jurassic and Cretaceous age. Leucogranites coeval with Valkyr shear zone motion lack mineral assemblages that are useful for geobarometry. A conservative depth estimate was obtained from the known stratigraphy, structure and plutonic geometry. On the west flank of the southern Valhalla complex, the Valkyr shear zone lies close to the base of the Mount Roberts Formation, which is about 1 km thick (Simony, 1979). It is overlain by $\sim$3 km of Lower Jurassic Rossland Group (Little, 1982; Höy and Andrew, 1991). This package was thickened by folding, thrusting and emplacement of Jurassic laccoliths to some 6–10 km (Halwas, 1986), and it was unconformably overlain in Eocene time by 1 km, perhaps 2 km, of volcaniclastics (Little, 1982; Fyles, 1984; Stinson and Simony, 1994). This gives a depth of 8–12 km, and in constructing the contours for the block diagram (Fig. 5), we picked the round number of 10 km.

A frontal ramp in the Valkyr shear zone

Geological relationships shown in Fig. 3 provide evidence that the Valkyr shear zone cuts down-section in the direction of transport and is in fact a normal fault (Figs 3 & 4, cross-section E–F). A stack of recumbent isoclinal folds, that affect the base of the Mount Roberts Formation, wraps around the southwest and south margin of the Valhalla complex (Fig. 3). The Pennsylvanian Mount Roberts Formation comprises metasiltstone, metasandstone and metaconglomerate at biotite and garnet grade, and it rests unconformably on the Trail gneiss, a complex of layered gneisses cut by Devonian intrusions (Simony *et al.*, 1990). The Trail gneisses on the east side of the Columbia River, much injected by leucogranite, lie structurally below the lowest Mount Roberts infolds, and are thus structurally below the stack of isoclinal folds. Northwest of Murphy Creek, a broad syncline of Mount Roberts Formation lies above it. The top and bottom of the stack of isoclines are truncated by the Mackie pluton but are projected 2.5 km along strike into cross-section E–F (Fig. 4).

The emplacement of Middle Jurassic and mid-Cretaceous plutons, like the Mackie–Bonnington complex and layered Kinnaird pluton (Halwas and Simony, 1986), was guided by older foliation in the Mount Roberts Formation and the Trail gneiss in such a manner as to create a layered intrusive stack. Some of the contacts within the stack are depicted in the cross-section E–F (Fig. 4). This cross-section shows how the Valkyr shear zone cuts downward to the east through the intrusive and structural stack to form an E-facing frontal ramp as shown in Fig. 5.

Displacement estimates—southern segment of the Valkyr shear zone

The fact that discontinuous bands of mylonite, up to 1 m thick and ~500 m long, were formed requires that there was at least some displacement on the southern Valkyr shear zone; however, the lack of significant offset and distortion of contacts at the map scale indicate that the displacement is small. We will outline below two lines of argument for assessing the order of magnitude of the displacement. First, we will use our map pattern to determine how much displacement is permissible while still maintaining the continuity of geology mapped throughout the ~500 m thick zone. This approach yields 500–1000 m of displacement. Second, we can estimate the shear strain required to produce observed angular relationships between plutonic contacts and the Valkyr shear zone, with and without dilation across the zone. This approach yields ~2.8–5 km of displacement, but represents an overestimate.

A lack of offset and distortion of contacts across the Valkyr shear zone is particularly clear where it crosses contacts of the Mackie and Kinnaird plutons (Fig. 2) and the stack of recumbent isoclinal folds of Trail gneiss and Mount Roberts Formation (cross-section E–F, Figs 3 & 4). Southwest of Genelle (Fig. 3), the Mount Roberts–Trail gneiss contact and the isoclinal folds can be traced from the upper plate, at garnet grade and with no Ladybird leucogranites, aplites or pegmatites, across the Valkyr shear zone into the underlying lower plate where the leucogranites dominate. There are uncertainties however, of the order of 50–200 m, where contacts may be locally placed. These result from a combination of gaps between outcrops, rock classification problems and local variations in the dip of contacts. The map data can therefore accommodate alternative interpolation of contacts, and local offsets or distortions of contacts within the Valkyr shear zone could be shown on our maps and cross-sections, within certain limits. Displacements in the range of 500–1000 m could be reasonably interpreted from such alternative versions of our maps.

A maximum estimate of displacement or shear strain may be obtained from the angle between pluton contacts and the Valkyr shear zone. Where the rock slopes are approximately normal to the direction of shear, there are intrusive contacts locally preserved at angles of nearly 90° to the shear plane. In contrast, on slopes that are nearly parallel to the shear direction, most contacts are nearly parallel to shear surfaces at the outcrop scale, and on the map scale make an angle with the shear zone of 10–15°. If many of these intrusive contacts had originally been at 90° to the Valkyr shear zone shear plane, and we consider all the strain to be simple shear related to the displacement on the Valkyr shear zone, which clearly it is not, we can obtain a crude maximum estimate of Valkyr shear zone displacement. The equation for shear strain in an homogeneous simple shear zone, with no identifiable strain gradients, is given by Ramsay (1967, equation 3-71, p. 88). It can be rearranged to solve for the displacement, D, due to simple shear:

$$D = t(\cot \alpha' - \cot \alpha),$$

where t is the shear zone thickness (500 m), α' is the angle between a marker and the shear plane after strain (10°), and α is that same angle before shear (90°). D is found to be 2.8 km. Dilation across the shear zone would permit yet larger displacements using the same parameters. As the southern Valkyr shear zone is distinguished from the surrounding gneisses only by the presence of discontinuous mylonite zones dilation must then be limited. Therefore displacement of less than twice 2.8 km, say 5 km, can be taken as an extreme maximum, with the actual displacement due to Valkyr shear zone strain likely to be much less, say, 1–3 km.

The shear zone is superimposed on and generally concordant with older planar and linear fabrics (Fig. 4). The intersection of pluton contacts and the Valkyr shear zone, magmatic lineations and stretching lineations in the lower part of the Mackie pluton are all generally parallel. Only in a minor way does this parallelism reflect Valkyr shear zone strain; it is instead largely the result of the controlling influence of Jurassic foliation on Jurassic magma emplacement and on Paleocene shearing. Using such parallelism as a measure of Valkyr shear zone strain leads to gross overestimates.

Low-angle initiation of the Valkyr shear zone

The large areal extent of low-angle ductile extensional detachment surfaces (Davis, 1980), and the low angle between normal faults and paleohorizontal in syn-extensional stratigraphy (Davis and Lister, 1988; Scott and Lister, 1992), have been taken as evidence that normal faults originated and were active at low angles. We also can demonstrate that the low-angle Valkyr shear zone has not been rotated into its present orientation due to subsequent tectonism. From our observations we may add yet another line of evidence in support of the low-angle initiation of ductile extensional detachments. Because of the small displacement on the southern Valkyr shear zone, the low-angle initiation and propagation stages of the shear zone have been preserved and have not been transposed, rotated or obliterated during subsequent extensional shear strain.

The pre-extensional geometry of the region is one of subhorizontal surfaces which include the unconformity at the base of the Mount Roberts Formation, the enveloping surface of the stack of isoclinal folds south of the Mackie pluton (cross-section E–F, Figs 3 & 4), the lower boundary of Middle Jurassic tonalitic laccoliths, and contacts and internal layers of Cretaceous and Paleocene orthogneiss (Fig. 4). The Valkyr shear zone is, in part, concordant or at a low angle to these surfaces. There are two lines of evidence to indicate that the post-Eocene rotation of rocks is regionally insignificant, and that the low angle between layering and the Valkyr shear zone is an Eocene relic. First, there is a Late Cretaceous unconformity surface preserved within a 600 m elevation range throughout an area of 700 km^2 to the south and west of Trail. Isolated outliers (Fig. 1; also see Little, 1982) of broadly warped and tilted, right-way-up, Late Cretaceous conglomerate and Eocene volcanics lie unconformably on about the same Lower Jurassic strata throughout the area. Second, upper plate rocks with essentially the same low grade of regional metamorphism are exposed at the surface for some 30 km to the east and west of the southern Valhalla complex. They comprise a Jurassic sedimentary and volcanic sequence (Fig. 1) that was folded into upright folds and locally cut by faults (Little, 1960, 1982; Höy and Andrew, 1991). These relationships, seen in rocks that were not rotated with respect to the flanks of Valhalla complex, indicate that tectonic movements that post-date Eocene Valkyr shear zone displacement resulted only in local tilts and broad open folds, and did not significantly modify the regional Eocene geometry.

Relationship to plutonism

Small displacement on the southern Valkyr shear zone in conjunction with insignificant post-Eocene deformation has left the plutonic geology essentially intact, and the igneous aspect of core complex formation is preserved without the overprint of large rotations, large strains and large-scale detachment faulting, as is commonly the case in core complexes. This situation leads to the following important observations about the extensional detachment in its incipient stage.

In the southern part of the Valhalla complex, over an area of at least 350 km^2, Paleocene–Eocene leucogranite was emplaced into the crust up to a level largely defined by the base of a Middle Jurassic laccolithic complex. It is only near the boundary between Jurassic and Eocene intrusives that the southern segment of the Valkyr shear zone nucleated and propagated. This relationship holds over such a large area that it cannot be ascribed to chance alone. That boundary and not merely the presence of leucogranite localized shear. This also holds true for much of the larger northern area (Fig. 1); however, there the original relationships are overprinted by large strains.

In the southern Valkyr shear zone there are mylonite bands in Jurassic tonalite, Cretaceous porphyritic granite, and Paleozoic schist and granofels that are tens of metres from Ladybird leucogranite. Nucleation of shear zones was therefore not limited either to leucogranitic bodies or to the presence of leucogranitic melts.

The abundance of leucogranite is in no way controlled by the amount of displacement, the shear zone width or the abundance of mylonitic bands in the Valkyr shear zone. The abundance of leucogranite tends to increase downward, away from the Valkyr shear zone. This can be seen in Columbia Valley, north of the Trail pluton, where leucogranite is more abundant in the structurally deeper east side of the valley than on the west side. It can also be seen in the lower part of the Mackie pluton where the abundance of scattered leucogranitic sheets gradually increases downward from the Valkyr shear zone. Clearly the formation of leucogranite is not controlled by shearing on the Valkyr shear zone.

A minimum volume of leucogranite can be estimated from its thickness and areal extent. For the entire exposed Valhalla complex the minimum volume of leucogranite is $\sim$4500 km^3. Such a volume emplaced under 1600 km^2 of surface area in a period of $\sim$4 Ma (Carr *et al.*, 1987; Parrish, 1992, 1995) corresponds to 700 m^3 of leucogranite per year beneath every 1 km^2. Such an input of leucogranite could produce the 'transient thermal pulses' envisaged by Lister and Baldwin (1993) and, with the associated pegmatitic fluids, would weaken the zone in which it was emplaced with contrast to the overlying zone which it did not penetrate.

RAMPS IN THE VALKYR SHEAR ZONE

The Arrow Lake ramp

The southern segment of the Valkyr shear zone lies at a lower structural level than the northern segment (Fig. 5), and we believe that this represents the pre- and syn-Valkyr shear zone configuration. As illustrated in cross-section A–B (Fig. 4), the Valkyr shear zone must pass over the crest of the Passmore dome at an altitude of about 4000 m in the vicinity of Ladybird mountain. This is determined from the orientation of the Valkyr shear zone where it is exposed on both flanks of the complex and the orientation of shear foliations in the Ladybird granite in the central part of the complex (Carr *et al.*, 1987). Mapping shows that the Valkyr shear zone is not present at this structural level south of Lower Arrow Lake, rather a shear zone that resembles the Valkyr shear zone and has the same hanging wall–footwall relationships passes over the crest of the complex at an altitude of 1500 m (cross-section C–D, Fig. 4). This can be determined from the map (Fig. 2) in the ridge south of Lower Arrow Lake, and from the trace of the shear zone in the footwall of the Champion Lakes fault in low cliffs south of Castlegar near Champion Creek (Fig. 3). If the shear zone south of Lower Arrow Lake is indeed the southern portion of the Valkyr shear zone, then a lateral ramp that dips 20° to the south, the Arrow Lake ramp, some 2500 m high, must connect the northern and southern portions.

Mesoscopic fabrics north of Lower Arrow Lake corroborate the interpretation of a lateral ramp connecting the northern and southern segments of the Valkyr shear zone. In the Ladybird granite on the S-facing slopes north of Lower Arrow Lake, foliations with a 20°S dip are found in distinct domains within rock that has the more usual W-dipping foliation that increases upward in intensity toward the Valkyr shear zone. The domains of S-dipping foliation vary in size from lenses 20 cm thick to regions tens of metres thick, and the domain boundaries are transitional such that locally the two foliations are seen in the same rock. In Fig. 6 we see that the stretching lineations, consisting of quartz 'ribbons', quartz–feldspar aggregates and elongate feldspar aggregates, fall both in the 'regional' and in the 'ramp' foliation planes. There is considerable scatter of foliation and lineation orientations and, therefore, the small departure of the mean lineation from lying on the 'regional' or the 'ramp' foliation is not significant. The line of intersection of mean 'regional' and mean 'ramp' foliations lies at 25° from the mean lineation. This is, at least in part, a consequence of the scatter in orientation data and the acute angle of intersection. We conclude that the presence of the 'ramp' foliation in the Ladybird granite on the mountain slopes north of Lower Arrow Lake supports the interpretation of the geological map pattern that there is a S-facing ramp, as illustrated in cross-section N–S (Fig. 4).

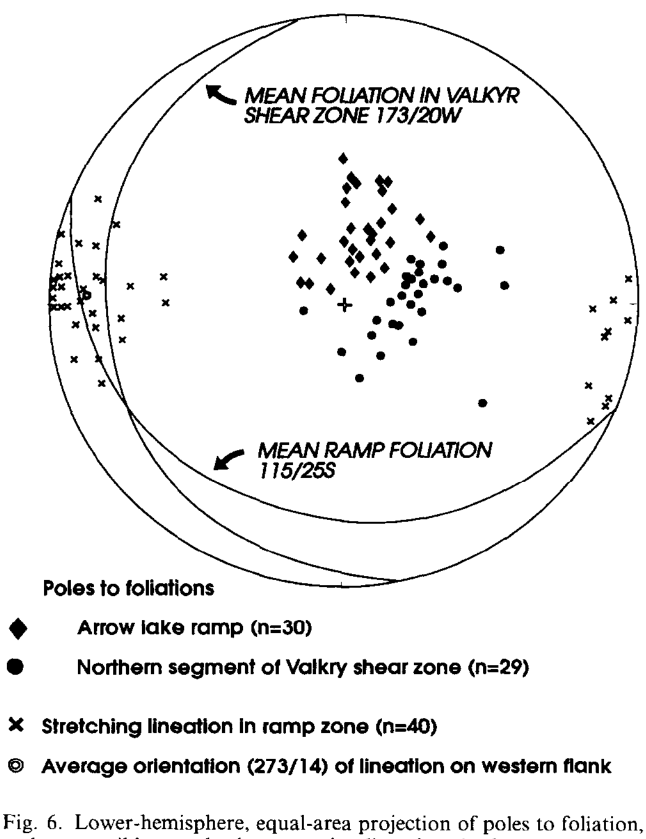


Fig. 6. Lower-hemisphere, equal-area projection of poles to foliation, and quartz ribbon and other extension lineations in the Lower Arrow Lake ramp zone of the Valkyr shear zone.

Before accepting the interpretation of such a large lateral ramp, other alternatives were considered and each is discussed below. These alternatives fall into two categories. First, we consider the possibility that the southern segment is not connected to the northern Valkyr shear zone; and, second, the possibility that the southern segment is at a lower elevation than the northern segment because of a transverse structure that is not a ramp.

One possibility is that the Valkyr shear zone continues southward and remains at the same elevation and structural level or even rises southward. In a N–S cross-section (N–S in Fig. 4), the Valkyr shear zone would project in the air to the south and, in this case, what we have termed the southern segment of the shear zone would be another shear zone at a deeper structural level. In three dimensions such an interpretation does not work. The Valhalla complex is an antiform with a N–S axis and, on a very broad scale, there is a regional southward plunge of 3–5°, from the core of Valhalla dome to the region south of Trail where outcrop is dominated by high-level Jurassic rocks of the upper plate (Fig. 1). The geology and topography are such that a continuation of the northern Valkyr shear zone to the south of Lower Arrow Lake would be exposed in the mountains on either side of the southern Valhalla complex. In this region Paleozoic and Jurassic rocks of known stratigraphy have been carefully mapped by Little (1982), Fyles (1984) and Höy and Andrew (1991), and are well-enough exposed that a shear zone would be revealed if it were present.

Another possibility is that the trace of the Valkyr shear zone lies in Lower Arrow Lake and the shear zone wraps around the southern end of Passmore dome (Fig. 1). In this case the Valkyr shear zone would project beneath the southern Valhalla complex, which would then constitute part of the upper plate. However, since geological contacts, including those of the Ladybird granite, Kinnaird pluton and a Middle Jurassic pluton, have been carefully mapped and cross Lower Arrow Lake (Fig. 2) (Parrish *et al.*, 1988), this hypothesis is not tenable.

We have also considered scenarios in which the difference in elevation between the northern and southern segments of the Valkyr shear zone are accommodated by either a transverse normal fault or a kink fold, rather than a lateral ramp. The key observation is that the Valkyr shear zone changes structural level, not just elevation, across the Arrow Lake ramp. A transverse structure that deforms the shear zone would lead to changes in elevation only, whereas a ramp cuts from one structural level to another. At Lower Arrow Lake, the Valkyr shear zone changes structural level and the geology in the footwall crosses the zone without a significant change in elevation (cross-section N–S, Fig. 4). This, in combination with observed ramp structures, supports the conclusion that the structure at Lower Arrow Lake is a S-facing lateral ramp.

Arrow Lake ramp in the hanging wall of the Slocan Lake–Champion Lakes fault

Northeast of Castlegar the southward decrease in the displacement on the Slocan Lake fault has led to local preservation of the Valkyr shear zone in its hanging wall (cross-section A–B, Figs 2 & 4). Its trace across the slopes east of Castlegar lies within the Ladybird granite, just below the intrusive contact with the Bonnington pluton, and it delineates the upper portion of a ramp with a ~30°SSE dip. The shear zone is cut off by the Champion Lakes fault and reappears near Champion Creek (Fig. 3) in the footwall of the fault. The continuation of the shear zone in the hanging wall of the fault is ~3 km below Champion Creek (cross-section E–F) because of the throw on the fault (Corbett, 1985). These relationships require a S-facing ramp just where one would expect the eastern continuation of the Arrow Lake ramp to be (Fig. 5).

The Murphy Creek ramp

North of the Trail pluton on the west side of the Columbia River (Fig. 3), the trace of the Valkyr shear zone cuts downward to the south across the structural layering. Along the north margin of the pluton, east of the Columbia River, mylonite zones dip south at 50–60° cutting across gently-dipping foliation (cross-section G–H, Fig. 4), and the Valkyr shear zone passes under the pluton, outlining a distinct S-facing ramp at least 1000 m high (cross-sections N–S and G–H, Figs 4 & 5). The trajectory of the ramp closely follows the sharp boundary between rocks with 50–80% Ladybird granite sheets and the Jurassic Trail pluton with no leucogranite. The existence of this smaller well-exposed ramp, where the shear zone changes structural level to follow the margin of leucogranite injection, supports our interpretation of the larger ramp at Lower Arrow Lake.

INITIATION AND PROPAGATION OF THE VALKYR SHEAR ZONE AND ITS LATERAL RAMPS

The Valkyr shear zone in the Valhalla complex is a natural example of the three-layer model proposed by Melosh (1990) to explain the development of low-angle detachments during crustal extension. In the model, an effectively rigid, elastic and brittle upper crustal layer undergoing extension by brittle faulting (upper plate of Valkyr shear zone) is separated from a deeper stiff but ductile layer (deeper part of lower plate Valhalla complex) by a middle layer of relatively low viscosity that undergoes simple shear (2–3-km thick zone of predominantly Ladybird granite). The low-angle detachment propagates near the top of the viscous layer. Forsyth (1992) showed that once such a low-angle detachment has formed it is more likely to continue to propagate and to accumulate large displacements than to be replaced by a set of more steeply-dipping normal faults.

Combining our observations with the concepts of Melosh (1990) and Forsyth (1992), we propose, in Fig. 7, one possible model for the evolution of the Valkyr shear zone with its ramps. Early in the Eocene, the upper boundary of the Valhalla complex was determined by the level to which leucogranite melts rose in the crust (Stage 1, Fig. 7). Field relationships, textures and geochronology show that the Ladybird granitic suite began to be emplaced during late stages of Cordilleran compression (Carr *et al.*, 1987; Parrish *et al.*, 1988; Carr, 1992, 1995).

As extension began there was a strong rheological contrast between the cool upper plate and the underlying layer, softened and, perhaps, rendered viscous as a consequence of the continuing emplacement of voluminous, hot leucogranite. Above the Valhalla complex, the upper crustal layer may have started to extend by normal faulting while simple shear was initiated in the zone below the laccolithic complex, as in the model presented by Melosh (1990). Once low-angle simple shear was initiated in the upper part of the viscous layer and the low-angle detachment had formed, it became the zone favoured for further detachment (Forsyth, 1992). The zone became foliated and many short, separate mylonite bands were nucleated. As extension progressed, these mylonite bands propagated and joined to form a continuous foliated and mylonitic zone in the north, while in the south the initial stage was, in part, preserved (Stage 2, Fig. 7).

The northern and southern segments of the Valkyr shear zone nucleated at two different structural levels. As displacement increased, the two segments would have spread at their respective levels and consequently the tip lines of the two shear zones would have approached each other. At this stage, at the site of the future Arrow Lake ramp, a 3-km thick sheet of hot ductile Ladybird leucogranite was adjacent to, and at the same structural level as, the Bonnington pluton and associated Middle Jurassic laccolithic rocks. At this site the rheological layering (Melosh, 1990) would have been the same, except for the southerly dip, as that in the large 'flats' of the northern and southern shear zones. When the tip line of the southern shear zone had propagated into the future ramp zone (Stage 3, Fig. 7) then the Bonnington pluton would have been moving eastward relative to the Ladybird granite thus localizing the Arrow Lake ramp. Simple shear would have been induced in the Ladybird granite on S-dipping planes close to the irregular but generally S-dipping base of the upper plate as predicted by the model of Melosh (1990). South-dipping 'ramp' foliations would then have been superimposed on, and combined with, the fabrics related to the top-to-the-east shear of the northern shear zone (Fig. 6).

It is unlikely that the Arrow Lake ramp was initiated as a simple tabular zone with parallel foliations and

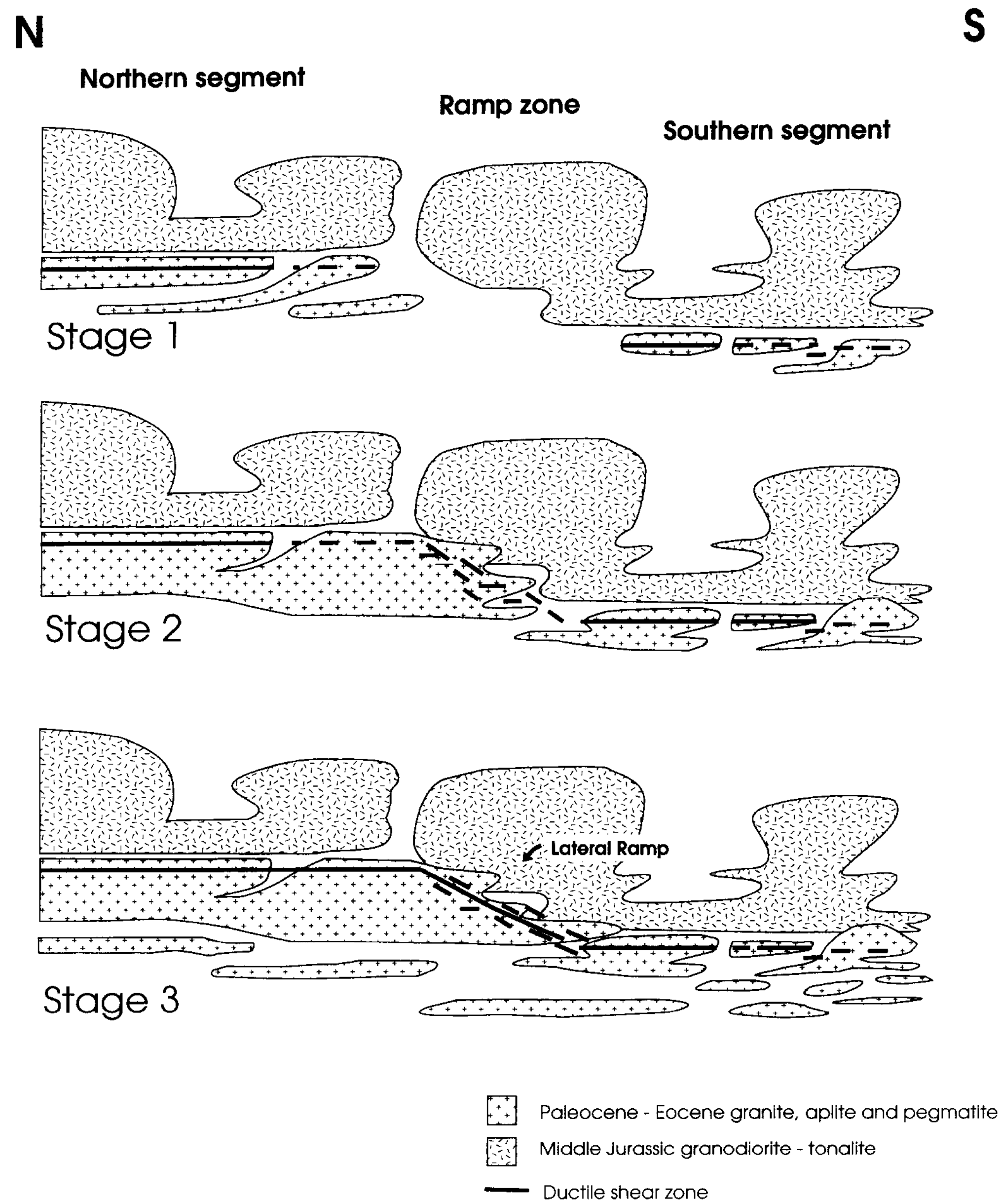


Fig. 7. Schematic N–S cross-sections illustrating the evolution of the Valkyr shear zone and Lower Arrow Lake ramp in three stages. See text for explanation.

mylonite zones. At the site of the developing ramp, the step in the base of laccolithic plutons was probably a S-dipping but irregular boundary. Moreover, a zone of complex strain probably developed between the two shear zone tip lines (Ramsay and Allison, 1979; Ramsay, 1980). With increasing displacement the ramp would have tended to become more planar and to have rotated such that the upper and lower ramp edges became subparallel with the transport direction. Some of the scatter in fabric orientations in the Arrow Lake ramp (Fig. 6) may reflect incompleteness of this rotation.

Late in the third and final stage (Fig. 7), discontinuous shear zones in the ramp region combined to form the Arrow Lake ramp (cross-section N–S, Fig. 4). The northern and southern segments of the upper plate would subsequently have moved eastward together in relation to the lower plate, which remained continuous in the footwall of the lateral ramp. The Murphy Creek ramp in the south (cross-sections N–S and G–H, Figs 4 & 5) evolved in a similar manner.

CONCLUSIONS

We summarize our main conclusions below, not in what we consider the order of importance, but in relation to the order in which we believe the Valkyr shear zone and its ramps evolved within the Jurassic, Cretaceous and Tertiary plutonic complex.

(1) In the region of the Valhalla complex, the level to which Paleocene–Eocene leucogranite rose in the crust was at least locally controlled by the level of the bases of a series of interconnected, flat-bottomed Middle Jurassic laccoliths that were exhumed and cooled by the Late Cretaceous. These cool, massive granodiorite–tonalite bodies formed a barrier to the upward migration of the younger leucogranite suite.

(2) At the onset of Eocene extension, the Jurassic laccoliths stiffened the upper plate relative to the lower plate, and enhanced the mechanical contrast between the cool upper plate and the lower plate made hot and ductile by the abundant leucogranite.

(3) In extension, detachment initiated preferentially at the level to which Paleocene–Eocene leucogranite rose and the detachment then propagated within that upper boundary zone rather than elsewhere in the hot leucogranite. It is the boundary between the hot leucogranite and the cool Jurassic tonalite that controlled the initiation and propagation of the extensional shear zone, rather than the alternative situation in which the shear zone localized intrusion of magma. This is consistent with the interpretations of Lister and Baldwin (1993) and may be explained by the rheological model of Melosh (1990).

(4) In general, the pervasive layering in the Valhalla complex, which comprises generally concordant contacts, foliation, intrusive sheets and isoclinal folds, dips gently and, except at ramps, the Valkyr shear zone developed at a low angle to the layering. Displacement on the southern segment of the Valkyr shear zone is small, displacements on younger faults are small, and regional stratigraphic and metamorphic relationships in the upper plate show that the Valkyr shear zone could not have been rotated into its present low-angle orientation. Therefore the detachment nucleated and propagated with a gentle dip.

(5) Differences in the general level of the base of interconnected Middle Jurassic laccoliths led to differences in the level at which the ductile extensional shear zone nucleated. This led to a situation in which cool upper plate rocks were adjacent to hot ductile rocks across S-dipping surfaces, and this ultimately led to the formation of S-facing lateral ramps. Lateral ramps in ductile shear zones elsewhere may well form in a similar way where there is a dipping boundary between contrasting lithologies with contrasting rheologies.

(6) In Valhalla-type core complexes, that is those in which abundant young granitic magma is emplaced up to a well-defined boundary, the core complex is only secondarily defined by the detachment faulting and is primarily an igneous complex. Clearly not all core complexes where "there is a clear spatial and temporal link between core complex formation and plutonic activity" (Lister and Baldwin, 1993) are of Valhalla type.

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