

An argument for channel flow in the southern Canadian Cordillera and comparison with Himalayan tectonics

RICHARD L. BROWN¹ & H. DANIEL GIBSON²

¹*Department of Earth Sciences, Carleton University, Ottawa, Ontario, Canada, K1S 5B6
(e-mail: richard.brown@gmail.com)*

²*Department of Earth Sciences, Simon Fraser University, Burnaby, British Columbia, Canada, V5A 1S6*

Abstract: Crustal thickening in excess of 55 km, and high heat flow, suggest that a high-standing plateau region in the Cordilleran hinterland was present in the Late Cretaceous. A low strength middle crust developed beneath the plateau, and parts of this layer were exhumed to upper crustal levels in Late Cretaceous to Eocene time. During Late Cretaceous time, structures in the hinterland were reactivated. Strata, buried to mid-crustal depths since the Jurassic, began to flow upward to higher levels; earlier structures were refolded and tightened, and a new transposition fabric developed. Some 10–20 km of the middle crust was involved in high temperature ductile flow. The lower boundary of the ductile zone lies with thrust sense on top of Precambrian rocks of Canadian Shield affinity, and splays upwards to the NE where it closely coincides with highly strained rocks in the hanging wall of the Purcell Thrust Fault. The upper boundary is marked by a normal-sense high strain zone, above which only minor Cretaceous deformation occurred. The boundaries were reactivated at upper crustal levels after cessation of flow in the mid-crustal channel. This reactivation resulted in formation of ductile to brittle extension faults such as the Okanagan Fault System. During final stages of flow, the Precambrian basement gneisses at the base of the channel became domed and exhumed to upper crustal levels. Comparisons with Himalayan tectonics are clearly drawn, but there are significant contrasts such as the long residence time of the proposed Cordilleran channel, and the nature of the channel boundaries.

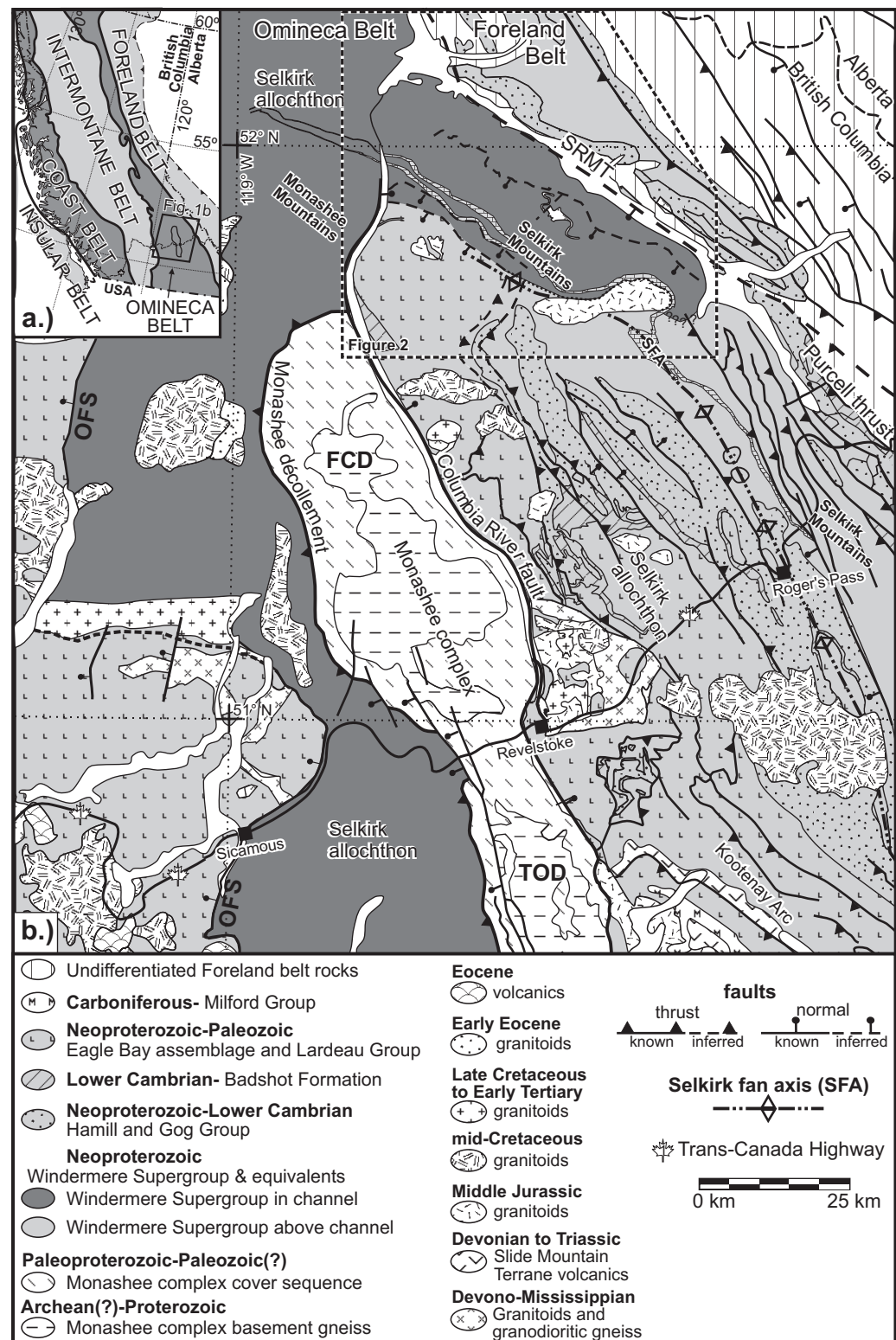
Deformation in the hinterland of the Rocky Mountain Thrust and Fold Belt of the southern Canadian Cordillera coincided with Early Jurassic terrane obduction onto the North American plate (Monger *et al.* 1982; Brown *et al.* 1986; Fig. 1a & b). From Late Jurassic to Eocene, deformation migrated northeastward into the foreland giving rise to the Rocky Mountain Thrust and Fold Belt (Price & Mountjoy 1970). Parts of the metamorphic hinterland (southern Omineca Belt, Fig. 1a) were deeply buried and then exhumed to high structural levels before the beginning of the Cretaceous (Brown & Tippet 1978; Parrish 1995; Colpron *et al.* 1998), but other areas within the Omineca Belt were not exhumed until the Late Cretaceous and early Tertiary (e.g. Sevigny *et al.* 1990). Recent structural analysis and geochronology by Gibson *et al.* (2004, 2005; see also Crowley *et al.* 2000; Gibson, 2003) across the Big Bend area of the southern part of the hinterland, point to the existence of a middle-crustal zone some 10 to 20 km thick, which was at upper amphibolite facies from as early as Middle Jurassic time until exhumation in the Late Cretaceous. The upper and lower boundaries of this ductile zone exhibit structural and thermal gradients that support a channel flow model of mid-crustal deformation. In this paper we outline the

evidence for channel flow and discuss possible relationships between exhumation of the channel, formation of Tertiary gneiss domes, and development of low-angle brittle–ductile detachment faults. Finally, we discuss similarities and contrasts with Himalayan tectonics.

Geological setting

The southern Omineca Belt of the Canadian Cordillera exposes a highly deformed region of metasedimentary, plutonic and metavolcanic rocks of mainly North American affinity, which form the southwestern hinterland of the Rocky Mountain Thrust and Fold Belt. A veneer of accreted terranes that was thrust northeastward onto the North American continental margin in the Jurassic is preserved in structural lows within this hinterland. The wide southern belt contrasts with the narrower belt north of 53°N, where metamorphic grade is generally lower. This difference is a reflection of the considerable Eocene extension and tectonic denudation of the southern region and its diminished impact to the north.

Obduction of the accreted terranes in the Jurassic was accompanied by crustal thickening and deep burial of North American rocks in a southwesterly-vergent



pro-wedge setting. The pro-wedge (Willett *et al.* 1993) grew southwestward (deformation in North American upper plate, with vergence toward the outboard NE-dipping subducting plate) accompanied by retro-wedge growth (deformation of upper plate with vergence towards the cratonic margin of the North American plate) NE across a regional zone of structural divergence (Brown *et al.* 1993; Gibson 2003; Fig. 6a). By Late Jurassic time, some of these deeply buried rocks had been exhumed and carried northeastward as the retro-wedge expanded. The Jurassic, SW-vergent structures are preserved at high structural levels along the western margins of the Omineca Belt where their northeastern boundary delimits a local zone of structural divergence known as the Selkirk fan (Figs 1b, 2 & 3; Wheeler 1963, 1965; Price & Mountjoy 1970; Brown & Tippett 1978; Brown *et al.* 1993; Colpron *et al.* 1998; Gibson *et al.* 2005).

Structural culminations within the southern Omineca Belt expose regions of upper-amphibolite-facies metamorphic and plutonic rocks, bounded by generally outward-dipping low-angle normal faults that contain low grade rocks in their hanging walls (Figs 1b & 2). These culminations have the characteristics of metamorphic core complexes and have been discussed in some detail in the literature (Coney 1980; Armstrong 1982; Parrish 1995; Vanderhaeghe & Teyssier 1997). Monashee and Valhalla are two complexes that expose important compressional shear zones at deep structural levels (Read & Brown 1981; Carr *et al.* 1987; Parrish 1995; Brown 2004; Carr & Simony 2006). These ductile zones carried hot and mobile middle-crustal rocks northeastward relative to the underlying basement rocks of the complexes, and are interpreted to extend northeastward into the discrete basal detachment of the Rocky Mountain Thrust and Fold Belt (Brown *et al.* 1986; Cook *et al.* 1992; Parrish 1995). Precambrian basement rocks of one of these domal complexes, the Monashee Complex (Fig. 1b), were not deeply buried by the advancing orogen until the Latest Cretaceous (Parrish 1995; Crowley *et al.* 1999, 2001; Gibson *et al.* 1999), as evidenced by the lack of metamorphism and absence of Cordilleran plutonism until this time. In contrast, the structurally overlying rocks contain evidence of a protracted and diachronous involvement in the deeper levels of the orogen that extend from the Middle Jurassic to

Tertiary time. The allochthonous rocks comprise highly deformed equivalents of the late Precambrian sedimentary and volcanic pile that filled the rift basins as they developed along the western North American margin during continental break-up (Windermere Supergroup and overlying Cambrian to Ordovician strata) (Fig. 1b). These strata were deposited outboard of the North American continental rocks of the Monashee Complex and were displaced northeastward over the complex during Cretaceous contraction and thickening of the orogen (Gabrielse & Yorath 1991a; Brown *et al.* 1993). The allochthonous rocks have been collectively referred to as the 'Selkirk allochthon' in the literature, and the boundary between these allochthonous rocks and the relatively autochthonous basement is known as the Monashee Décollement (see Parrish (1995) for review; see also Williams & Jiang (2005) for a contrary view). The metamorphosed and locally migmatized rocks that form the lower part of the Selkirk allochthon were highly ductile and penetratively deformed as they flowed northeastward. In the Late Cretaceous the Monashee Complex was deeply buried by the overriding rocks of the Selkirk allochthon. In the following sections we describe relationships within this mid-crustal ductile zone and propose that deformation within the zone can, in part, be interpreted in terms of channel flow.

The Cretaceous mid-crustal ductile zone

Regional studies have established that the southern Omineca Belt exposes three distinct structural levels (Figs 1 & 2; Brown & Carr 1990; Carr 1991). The lowest level exposures are of middle to lower crustal rocks coring domal metamorphic complexes that were deeply buried in the Palaeocene and rapidly exhumed in the Eocene (Parrish 1995). Structurally above and flanking these outward-dipping domal exposures are the mid-crustal rocks within the Selkirk allochthon that were mobile and at high metamorphic grade through most of Cretaceous time (Gibson 2003; Gibson *et al.* 2005). The highest levels exposed within the Selkirk allochthon contain strata that were variably deformed and metamorphosed in the Middle Jurassic and exhumed to upper crustal

Fig. 1. (a) Morphologic belts of the Canadian Cordillera. (b) Tectonic assemblage map of the southern Omineca Belt (modified after Wheeler & McFeely 1991) showing lithological map units of the autochthonous Monashee Complex (North American basement) and overlying Selkirk allochthon. 'Monashee Complex' exposes the deepest structural level. 'Selkirk allochthon' includes the metamorphic rocks of the middle-crustal layer in dark grey (interpreted as channel flow in the Selkirk and Monashee mountains), and the light grey panel is the upper crustal level overlying the channel. FCD, Frenchman Cap Dome; OFS, Okanagan Fault System; TOD, Thor Odin Dome.

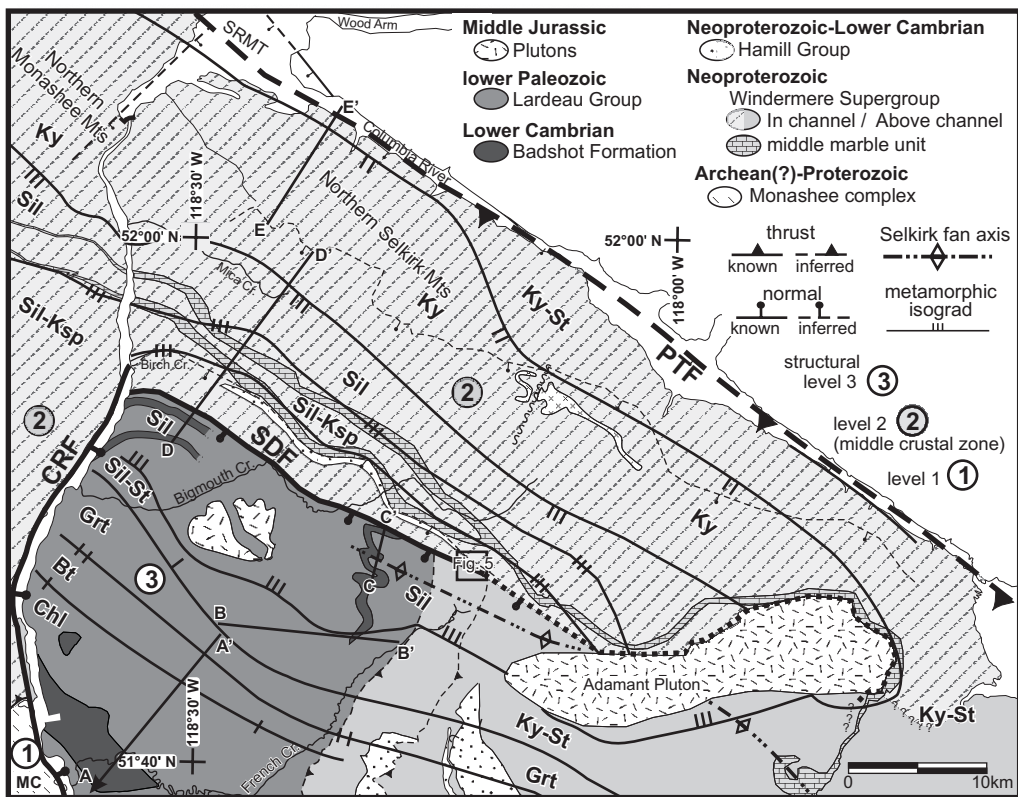


Fig. 2. Generalized geological map of the northern Selkirk Mountains illustrating simplified lithostratigraphy, regional metamorphic isograds, major structures, and structural levels discussed in the text. The middle crustal zone is bounded by the Selkirk Detachment Fault (SDF) at the top and the Purcell Thrust Fault (PTF) at the base. Box inset straddling SDF locates Figure 5. Section lines are for Figure 3 (e.g. A–A'). CRF, Columbia River Fault; MC, Monashee Complex. SRMT, Southern Rocky Mountain Trench. Mineral abbreviations for isograds are after Kretz (1983). See Figure 1 for location of Figure 2.

levels by the Late Jurassic. The present stacking of the three structural levels is the combined result of Jurassic–Cretaceous NE-over-SW imbrication and ductile flow during crustal thickening (Brown *et al.* 1986), followed by Late Cretaceous mid-crustal extrusion (Johnston *et al.* 2000) and Tertiary normal-sense low-angle extension faulting (Parrish *et al.* 1988).

The Big Bend area

The exposed area of the Cretaceous mid-crustal ductile zone in the Big Bend area is shown in Figure 4. Upper-amphibolite-facies migmatitic schists and gneisses predominate, and are derived from transposed equivalents of the Proterozoic Windermere Supergroup together with local slices of infolded lower Palaeozoic Hamill Group (Wheeler 1965; Brown & Tippet 1978; Wheeler & McFeely 1991). Characteristically these highly

strained rocks exhibit boudinage of competent units, isolated fold hinges and complex fabrics indicative of at least two generations of transposition and later superimposed folding. These late folds (F_3) are overturned to the NE on the northeastern side of the Selkirk Fan (Fig. 3; Brown & Tippet 1978; Brown *et al.* 1993). The folds were generated in the Late Cretaceous during the final stages of transposition while the rocks were still at upper amphibolite facies (Fig. 3; Gibson 2003; Gibson *et al.* 2005).

Within the Big Bend area the exhumed mid-crustal zone lies in the hanging wall of the Purcell Thrust Fault (PTF). These relationships are complicated by superimposed Tertiary normal faults that extend along the physiographic trend of the Southern Rocky Mountain Trench (SRMT; Figs 1 & 2). To the NE lie the Main Ranges of the Rocky Mountains with characteristic structures of the upper crustal Thrust and Fold Belt (Price & Mountjoy 1970;

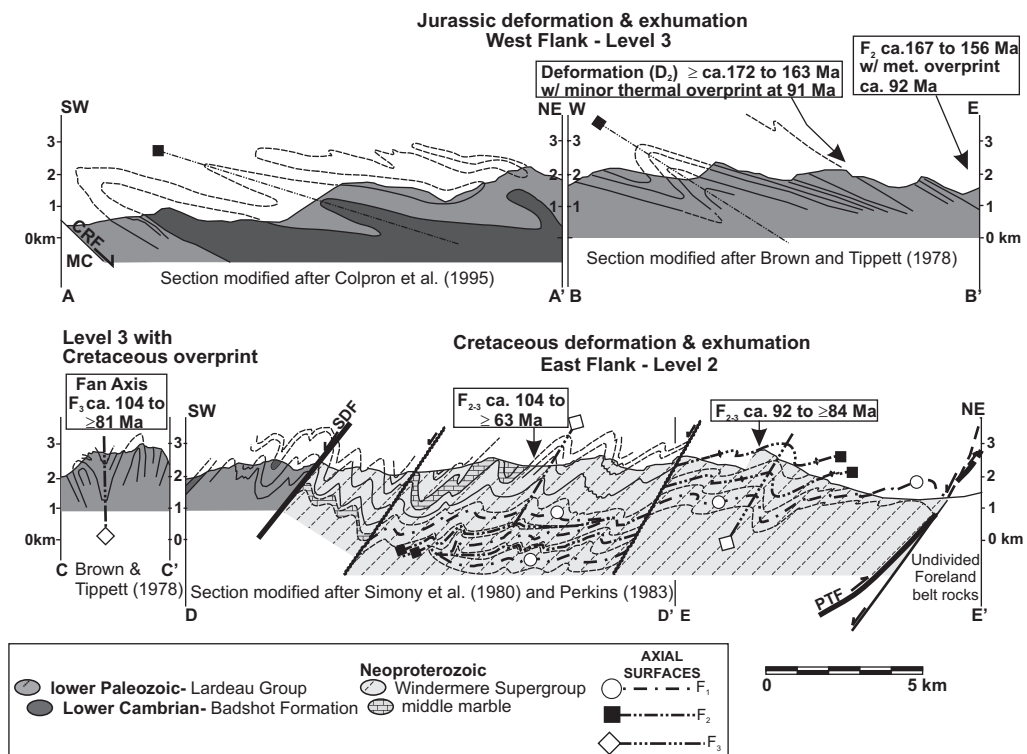
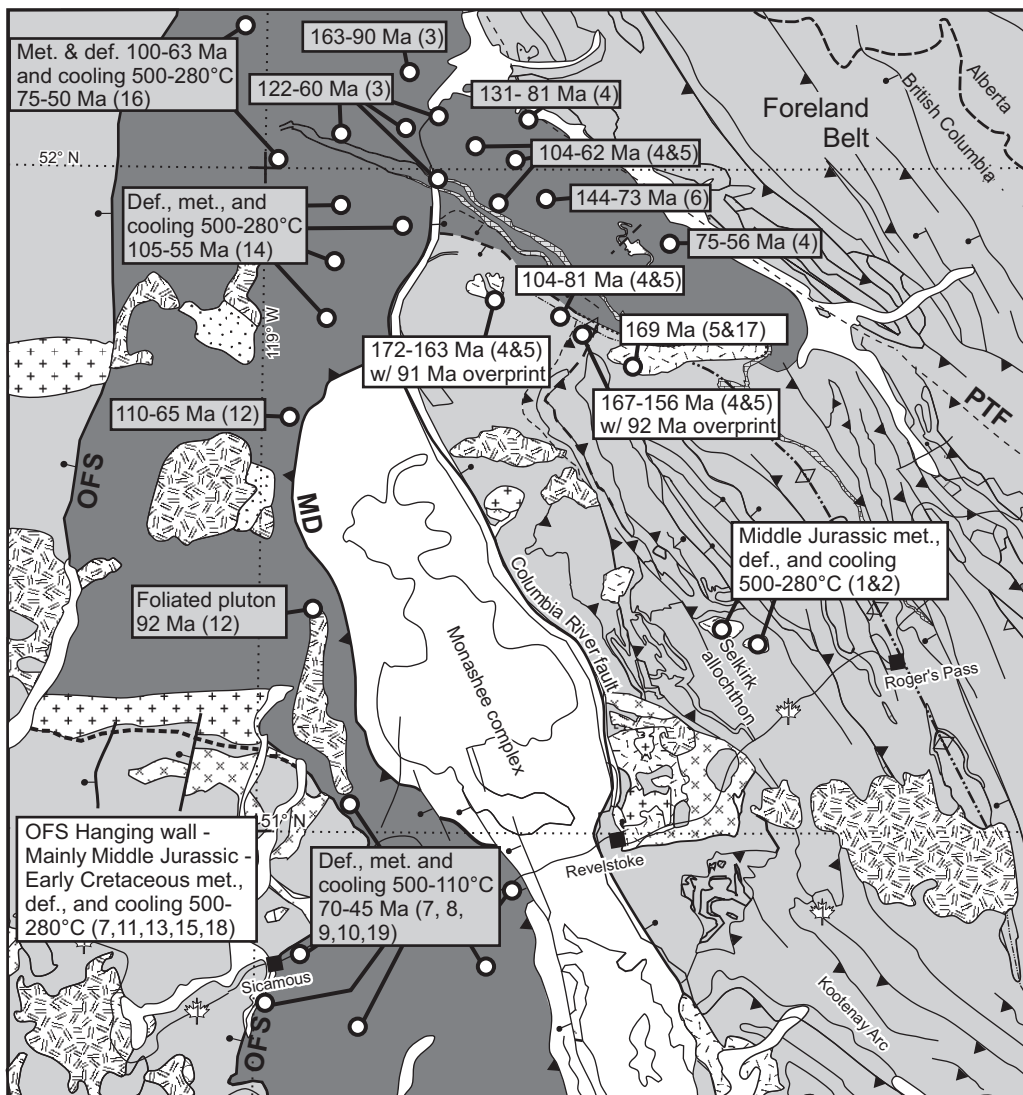


Fig. 3. Composite structural cross-section that transects the studied area, illustrating the geometry of the Selkirk fan structure modified after Brown & Tippet (1978), Simony *et al.* (1980), Perkins (1983), Colpron *et al.* (1995) and Gibson *et al.* (2005). PTF, Purcell Thrust Fault; SDF, Selkirk Detachment Fault; CRF, Columbia River Fault. Rocks lying within the proposed channel are in the footwall of the SDF and the hanging wall of the PTF. Section lines are located on Figure 2. Geochronology results of Gibson *et al.* (2005) have been projected along-strike into the line of section. Note: subdivisions of Windermere Supergroup are included to highlight structural geometry.

Wheeler & McFeely 1991). At this latitude, north-easterly directed thrusting on the Purcell Thrust Fault and associated erosion has most likely been in part responsible for exhumation of the metamorphic rocks of the Omineca Belt that lie in its hanging wall (Simony *et al.* 1980; Wheeler & McFeely 1991). The thrust is 'out of sequence' in that the orogenic front had migrated northeastward well into the Rocky Mountain foreland before Late Cretaceous time (Price & Mountjoy 1970); brittle faults associated with the Purcell Thrust Fault cut across these earlier thrusts. It is recognized that the trace of the Purcell Thrust Fault has a steeper dip than the ductile rocks in its hanging wall, and that locally exposed metamorphic rocks in the footwall probably represent a northeastward continuation of the ductile zone (see Fig. 6c). As such, the most recent motion on the Purcell Thrust Fault, together with erosion, were responsible for exhumation of the proposed channel. The lower boundary of the

channel, while it was active, is inferred to have been the northeastward continuation of the Monashee Décollement (or a related shear zone). The distinction between the current boundaries, that were presumably active during exhumation of the ductile zone, and the boundaries that prevailed during active flow is important in understanding the tectonic evolution of the channel. This point is discussed more completely in the final sections of the paper.

The upper boundary of the ductile zone, herein named the Selkirk Detachment Fault (SDF; Figs 2, 5a & 6c), is well exposed within the Big Bend area where it is marked by ductile shearing, rotation of pre-existing structures, ubiquitous lenses of pegmatite and leucogranite, stratigraphic omissions and cut-offs, together with local brittle faulting. The area was first mapped by Wheeler (1965) and later by Brown and graduate students in the early 1970s (see Brown & Tippet 1978). A study of metamorphic assemblages by Leatherbarrow (1981)



(1) Brown et al. (1992b)

(2) Colpron et al. (1996)

(3) Crowley et al. (2000)

(4) Gibson (2003)

(5) Gibson et al. (2005)

(6) Gibson et al. (2004)

(7) Johnson (1994)

(8) Johnston et al. (2000)

(9) Kuiper (2003)

(10) Lorencak et al. (2001)

(11) Okulitch (1979)

(12) Parrish (1995)

(13) Parrish et al. (1988)

(14) Scammell (1993)

(15) Schiazza and Preto (1987)

(16) Sevigny et al. (1989, 1990)

(17) Shaw (1980)

(18) Stevens et al. (1982)

(19) Vanderhaeghe et al. (2003)

Middle Jurassic met.,
def., and cooling
<300°C (1&2)

= ages within cover of channel

Def., met., and
cooling 500-280°C
105-55 Ma (14)

= ages within the channel

across the zone suggested a pressure change from 5 kbar on the western side to 7 kbar on the eastern side, but the times at which the rocks attained these pressures were not known. It now appears that the 5 kbar assemblages most likely originated in Jurassic time, whereas the 7 kbar assemblages are Late Cretaceous. These diachronous relationships were not understood until geochronologic work by Gibson (2003), and Gibson *et al.* (2005). U–Th–Pb monazite and zircon dating of metamorphic rocks and related intrusions across the structural thickness of the ductile zone has established that rocks to the east of the shear zone remained hot and deeply buried until the mid-Cretaceous (c. 100 Ma), but strata to the west, in the hanging wall, were at upper crustal levels in the Middle to Late Jurassic (172–167 Ma; see also Brown *et al.* 1992b; Colpron *et al.* 1996). Within the Big Bend area Neoproterozoic rocks of the Windermere Supergroup generally lie to the NE of the shear zone. Lower Palaeozoic rocks of the Lardeau Group characterize the strata of the southwestern panel. Highly strained quartzite and carbonate lenses within the shear zone are most likely remnants of Eocambrian strata of the Hamel Group and Ordovician units of the Badshot Formation, respectively. Upper units of the Windermere Supergroup are cut out in the footwall of the shear zone. Based on these observations the shear zone is interpreted to be a major extensional ductile fault zone. The fault zone at the surface dips steeply to the SW (Fig. 3); it is inferred to flatten at depth and be truncated by the northeasterly dipping Columbia River normal fault (Figs 1 & 6c). As shown in the cross-section of Figure 3, the folded transposition fabric of the channel rocks intersects the trace of the fault at a high angle, but is parallel with the F_3 axial planar fabric. We interpret this relationship as post-channel flow normal faulting along the SDF that may have been concurrent with generation of the post-transposition F_3 structures. Future workers may discover that beyond our study area the tectonic boundary lies at higher or lower stratigraphic levels than presently defined. The hanging wall rocks, which were exhumed in Jurassic time, are locally at high metamorphic grade, and in the absence of detailed geochronological constraints,

juxtaposition of highly strained amphibolite-facies rocks exhumed in the Jurassic with similar grade rocks exhumed in the Late Cretaceous may not be readily identified in the field.

The relationship of the Adamant pluton (Figs 1 & 2) to the channel boundaries requires additional study. Metamorphic grade decreases south of the Adamant pluton (Fig. 2) and there is little evidence of high-temperature ductile flow or melt generation in these lower grade rocks. The Adamant pluton was emplaced in the Jurassic, and its metamorphosed boundary is highly deformed (Shaw 1980; Gibson 2003). At the southwestern margin there is evidence of mainly Jurassic deformation and metamorphism with a weak Cretaceous overprint, but data are not yet available for the timing of deformation and metamorphism at the pluton's eastern margin. The transposition fabric of the ductile zone (channel) is concordant with the northern boundary of the pluton and wraps around its eastern end. These data suggest that the pluton lies in the hanging wall of the ductile zone. Apparently the folded carapace of the ductile zone plunges southward beneath the Adamant pluton and presumably continues southward in the subsurface. A marble unit (middle marble of Fig. 2) lies within the ductile zone of the study area. At the eastern end of the Adamant pluton it is preserved as a highly strained unit in sheared contact with the pluton boundary. The marble apparently continues southeastward beyond the limits of the current study where it is less deformed and is associated with lower grade stratigraphy.

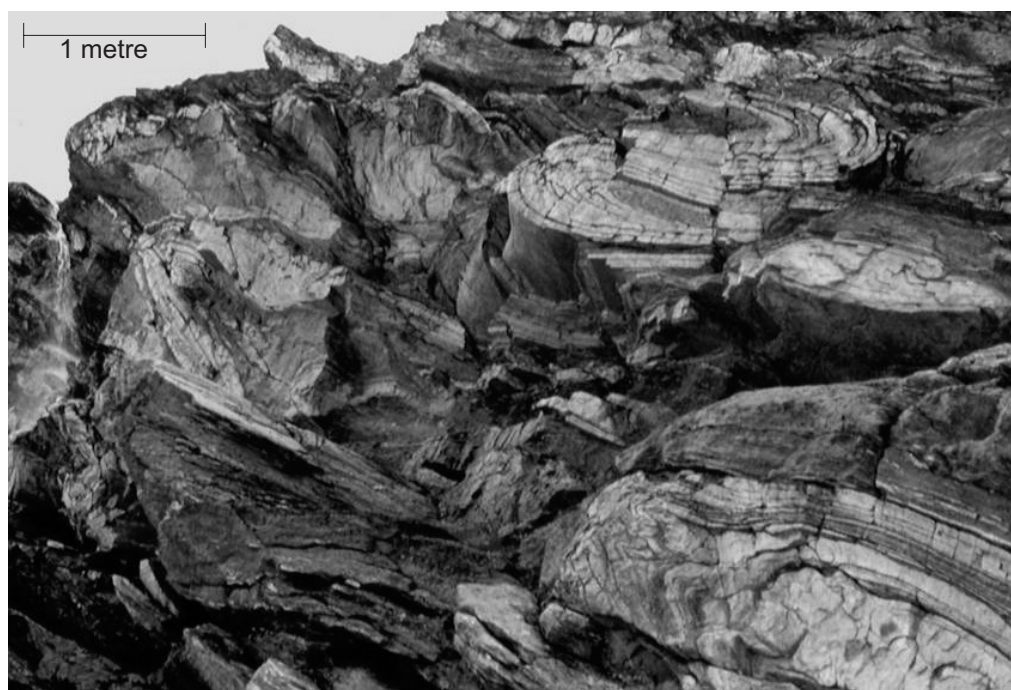
Timing of deformation and exhumation within the Big Bend area

Exhumation of the mid-crustal zone to upper crustal levels by Late Cretaceous to early Tertiary time is well constrained by monazite and zircon geochronology (Gibson 2003; Gibson *et al.* 2004, 2005). Determination of when the rocks were flowing at middle-crustal levels is more difficult to establish. As previously mentioned, Gibson concluded that the NE-verging F_3 folds formed in the Late Cretaceous and that metamorphic minerals orientated in the pre- F_3 transposition fabric (S_1 – S_2) is also Late

Fig. 4. Location and general summary of geochronological results from the proposed mid-crustal channel within the southern Omineca belt and from overlying cover rocks. The channel rocks are shown in dark grey, the cover rocks are in light grey, and the underlying Monashee Complex is white. Boxes that provide only a range of ages constrain the time of deformation (def.) and metamorphism (met.) for their respective locations. Additional text is included in the boxes for locations where the ages also constrain the cooling history or a metamorphic overprint, or only relate to the time of deformation (e.g. 'foliated pluton'). Details of these locations may be found by referring to the numbered reference. MD, Monashee Décollement; PTF, Purcell Thrust Fault; OFS, Okanagan Fault System.



(a)



(b)

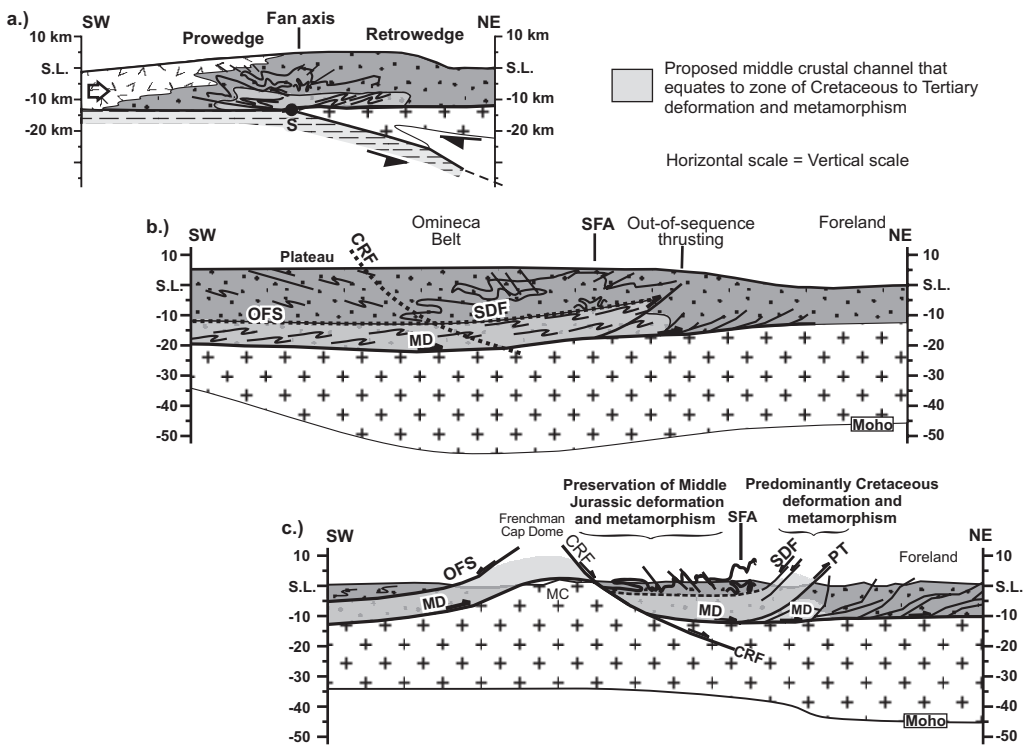


Fig. 6. Generalized cross-sections demonstrating (a) Late Jurassic configuration of the evolving orogen above an easterly dipping subduction zone. The pro-wedge illustrates obducted and accreted terrane at the highest structural level with underlying rocks of North American affinity. The dark grey layer schematically illustrates development of the mid-crustal channel above attenuated basement rocks of the North American plate. (b) Late Cretaceous-Palaeocene configuration of middle crustal channel prior to extensional faulting. (c) Present-day geometry across Frenchman Cap Dome; geometry of the Moho is constrained by Lithoprobe seismic reflection profile of Cook *et al.* (1992). The middle-crustal layer is interpreted to have been a zone of channel flow in the Late Cretaceous. Formation of Frenchman Cap Dome and displacement on Columbia River Fault (CRF) post-date the proposed channel flow. MC, Monashee Complex; MD, Monashee Décollement; OFS, Okanagan Fault System; PT, Purcell Thrust Fault; SDF, Selkirk Detachment Fault; SFA, Selkirk Fan Axis. See text for additional explanation and references. These diagrams are modified from Gibson 2003.

Cretaceous in age (Figs 3 & 4). The F_3 folds are tight to open flexural flow folds that have shortened the original width of the ductile zone, and have locally folded metamorphic isograds (Simony *et al.* 1980;

Leatherbarrow 1981). Monazite and zircon analyses indicate that at least some of the rocks in the zone were hot and ductile as early as c. 140 Ma (Gibson 2003; Gibson *et al.* 2005) and there is local evidence

Fig. 5. (a) View of the upper boundary of the proposed mid-crustal channel as exposed within the northern Selkirk Mountains. See Figure 2 for location. The Selkirk Detachment Fault (SDF) is drawn below the cliffs that expose marbles of the Ordovician Badshot Formation. These marbles are truncated by the SDF. Neoproterozoic units of the Windermere Supergroup form the cliffs below the SDF. The Badshot Formation and overlying Lardeau Group seen above the SDF were exhumed to high structural levels in the Jurassic. Underlying Windermere Supergroup rocks were at mid-crustal levels in the Late Cretaceous. These footwall rocks are highly transposed, migmatized and intruded by leucogranite and pegmatite (outlined by black lines). See text for further explanation. (b) Outcrop view of typical highly deformed unit of the Windermere Supergroup in the proposed mid-crustal channel. First- and second-generation folds are rootless and lithologic units are transposed. The exposure is within the Windy Range approximately 10 km NE of the SDF shown above.

of high temperature flow as early as c. 160 Ma (Crowley *et al.* 2000). Together these results indicate the presence of a mid-crustal ductile zone that was active, either continuously or discontinuously, from Middle Jurassic time until Late Cretaceous, a period of approximately 100 million years. Parrish (1995) demonstrated that the ages of peak metamorphism within the middle-crustal zone are younger in the structurally deeper levels compared to the higher levels. Brown (2004) pointed out that during the prolonged period of middle-crustal deformation, new strata would be incorporated into the deforming zone by progressive underplating as the orogenic front advanced. The development of transposition fabrics was apparently diachronous; the earlier formed tectonites must have been redeformed and transported northeastward by the younger deformation events within the evolving orogen. Generation of the F_3 folds marks the final stages of ductile flow as the middle crust was exhumed.

The ductile zone west of the Monashee Complex

The distribution of rocks that were at mid-crustal depth in Late Cretaceous time is shown in Figure 4. Structures and metamorphic relationships within this region have been described in detail by several authors (Simony *et al.* 1980; Carr 1991; Johnson & Brown 1996; Johnston *et al.* 2000). Mineral assemblages characteristically indicate upper-amphibolite-facies conditions; the rocks are commonly migmatitic and contain plutonic sheets ranging in age from Palaeozoic through Mesozoic to as young as Eocene. The upper boundary of the zone is marked by the Okanagan Fault System (OFS, Fig. 1). The fault zone has been interpreted to be a low-angle extensional structure that was active in the Eocene during a period of crustal extension and core complex formation (Templeman-Kluit & Parkinson 1986; Parrish *et al.* 1988; Cook *et al.* 1992). There is evidence in the footwall rocks of rapid cooling and exhumation of high-temperature migmatitic rocks as early as the Late Cretaceous (Scammell 1993; Parrish 1995; Johnson & Brown 1996). Mylonitic fabrics in these footwall rocks exhibit a pronounced east–west trending mineral (commonly sillimanite) and stretching lineation; kinematic indicators are consistent with upper-plate-down-to-the-west sense of motion. Adjacent to the hanging wall the rocks are commonly retrogressed to chlorite grade and overprinted by brittle fabrics. Rocks in the upper plate of the OFS are generally of low metamorphic grade, but also contain high-grade assemblages. These metamorphic rocks were exhumed by the end of the Jurassic and were at upper crustal levels by mid-Cretaceous time

(Schiarizza & Preto 1987; Johnson & Brown 1996). The sillimanite–K feldspar-bearing migmatitic rocks in the footwall of the OFS extend eastward and structurally down-section through a thickness of approximately 10 km. At the lowest structural level the migmatites are in sheared contact with the Precambrian basement rocks of the Monashee Complex. This lower boundary has previously been discussed extensively in the literature and is known as the Monashee Décollement (Read & Brown 1981; Brown *et al.* 1986; Journeay 1987; Cook *et al.* 1992; Parrish 1995). For a distance of several kilometres from the boundary, kinematic indicators are well developed in the highly transposed migmatites, which clearly show top-to-the-NE sense of shear (Journeay 1987; Brown *et al.* 1992a; Johnson 1994; Johnston *et al.* 2000). Locally superimposed on these fabrics are top-to-the-west extensional shear bands and associated normal faults (Johnston *et al.* 2000). Within the underlying rocks of the Monashee Complex metamorphic grade is generally lower but maintains amphibolite facies. In the northern part of the complex (Frenchman Cap Dome; Fig. 1b) the effects of the middle-crustal deformation appear to decrease structurally downwards away from the décollement (Gibson *et al.* 1999; Crowley *et al.* 2001). However, to the south in the Thor Odin Dome (Fig. 1b) there is a very intense Eocene migmatitic and deformation event that appears to have masked these earlier relationships (Parrish *et al.* 1988; Carr 1991; Vanderhaeghe & Teyssier 1997; Johnston *et al.* 2000).

Continuity of the mid-crustal ductile zone

The regional extent of the Cretaceous mid-crustal ductile zone in the southern Omineca Belt is illustrated in Figures 1b, 2 and 4. Within the Big Bend area the zone is bounded above by the Eocene age Columbia River extension fault (Fig. 2). This fault leaves the river valley at its northern extremity and loses displacement as it curves into the Selkirk Mountains in the vicinity of Birch Creek. Footwall rocks of the mid-crustal zone extend northwestward beyond Birch Creek and cross the Columbia River valley into the ranges of the Monashee Mountains. These rocks of the Windermere Supergroup then swing westward around the northern end of the Monashee Complex and are continuous with the mid-crustal zone that has been mapped on the western margin of the complex (Figs 1b, 2 & 4). A detailed study of these strata at the northern end of the Monashee Complex was carried out by Scammell (1993), and at higher structural levels by Sevigny *et al.* (1989, 1990). We have also worked in the region and have found that the style of deformation

and intensity of transposition is similar to the mid-crustal zone within the Big Bend area. Results of field and geochronological studies in the region are reviewed in Parrish (1995). He concluded that the crustal zone has a diachronous thermal history with higher levels indicating older ages of peak metamorphism and generation of leucogranitic melt. The deepest structural level of the zone gives ages that range from Late Cretaceous to Palaeocene, while at higher levels thermal peak conditions were reached in Early to mid-Cretaceous time. This diachroneity may be explained in part by progressive underplating and exhumation, as suggested by Brown (2004). The middle-crustal zone appears to have been ductile and highly mobile throughout Cretaceous time, and the zone was a continuous crustal feature from as far west as the bounding Okanagan Fault System, to as far east as the Purcell Thrust Fault, which is interpreted to be a splay of the Monashee Décollement exposed in the southern Rocky Mountain Trench. Since the Big Bend panel is continuous with the exposed ductile zone to the west of the Monashee Complex, it is reasonable to assume that the boundaries of the zone may also be correlated. Palinspastic reconstruction by Johnson & Brown (1996) illustrates the continuity of the mid-crustal zone after restoration of the Columbia River Fault. It appears to be a requirement of this reconstruction that the Selkirk Detachment Fault correlates westward with the Okanagan Fault System.

Interpretation of the Cretaceous mid-crustal zone

Johnston *et al.* (2000) concluded that the panel of mid-crustal rocks exposed west of the Monashee Complex was extruded northeastward in Late Cretaceous time. The argument for extrusion is based largely on a vergence reversal of F_3 folds from southwesterly in the upper part of the panel to northeasterly in the lower part. Before generation of the F_3 folds, the panel developed F_1/F_2 penetrative structures that indicate northeasterly vergence across the width of the panel. The model presented in Johnston *et al.* (2000, Fig. 10) proposes that in F_1/F_2 times northeastward ductile thrusting carried hinterland rocks (Selkirk allochthon) towards the Rocky Mountain foreland, and ductile flow in the hinterland was balanced by contraction on thrust faults within the foreland. We interpret the upper boundary of ductile deformation (the upper crust–middle crust boundary) through Cretaceous time to have been located in the vicinity of the future Okanagan Fault System. The lower boundary lies within the upper part of the basement rocks of the Monashee Complex. During F_1/F_2 times, the upper levels of the orogen together with

the ductile rocks of the middle crust were carried northeastward across the more competent basement rocks of the Monashee Complex. Whether or not the upper and lower boundaries were defined in Cretaceous time by discrete shear zones or more diffuse crustal-scale gradients remains unclear. In this paper the term Monashee Décollement is retained (see Brown *et al.* 1992a, and references therein) to refer to this lower boundary of the mid-crustal ductile zone. Similarly the upper boundary is called the Okanagan Fault System, even though the boundary is not known to have been a discrete extensional fault zone until Tertiary time.

Do the data support a channel flow model?

In the Late Cretaceous, when F_3 folds were being generated within the ductile zone to the west of the Monashee complex, channel flow appears to be qualitatively supported by the data for the panel west of the Monashee Complex (Johnston *et al.* 2000).

In the Big Bend area, late to post-transposition folds (F_3) are overturned towards the NE across the width of the belt and vergence reversals of minor folds reflect their superposition on the limbs of the major folds. In this region it appears that most of the high-temperature ductile flow and associated transposition occurred during F_1/F_2 deformation, and vergence of these tight to isoclinal folds is also predominantly northeasterly across the width of the belt. Associated discrete mylonitic shear zones also exhibit kinematic indicators that suggest a NE-over-SW sense of shear. The F_3 folding resulted in an anticlinorium within the central part of the ductile zone (Brown & Tippet 1978). The structurally deepest rocks expose the highest metamorphic grade (Fig. 2). These structural observations, in the Big Bend area, are compatible with northeasterly motion and folding of a crustal-scale ductile thrust sheet and do not in themselves require channel flow. During exhumation of the mid-crustal ductile zone, normal-sense motion on SDF and thrust-sense motion on the Purcell Thrust Fault appear to have overlapped in time. To this extent the mid-crustal layer was being structurally unroofed while it was still moving northeastward as an active thrust sheet. The timing constraints presented in this paper and elsewhere indicate that concurrent motion on the SDF and Purcell Thrust Fault occurred in the Late Cretaceous when, at mid-crustal levels in the thrust sheet, migmatites, local melts and ductile transposition fabrics were being generated. These data lead the authors to a working hypothesis of Late Cretaceous mid-crustal channel flow.

Tectonic model

Figure 6c is a simplified cross-section illustrating the present geometry after doming and erosion. In this figure, the mid-crustal ductile zone is shown bounded by the Monashee Décollement and Purcell Thrust Fault at its base and by the Okanagan Fault System and Selkirk Detachment Fault at the top. Flow within the ductile zone is envisaged to have occurred in two distinct periods. The early period (F_1/F_2), which extended from Jurassic to Late Cretaceous, is the time of crustal thickening involving westward underplating of the orogen by the sediments of the foreland and underlying cratonic rocks of North America (Fig. 6a & b). The earliest deformed rocks of the hinterland were exhumed from mid-crustal depths as early as Middle Jurassic time and were carried northeastward above the underlying rocks of the mid-crustal ductile zone (Fig. 6a; Brown *et al.* 1986; Colpron *et al.* 1996). Crustal thickening on the order of 55 km was achieved by Late Cretaceous time (Johnson & Brown 1996; Foster *et al.* 2004). We assume that this thickness, together with high heat flow in the hinterland of the orogen, would have created an extensive plateau region (Fig. 6b). Extensional deformation in the hinterland occurred in Eocene time (Parrish *et al.* 1988), and the present crustal thickness had been reduced to less than 35 km (Cook *et al.* 1992). Whether or not there was significant crustal thinning before the Tertiary is not clearly resolved. However, within the ductile zone to the north of the Monashee Complex, pressure–temperature–time results of Scammell (1993) suggest that part of the zone was rapidly exhumed as early as 100 Ma. He envisaged a mechanism of ductile thrusting and thrust-parallel extension within the zone to account for decreases in pressure during progressive ductile flow. It is in this time period, continuing into the Tertiary, that channel flow is thought to have been ongoing in the mid-crustal zone.

The possibility that erosion at the front of the thrust sheet may have facilitated channel flow at depth should be considered. This time was a period of rapid sediment accumulation in the fore-deep and some of these deposits are presumed to have been derived from the Omineca Belt. However, testing of such a hypothesis is beyond the scope of this paper.

Gneiss dome formation

The Monashee Complex exposes Precambrian basement in the cores of the gneiss domes of Frenchman Cap and Thor Odin (Fig. 1b). Geochronology and plutonic history have demonstrated that these core

rocks are part of the North American Precambrian crust that underlies the Rocky Mountain Thrust and Fold Belt (Crowley 1999). Field structural studies over the past 30 years have elucidated the geometry of these basement rocks and an unconformably overlying, but highly transposed, Precambrian to Palaeozoic cover sequence (e.g. Journeay 1987; Scammell & Brown 1990; Parrish 1995; Gibson *et al.* 1999; Crowley *et al.* 2001). Above these crustal rocks is the Monashee Décollement, which carries allochthonous rocks of the Cordilleran orogen in its hanging wall. The main body of the proposed mid-crustal channel that is discussed in this paper lies above the basement rocks that core the domes (Fig. 6c). However, during emplacement of the channel rocks onto the basement rocks of the Monashee Complex in the latest Cretaceous to Eocene, these basement rocks were metamorphosed, locally migmatized and highly deformed. Restoration of sections to pre-doming configuration, together with timing constraints from geochronology, indicates that flow within the mid-crustal channel was completed before exhumation of the domes (Johnson & Brown 1996). The migmatites within the basement rocks of the domes are of two distinct origins. The first episode of migmatization occurred in the Palaeoproterozoic and is part of the pre-Cordillera basement history (Crowley 1999). The second migmatization occurred in Palaeocene to Eocene time; thermal and structural data from the Frenchman Cap Dome point to a decrease downwards in heat and deformation during this time interval (Parrish 1995; Gibson *et al.* 1999; Crowley 1999; Crowley *et al.* 2001). These observations indicate that the hottest part of the crust was above the basement rather than within it. Structural–metamorphic data combined with detailed geochronology indicate that these hot migmatites were flowing northeastwards across the cooler and less mobile underlying basement rocks. In parts of the core of Thor Odin Dome there is evidence of partial melting in the Eocene, and it has been suggested that this melt weakening led to important ductile flow during exhumation associated with crustal thinning (Vanderhaeghe & Teyssier 1997). Although closely associated in time, it is important to distinguish between the Late Cretaceous to Palaeocene proposed channel flow, that was active mainly in the ductile zone above the basement gneisses, and heating of the basement gneisses in the Eocene after major flow within the channel was completed. Flow in the channel culminated in the earliest Palaeocene *c.* 65 Ma; Tertiary migmatites in Thor-Odin were primarily generated at *c.* 55 Ma. It is likely that by this time, heating of the basement rocks was related to deep crustal or subcrustal processes associated with the onset of crustal extension (Ranalli *et al.* 1989).

A scenario that appears to best fit the data available in the literature, as well as our own observations, includes the following: Late Cretaceous to Palaeocene initiation of doming (Brown & Journeay 1987; Scammell 1993; Johnson & Brown 1996) possibly related to thinning of the overlying channel; Eocene boudinage of the middle crust, possibly including the lower crust, (Price *et al.* 1981) with associated partial melting in the Eocene (Vanderhaeghe & Teyssier 1997); Eocene formation of low-angle normal faults in the upper crust associated with rapid exhumation of the domes (Parrish *et al.* 1988; Parrish 1995).

Comparison with channel flow in the High Himalaya

Similarities in the tectonic model proposed for the southern Canadian Cordillera and models for the High Himalaya are obvious, but important differences may be as significant as the similarities.

At the latitude of the current study, the Purcell Thrust Fault marks the transition from exhumed mid-crustal rocks in its hanging wall to upper crustal rocks in its footwall. This boundary has similar characteristics to the Main Central Thrust zone at the base of the High Himalayan channel. The Okanagan Fault System marks the transition from exhumed middle crust in its footwall to upper crustal rocks in its hanging wall. This boundary has similar characteristics to the South Tibetan Detachment System at the top of the proposed Himalayan channel. In the Cordillera it is recognized that the proposed boundaries of the channel were modified during exhumation and are oblique to the transposition fabric in the channel rocks. This also appears to be the case in the Himalaya at least for the Main Central Thrust (Searle & Szulc 2005). Structures within both channels are characterized by transposition of original stratigraphic boundaries, rootless isoclinal folds, boudinage of competent units, and polyphase folding. Metamorphic assemblages, migmatites and leucogranitic sheets in both channels reflect temperature and pressure conditions compatible with residence at mid-crustal depths. Strata within the Cordilleran channel are primarily derived from sediments originally deposited on the western margin of the North American continent. Strata within the Himalayan channel are primarily derived from the northern margin of the Indian continent. Deformation of these sediments and crustal thickening in the hinterland of both orogens is a result of underthrusting of their cratonic margins. Gneiss domes are exposed in the hinterland of both orogens behind the erosion front of the extruded channel. The high elevation of the Tibetan Plateau, together with erosion along its southern flank are

modelled as being the driving forces of channel flow in the Himalayan orogen (Beaumont *et al.* 2001a). A similar gradient is proposed in the hinterland of the Cordillera for the time of flow within the Cordilleran channel. Erosion of the eastern flank of the hinterland during channel flow is suggested by synchronous accumulation of sediment in the foredeep (Price & Mountjoy 1970).

Conversely, the mid-crustal zone in the southern Canadian Cordillera was, intermittently or possibly continuously, deforming at high temperature for approximately 100 million years. Channel flow in the Himalayas is thought to have been short-lived, occurring from as early as 30 Ma to about 17 Ma. Rapid erosion of the High Himalayan southern margin was facilitated by monsoon conditions. The eastern margin of the proposed Cordilleran plateau was an arid area in the lee of prevailing westerly Pacific winds. Channel flow occurred within the 'pro-wedge' of the Himalayan orogen, and in the 'retro-wedge' of the Cordillera. The Tibetan Plateau remains today as the largest high-standing area in the world. Modest elevations are currently present in the hinterland of the Cordillera, with areas in the Intermontane region almost at sea level. During proposed channel flow in the Himalaya, plate convergence was essentially orthogonal, but in the Cordillera Late Cretaceous and Tertiary convergence was oblique. The High Himalayan ductile zone is continuously exposed along the strike length of the orogen. In the Cordillera the complete along-strike exposure and structural characteristics of the mid-crustal zone remain to be established. It is clear from available data that the mid-crustal zone is discontinuously exposed in structural culminations. It may turn out that along parts of the strike length of the Cordillera, the mid-crustal layer behaved primarily as a ductile thrust sheet with limited or no evidence of channel flow (e.g. Carr & Simony 2006). Such variation along-strike may perhaps be attributed to oblique convergence, as recently proposed for the Kaoko Belt of Namibia (Goscombe *et al.* 2005).

Discussion

The above comparison of the setting of channel flow in the southern Canadian Cordillera with the setting of channel flow in the High Himalaya raises several points for discussion. The apparent longevity of the mid-crustal ductile zone in the Cordillera, compared with that of the Himalaya, may well be explained by the different climatic setting of the two orogens. Beaumont *et al.* (2001b) demonstrated that in the absence of rapid erosion on the foreland side of an orogen, in this case the Canadian Cordillera, the ductile zone will

remain deeply buried. The absence of a high plateau in the Intermontane region of the southern Canadian Cordillera is presumed to be a reflection of the intensity of crustal extension in the Eocene. Crust in the hinterland exceeded 55 km in thickness in the Late Cretaceous and has since been reduced by c. 40% due to tectonic denudation and subsequent erosion. The Eocene is known to have been a time of relaxed orthogonal plate convergence and development of a dextral plate boundary setting (Gabrielse & Yorath 1991*b*). In contrast, the Himalayan region is still experiencing orthogonal plate convergence. The High Himalaya lies in a pro-wedge setting (Willett *et al.* 1993) if it is accepted that the Indian plate is being subducted northward beneath the Tibetan Plateau (cf. Jamieson *et al.* 1996). In this interpretation the channel was extruded towards the subducting plate. Irrespective of how lithosphere is ultimately incorporated into the upper mantle, the observation that the Indian plate is underthrust northward relative to the overriding orogen is not in dispute. In the North American Cordillera the current polarity of subduction is clear in that oceanic rocks of the Pacific and Juan de Fuca plates are obliquely underthrusting the North American margin. This polarity is thought to have persisted from at least Jurassic time to the present (Oldow *et al.* 1990; Gabrielse & Yorath 1991*b*; Brown *et al.* 1993). In this respect, the Rocky Mountain Thrust and Fold Belt together with its hinterland evolved in a retro-wedge setting; the front of the orogenic wedge migrated northeastward in the direction of the subducting plate (Willett *et al.* 1993). Despite these differences in the two orogens, both experienced underthrusting of continental crust beneath the orogenic wedge. A plateau region developed with growth of the wedge, and a mid-crustal ductile channel developed beneath the plateau regions. In both cases, flow within the channel was directed outwards from beneath the plateau region towards the evolving thrust belt that had developed above the underthrusting continental margin.

Conclusions

A hot and low-strength, 10–20 km thick mid-crustal layer formed beneath a plateau region in the hinterland of the Rocky Mountain Thrust and Fold Belt. Ductile flow within this layer was active from initial crustal thickening in the Early Jurassic to its exhumation in Late Cretaceous to Palaeocene time. F_1/F_2 flow within the channel resulted in ductile folding and transposition of stratigraphy. Initially, the upper crust was carried passively above the ductile thrust sheet as it progressed northeastward towards the foreland. It is suggested that in the

later stages of F_1/F_2 deformation the passive roof to the ductile thrust sheet began to lag behind and the Okanagan Fault System became established as a normal-sense shear zone at the top of the mid-crustal layer. F_3 folding within the southwestern part of the ductile zone developed during channel flow. In the northeastern part of the ductile zone the F_3 folds appear to post-date the proposed channel flow. The lower boundary of the channel was the Monashee Décollement, and the upper boundary was the Okanagan Fault System that included the Selkirk Detachment Fault. The Purcell Thrust Fault is interpreted to be a splay of the Monashee Décollement that was active during exhumation of the eastern part of the channel. Doming of the channel and underlying basement gneisses post-dated the proposed channel flow, but the domes may have been localized by earlier necking of the channel.

The authors gratefully acknowledge a National Science and Engineering Research Council grant to R.L.B. The authors benefited from discussions with C. Beaumont, S. Carr, R. Jamieson, R. Price, P. Simony and P. Williams during the research for this publication. C. Teyssier and P. Williams are thanked for their constructive reviews.

References

- ARMSTRONG, R. L. 1982. Cordilleran metamorphic core complexes – from Arizona to southern Canada. *Annual Review of Earth and Planetary Sciences*, **10**, 129–154.
- BEAUMONT, C., JAMIESON, R. A., NGUYEN, M. H. & LEE, B. 2001*a*. Himalayan tectonics explained by extrusion of a low viscosity crustal channel coupled to focussed surface denudation. *Nature*, **414**, 738–742.
- BEAUMONT, C., JAMIESON, R. A., NGUYEN, M. H. & LEE, B. 2001*b*. Mid-crustal channel flow in large hot orogens: results from coupled thermal-mechanical models. In: COOK, F. & ERDMER, P. (eds) *Slave-Northern Cordillera Lithospheric Evolution (SNORCLE) and Cordilleran Tectonics Workshop*, Victoria, BC, 112–170.
- BROWN, R. L. 2004. Thrust belt accretion and hinterland underplating of orogenic wedges: an example from the Canadian Cordillera. In: MCCLAY, K. R. (ed.) *Thrust Tectonics and Hydrocarbon Systems*. American Association of Petroleum Geologists, Memoir **82**, 51–64.
- BROWN, R. L. & CARR, S. C. 1990. Lithospheric thickening and orogenic collapse within the Canadian Cordillera. *Pacific Rim '90 Congress*. Australasian Institute of Mining and Metallurgy, Brisbane, Australia, 1–10.
- BROWN, R. L. & JOURNEAY, J. M. 1987. Tectonic denudation of the Shuswap metamorphic terrane of southeastern British Columbia (Canada). *Geology*, **15**, 142–146.

- BROWN, R. L. & TIPPETT, C. R. 1978. The Selkirk fan structure of the southeastern Canadian Cordillera. *Geological Society of America Bulletin*, **89**, 548–558.
- BROWN, R. L., JOURNEAY, J. M., LANE, L. S., MURPHY, D. C. & REES, C. J. 1986. Obduction, backfolding and piggyback thrusting in the metamorphic hinterland of the southeastern Canadian Cordillera. *Journal of Structural Geology*, **8**, 255–268.
- BROWN, R. L., CARR, S. D., JOHNSON, B. J., COLEMAN, V. J., COOK, F. A. & VARSEK, J. L. 1992a. The Monashee décollement of the southern Canadian Cordillera: a crustal-scale shear zone linking the Rocky Mountain Foreland to lower crust beneath accreted terranes. In: MCCLAY, K. R. (ed.) *Thrust Tectonics*. Chapman and Hall, London, 357–364.
- BROWN, R. L., MCNICOLL, V. J., PARRISH, R. R. & SCAMMELL, R. J. 1992b. Middle Jurassic plutonism in the Kootenay Terrane, northern Selkirk Mountains, British Columbia. *Geological Survey of Canada Paper*, **91-2**, 135–141.
- BROWN, R. L., BEAUMONT, C. & WILLETT, S. D. 1993. Comparison of the Selkirk fan structure with mechanical models: implications for interpretation of the southern Canadian Cordillera. *Geology*, **21**, 1015–1018.
- CARR, S. D. 1991. Three crustal zones in the Thor-Odin-Pinnacles area, southern Omineca Belt, British Columbia. *Canadian Journal of Earth Sciences*, **28**, 2003–2023.
- CARR, S. D. & SIMONY, P. S. 2006. Ductile thrusting versus channel flow in the southeastern Canadian Cordillera: evolution of a coherent crystalline thrust sheet. In: LAW, R. D., SEARLE, M. P. & GODIN, L. (eds) *Channel Flow, Ductile Extrusion and Exhumation in Continental Collision Zones*. Geological Society, London, Special Publications, **268**, 541–548.
- CARR, S. D., PARRISH, R. R. & BROWN, R. L. 1987. Eocene structural development of the Valhalla Complex, southeastern British Columbia. *Tectonics*, **6**, 175–196.
- COLPRON, M., LOGAN, J. M., GIBSON, G. & WILD, C. J. 1995. *Geology and Mineral Occurrences of the Goldstream River Area, Northern Selkirk Mountains (82M/9 and part of 10)*. British Columbia Ministry of Energy, Mines and Petroleum Resources Map 1995-2.
- COLPRON, M., PRICE, R. A., ARCHIBALD, D. A. & CARMICHAEL, D. M. 1996. Middle Jurassic exhumation along the western flank of the Selkirk fan structure: thermobarometric and thermochronometric constraints from the Illecillewaet synclinorium, southeastern British Columbia. *Geological Society of America Bulletin*, **108**, 1372–1392.
- COLPRON, M., WARREN, M. J. & PRICE, R. A. 1998. Selkirk fan structure, southeastern Canadian Cordillera: tectonic wedging against an inherited basement ramp. *Geological Society of America Bulletin*, **110**, 1060–1074.
- CONEY, P. J. 1980. Cordilleran metamorphic core complexes: An overview. In: CRITENDEN, M. L., CONEY, P. J. & DAVIS, G. H. (eds) *Cordilleran Metamorphic Core Complexes*. Geological Society of America, Memoir, **153**, 7–31.
- COOK, F. A., VARSEK, J. L., CLOWES, R. M. ET AL. 1992. Lithoprobe crustal reflection cross section of the southern Canadian Cordillera. 1. Foreland thrust and fold belt to Fraser River Fault. *Tectonics*, **11**, 12–35.
- CROWLEY, J. L. 1999. U-Pb geochronologic constraints on Paleoproterozoic tectonism in the Monashee complex, Canadian Cordillera: Elucidating an overprinted geologic history. *Geological Society of America Bulletin*, **111**, 560–577.
- CROWLEY, J. L., GHENT, E. D., CARR, S. D., SIMONY, P. S. & HAMILTON, M. A. 2000. Multiple thermotectonic events in a continuous metamorphic sequence, Mica Creek area, southeastern Canadian Cordillera. *Geological Materials Research*, **2**, 1–45.
- CROWLEY, J. L., BROWN, R. L. & PARRISH, R. R. 2001. Diachronous deformation and a strain gradient beneath the Selkirk allochthon, northern Monashee complex, southeastern Canadian Cordillera. *Journal of Structural Geology*, **23**, 1103–1121.
- FOSTER, G., PARRISH, R. R., HORSTWOOD, M. S. A., CHENERY, S., PYLE, J. & GIBSON, H. D. 2004. The generation of prograde P-T-t points and paths; a textural, compositional, and chronological study of metamorphic monazite. *Earth and Planetary Science Letters*, **228**, 125–142.
- GABRIELSE, H. & YORATH, C. J. 1991a. Introduction. In: GABRIELSE, H. & YORATH, C. J. (eds) *Geology of the Cordilleran Orogen in Canada*. Geology of Canada. Geological Survey of Canada, 3–11.
- GABRIELSE, H. & YORATH, C. J. 1991b. Tectonic synthesis. In: GABRIELSE, H. & YORATH, C. J. (eds) *Geology of the Cordilleran Orogen in Canada*. Geology of Canada. Geological Survey of Canada, 677–705.
- GIBSON, H. D. 2003. *Structural and thermal evolution of the northern Selkirk Mountains, southeastern Canadian Cordillera: Tectonic development of a regional-scale composite structural fan*. PhD thesis, Carleton University.
- GIBSON, H. D., BROWN, R. L. & PARRISH, R. R. 1999. Deformation-induced inverted metamorphic field gradients: An example from the southeastern Canadian Cordillera. *Journal of Structural Geology*, **21**, 751–767.
- GIBSON, H. D., CARR, S. D., HAMILTON, M. A. & BROWN, R. L. 2004. Correlations between chemical and age domains in monazite, and metamorphic reactions involving major pelitic phases: an integration of ID-TIMS and SHRIMP geochronology with Y-Th-U X-ray mapping. *Chemical Geology*, **211**, 237–260.
- GIBSON, H. D., BROWN, R. L. & CARR, S. D. 2005. U-Th-Pb geochronologic constraints on the structural evolution of the Selkirk fan, northern Selkirk Mountains, southeastern British Columbia. *Journal of Structural Geology*, **27**, 1899–1924.
- GOSCOMBE, B., GRAY, D. & HAND, M. 2005. Extrusional tectonics in the core of a transpressional orogen; the Kaoko Belt, Namibia. *Journal of Petrology*, **46**, 1203–1241.

- JAMIESON, R. A., BEAUMONT, C., HAMILTON, J. & FULLSACK, P. 1996. Tectonic assembly of inverted metamorphic sequences. *Geology* **24**, 839–842.
- JOHNSON, B. J. 1994. *Structure and tectonic setting of the Okanagan Valley fault system in the Shuswap Lake area, southern British Columbia*. PhD thesis, Carleton University.
- JOHNSON, B. J. & BROWN, R. L. 1996. Crustal structure and early Tertiary extensional tectonics of the Omineca belt at 51 degrees N latitude, southern Canadian Cordillera. *Canadian Journal of Earth Sciences*, **33**, 1596–1611.
- JOHNSTON, D. H., WILLIAMS, P. F., BROWN, R. L., CROWLEY, J. L. & CARR, S. D. 2000. Northeastward extrusion and extensional exhumation of crystalline rocks of the Monashee complex, southeastern Canadian Cordillera. *Journal of Structural Geology*, **22**, 603–625.
- JOURNEY, J. M. 1987. *Stratigraphy, internal strain and thermo-tectonic evolution of northern Frenchman Cap dome: An exhumed duplex structure, Omineca Hinterland, southeastern Canadian Cordillera*. PhD thesis, Queen's University.
- KRETZ, R. 1983. Symbols for rock-forming minerals. *American Mineralogist*, **68**, 277–279.
- KUIPER, Y. 2003. *Isotopic constraints on timing of deformation and metamorphism in the Thor-Odin dome, Monashee Complex, southeastern British Columbia*. PhD thesis, University of New Brunswick.
- Leatherbarrow, R. W. 1981. *Metamorphism of pelitic rocks from the northern Selkirk Mountains, southeastern British Columbia*. PhD thesis, Carleton University.
- LORENCAK, M., BURG, J. P., SEWARD, D., VANDERHAEGHE, O. & TEYSSEIER, C. 2001. Low-temperature cooling history of the Shuswap metamorphic core complex, British Columbia: Constraints from apatite and zircon fission-track ages. *Canadian Journal of Earth Sciences*, **38**, 1615–1625.
- MONGER, J. W. H., PRICE, R. A. & TEMPELMAN-KLUIT, D. J. 1982. Tectonic accretion and the origin of the two major metamorphic and plutonic belts in the Canadian Cordillera. *Geology*, **10**, 70–75.
- OKULITCH, A. V. 1979. *Lithology, stratigraphy, structure and mineral occurrences of the Thompson-Shuswap-Okanagan area, British Columbia*. Geological Survey of Canada, Open File **637**.
- OLDOW, J. S., BALLY, A. W. & AVE-LALLEMANT, H. G. 1990. Transpression, orogenic float, and lithospheric balance. *Geology*, **18**, 991–994.
- PARRISH, R. R. 1995. Thermal evolution of the southeastern Canadian Cordillera. *Canadian Journal of Earth Sciences*, **32**, 1618–1642.
- PARRISH, R. R., CARR, S. D. & PARKINSON, D. L. 1988. Eocene extensional tectonics and geochronology of the southern Omineca Belt, British Columbia and Washington. *Tectonics*, **7**, 181–212.
- PERKINS, J. M. 1983. *Structural geology and stratigraphy, Big Bend of the Columbia River, Selkirk Mountains, B.C.* PhD thesis, Carleton University.
- PRICE, R. A. & MOUNTJOY, E. W. 1970. Geological structure of the Canadian Rocky Mountains between Bow and Athabasca Rivers – A progress report. In: WHEELER, J. O. (ed.) *Structure of the Southern Canadian Cordillera*. Geological Association of Canada, Special Paper, **6**, 7–25.
- PRICE, R. A., ARCHIBALD, D. & FARRAR, E. 1981. Eocene stretching and necking of the crust and tectonic unroofing of the Cordilleran metamorphic infrastructure, southeastern British Columbia and adjacent Washington and Idaho (abstract). *Geological Association of Canada – Mineralogical Association of Canada Annual Meeting*, A-47.
- RANALLI, G., BROWN, R. L. & BOSDACHIN, R. 1989. A geodynamic model for extension in the Shuswap core complex, southeastern Canadian Cordillera. *Canadian Journal of Earth Sciences*, **26**, 1647–1653.
- READ, P. B. & BROWN, R. L. 1981. Columbia River fault zone: southeastern margin of the Shuswap and Monashee complexes, southern British Columbia. *Canadian Journal of Earth Sciences*, **18**, 1127–1145.
- SCAMMELL, R. J. 1993. *Mid-Cretaceous to Tertiary thermotectonic history of former mid-crustal rocks, southern Omineca belt, Canadian Cordillera*. PhD thesis, Queen's University.
- SCAMMELL, R. J. & BROWN, R. L. 1990. Cover gneisses of the Monashee Terrane: a record of syndimentary rifting in the North American Cordillera. *Canadian Journal of Earth Sciences*, **27**, 712–726.
- SCHIARITZA, P. & PRETO, V. A. 1987. *Geology of the Adams plateau-Clearwater-Vavenby area*. British Columbia Ministry of Energy, Mines, and Petroleum Resources, Paper **1987-2**.
- SEARLE, M. P. & SZULC, A. G. 2005. Channel flow and ductile extrusion of the High Himalayan slab-the Kangchenjunga-Darjeeling profile, Sikkim Himalaya. *Journal of Asian Earth Sciences*, **25**, 173–185.
- SEVIGNY, J. H., PARRISH, R. R. & GHENT, E. D. 1989. Petrogenesis of peraluminous granites, Monashee Mountains, southeastern Canadian Cordillera. *Journal of Petrology*, **30**, 557–581.
- SEVIGNY, J. H., PARRISH, R. R., DONELICK, R. A. & GHENT, E. D. 1990. Northern Monashee Mountains, Omineca Crystalline Belt, British Columbia: Timing of metamorphism, anatexis, and tectonic denudation. *Geology*, **18**, 103–106.
- SHAW, D. 1980. A concordant uranium-lead age for zircons in the Adamant Pluton, British Columbia. *Geological Survey of Canada, Paper* **80-1C**, 243–246.
- SIMONY, P. S., GHENT, E. D., CRAW, D., MITCHELL, W. & ROBBINS, D. B. 1980. Structural and metamorphic evolution of the northeast flank of Shuswap complex, southern Canoe River area, British Columbia. In: CRITENDEN, M. L., CONEY, P. J. & DAVIS, G. H. (eds) *Cordilleran Metamorphic Core Complexes*. Geological Society of America, Memoir **153**, 445–461.
- STEVENS, R. D., DELABIO, R. N. & LACHANCE, G. R. 1982. *Age determinations and geological studies*

- K-Ar isotopic ages, Report 15*. Geological Survey of Canada, Paper **81-02**.
- TEMPLEMAN-KLUIT, D. J. & PARKINSON, D. 1986. Extension across the Eocene Okanagan crustal shear in southern British Columbia. *Geology*, **14**, 318–321.
- VANDERHAEGHE, O. & TEYSSIER, C. 1997. Formation of the Shuswap metamorphic core complex during late-orogenic collapse of the Canadian Cordillera: Role of ductile thinning and partial melting of the mid- to lower crust. *Geodinamica Acta*, **10**, 41–58.
- VANDERHAEGHE, O., TEYSSIER, C., MCDUGALL, I. & JAMES, W. 2003. Cooling and exhumation of the Shuswap metamorphic core complex constrained by $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology. *Geological Society of America Bulletin*, **115**, 200–216.
- WHEELER, J. O. 1963. *Rogers Pass Map-area, British Columbia and Alberta (82N West Half)*. Geological Survey of Canada, Paper **62-32**.
- WHEELER, J. O. 1965. *Big Bend map-area, British Columbia*. Geological Survey of Canada, Paper **64-32**.
- WHEELER, J. O. & McFEELY, P. 1991. *Tectonic assemblage map of the Canadian Cordillera and adjacent parts of the United States of America*. Geological Survey of Canada, Map **1712A**.
- WILLIAMS, P. F. & JIANG, D. 2005. An investigation of lower crustal deformation: evidence for channel flow and its implications for tectonics and structural studies. *Journal of Structural Geology*, **27**, 1486–1504.
- WILLETT, S., BEAUMONT, C. & FULLSACK, P. 1993. Mechanical model for the tectonics of doubly vergent compressional orogens. *Geology*, **21**, 371–374.