CTG NUNA FIELD TRIP
in honour of Paul F. Williams

Transect of the Rocky Mountain fold and thrust belt
Canmore to Revelstoke

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INTRODUCTION

During the first part of the field trip we travelled westward from the Cordilleran mountain front across the Rocky Mountain Belt to the edge of the Omineca Belt, which forms the eastern hinterland of the Cordilleran orogen. This second part of the trip approaches the hinterland from the west, starting in the accreted terranes of the Intermontane Belt and progressing eastward across the Omineca Belt, ultimately returning to its eastern margin at the Rocky Mountain Trench.

Many years of work by numerous dedicated students of Cordilleran tectonics have resulted in a large and complex data base for the region. In order to present the information in a straightforward and easy to read style, we have minimized the number of references in the text. However, the source of all previously unpublished information is referenced in the text, and the published sources of all figures are acknowledged in the figure captions; the reader may wish to refer to the bibliography in the last section for a more comprehensive guide to source material.

In the following section we briefly describe the major tectonic elements of the region and present a model of Mesozoic and Cenozoic events that in our view best fits the available data. While recognizing that the history of the Cordilleran orogen began with Late Proterozoic and Cambrian rifting, which was followed by a murky Paleozoic period that included important arc-related and possibly collisional events, we have chosen to focus the field trip on the Mesozoic and Cenozoic evolution of the orogen.

In the three days of this part of the field trip we will examine rock exposures and discuss field and laboratory results; we hope that you will challenge our interpretations, and we look forward to lively discussions.

TECTONIC ELEMENTS AND INTERPRETATION OF THE TECTONIC SETTING

ACCRETION

In earliest Jurassic time the **Intermontane Superterrane** was in sight of the North American plate and preparing itself for obduction. Most if not all of the superterrane was presumably carried on the Farallon plate or related microplates and was progressively transferred to the North American plate during collision. The eastern edge of the obducted superterrane currently overlaps and in part defines the western boundary of the southern Omineca Belt (Figures 1, 2). Structures considered to have developed in the North American plate during collision and obduction of the superterrane are preserved within the Omineca Belt and are particularly well displayed in the Selkirk mountains of southern British Columbia. Within this range the **Selkirk fan structure** marks a major vergence reversal (Figure 2, 5), which we interpret as having originated at the western edge of the North American plate. During progressive obduction of the Intermontane Superterrane the Selkirk fan structure was detached from its underlying roots and displaced northeastwards. Palinspastic reconstruction and interpretation of LITHOPROBE seismic reflection profiles imply a total displacement of approximately 300 km. These results suggest that prior to accretion the North American plate margin lay in a position geographically equivalent to the present eastern margin of the Coast Belt (Figures 3-5).

MIDDLE CRUSTAL DECOLLEMENT

The **Monashee decollement**, which is exposed within the Omineca Belt (Figure 1) and recognized in the subsurface in LITHOPROBE seismic reflection profiles (Figure 4), is interpreted as the shear zone that accommodated the northeastward displacement of the Selkirk fan structure. It extends eastward to merge with the Rocky Mountain sole decollement; westward it descends gradually to lower crustal depths and continues as a recognizable feature as far west as the Fraser River - Yalakom strike-slip fault system.

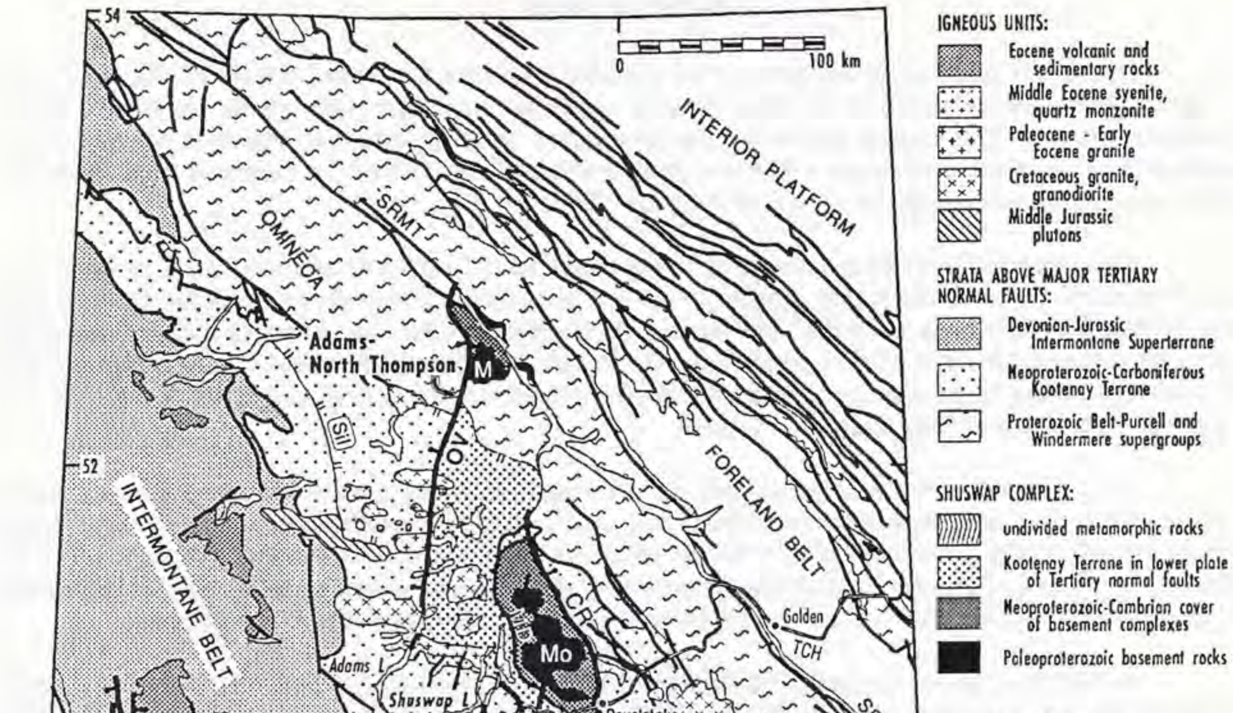


Figure 1. Tectonic assemblage map, simplified after Wheeler and McFeely (1991). Insets locate the Insular and Intermontane superterranes and the morphogeological belts: R = Rocky Mountain (Foreland), O = Omineca, IM = Intermontane, C = Coast, IS = Insular.

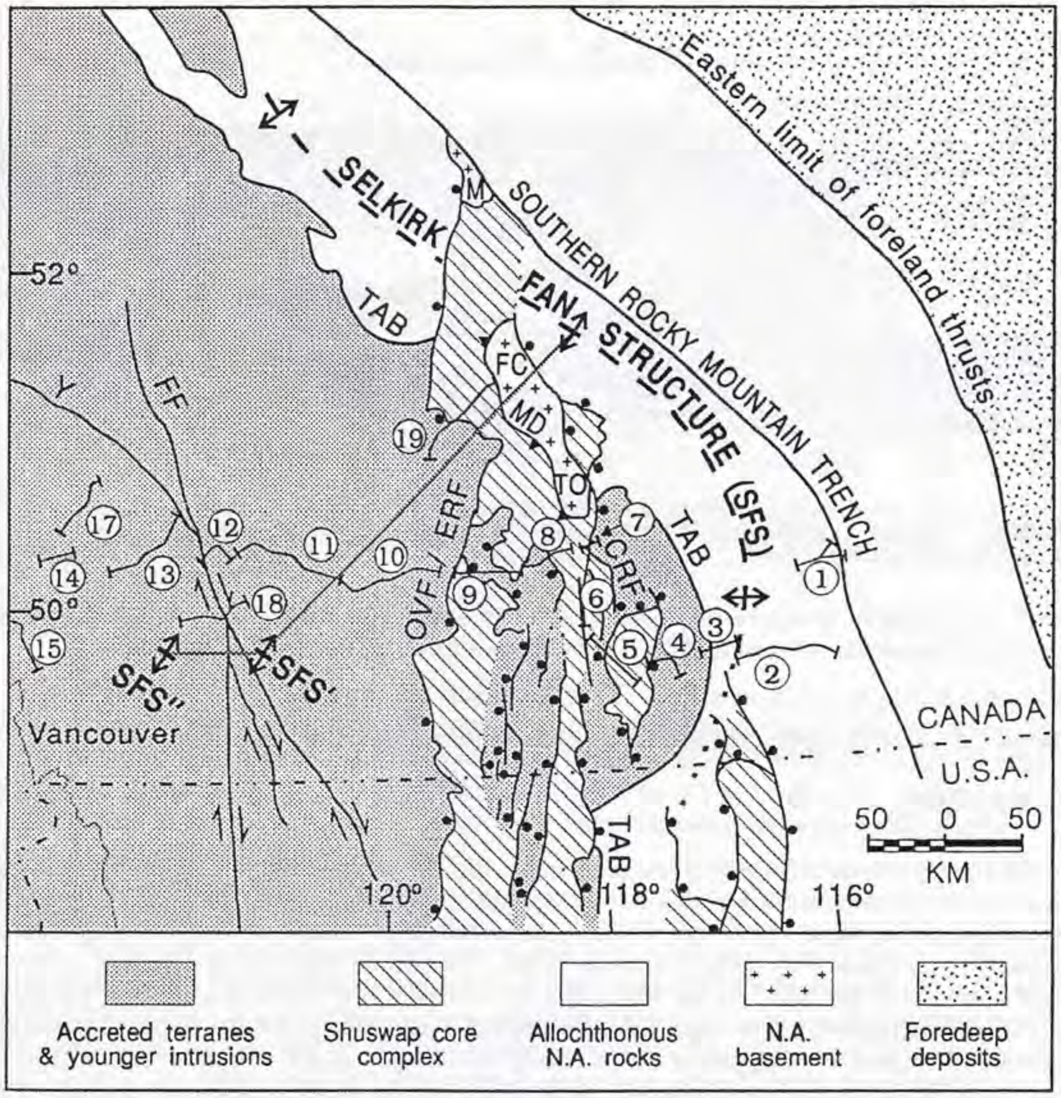


Figure 2. Tectonic map of the southern Canadian Cordillera: numbers identify LITHOPROBE lines (see Figure 4 for cross section). SFS = Selkirk fan structure, TAB = terrane accretion boundary, OVF/ERF = Okanagan Valley - Eagle River normal fault system, CRF = Columbia River fault, FF = Fraser River fault, Y = Yalakom fault, MD = Monashee decollement, FC and TO = Frenchman Cap and Thor-Odin culminations of the Monashee complex, M = Malton complex.

SHUSWAP METAMORPHIC COMPLEX

Exhumation of middle crustal rocks that are currently exposed within the southern Omineca Belt is attributed to a combination of tectonic denudation and erosion. Early exhumation brought some middle crustal rocks of the Selkirk fan structure to upper crustal conditions by the Middle Jurassic, but Cretaceous exhumation is also documented in the allochthonous rocks that overlie the Monashee decollement. The Shuswap metamorphic complex has been redefined to include only those middle crustal rocks that were not exhumed to upper crustal levels until the Late Paleocene to Eocene (Figure 2). These middle crustal rocks were exhumed primarily by tectonic denudation, resulting in the largest metamorphic core complex in the North American Cordillera. The bounding normal sense shear zones and detachment faults such as the **Okanagan Valley - Eagle River fault system** and **Columbia River fault** carry rocks in their

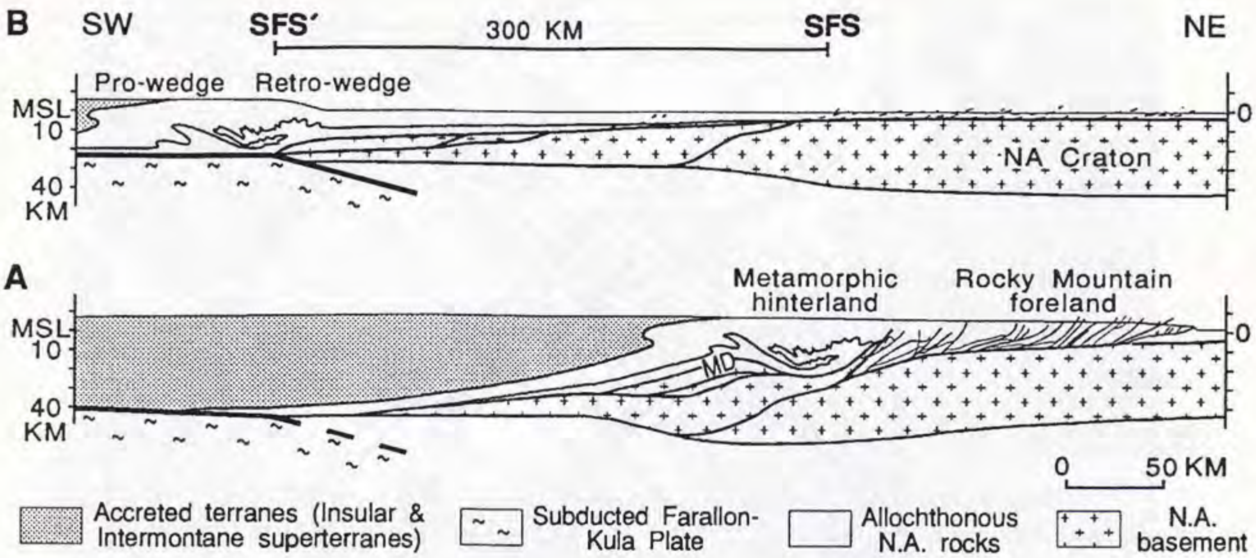


Figure 3. A: Tectonic cross section prior to Eocene extension. B: Middle Jurassic palinspastic restoration of Selkirk fan structure (SFS). From Brown et al. (submitted for publication).

hanging walls that were at upper crustal levels before the onset of extension.

MONASHEE COMPLEX

The Monashee decollement is exposed within the Shuswap metamorphic complex. Rocks that lie in the footwall of the decollement are known as Monashee complex and are correlated in part with Early Proterozoic rocks of the North American craton. These basement rocks are unconformably overlain by Upper Proterozoic to lower Paleozoic platformal strata. Monashee complex is exposed in the tectonic window that is bound to the west by the Monashee decollement and to the east by the Columbia River fault. The complex is highly strained and is considered to be allochthonous with respect to deeper crustal levels. Its internal geometry suggests a northeasterly to northerly sense of displacement; however, the magnitude of the displacement is unresolved. Much of the internal strain appears to have been imparted in the early Tertiary during a final climactic contractional development of the orogen.

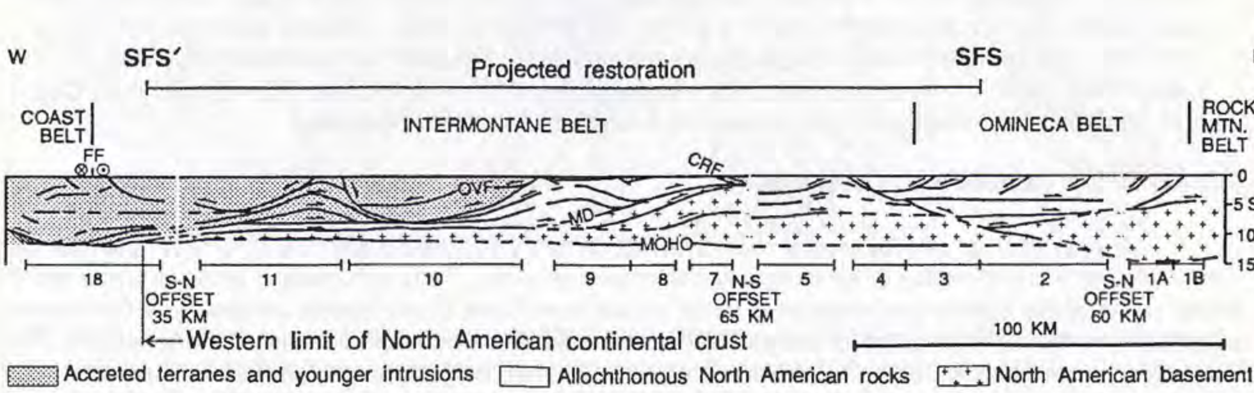


Figure 4. LITHOPROBE profile (after Cook et al., 1992): numbers indicate LITHOPROBE lines (see Figure 2 for locations), FF = Fraser River fault, OVF = Okanagan Valley fault, CRF = Columbia River fault, MD = Monashee decollement.

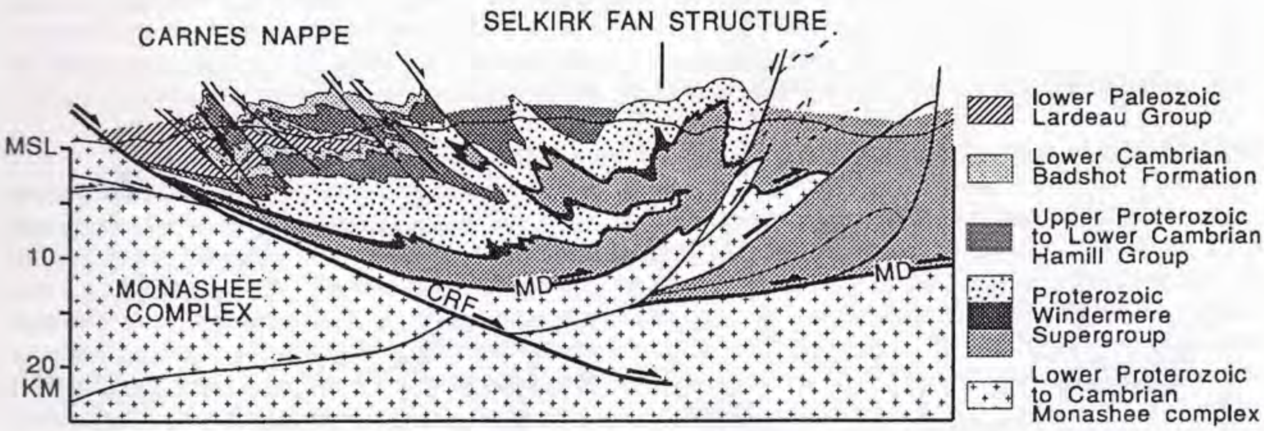


Figure 5. Cross section of Selkirk fan structure: MD = Monashee decollement, CRF = Columbia River fault (see Figure 27 for close-up of Carnes nappe). From Brown et al., submitted for publication.

COLUMBIA RIVER FAULT

The Monashee complex lies in the footwall of this Eocene extensional fault and associated shear zone. The Selkirk fan structure and underlying Monashee decollement are contained within its hanging wall. In the vicinity of Revelstoke, the Columbia River fault and Monashee decollement appear locally to merge as tectonic features. Mylonitic rocks exposed at the base of the hanging wall of the Columbia River fault are interpreted in part as reactivated relics of the compressional Monashee decollement.

PERICRATONIC TERRANES

The **Kootenay terrane** is exposed over a wide area of the southern Omineca Belt and is shown on the recently published tectonic assemblage map of the Canadian Cordillera (see Figure 1) as underlying the accreted Intermontane Superterrane at the western boundary of the belt and to extend in the hanging wall of the Monashee decollement as far east as the Selkirk fan structure; there, the terrane appears to conformably overlie Cambrian and Upper Proterozoic sequences of the North American shelf-slope margin. This terrane is generally considered to have developed on the North American plate outboard of the continental shelf.

The **Clachnacudainn terrane** (Figures 1 and 23) has been included in the Kootenay terrane on the Tectonic Assemblage Map but elsewhere has been ascribed a variety of origins, including correlation with the Monashee complex and affinities to far-travelled accreted terranes. We support the view that it is an integral part of the Kootenay terrane and question any suggestion that it is separated from the overlying strata by a major fault.

FIELD TRIP SUMMARY

The field trip is designed to illustrate the major tectonic features of the region as exposed in roadside outcrops and as viewed at a distance in mountain faces. A complete demonstration of the field relationships requires helicopter access to alpine areas, which unfortunately is not possible in the early spring. However, there are sufficient excellent exposures at low altitude to permit reasonable evaluation of our interpretations. We will also be well armed with photographs and slides of alpine exposures, together with illustrations of laboratory data.

We start the **first day of Part 2** at Kamloops (Figure 6) in the Intermontane Superterrane and work our way southeastward on Route 97 to the superterranes's leading edge in the Okanagan Valley.

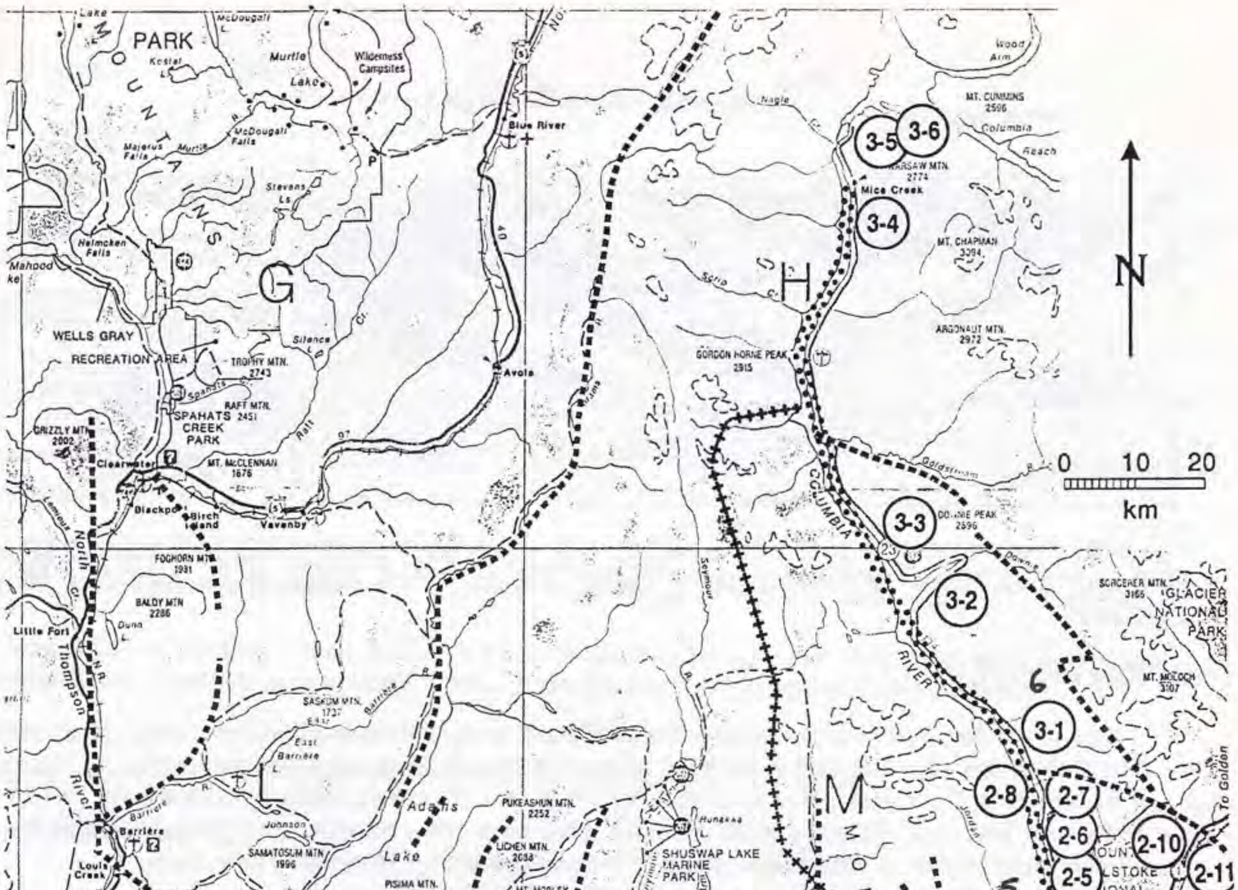


Figure 6. Map showing stop locations and prominent faults, which are indicated by patterned lines - in particular, the line of crosses indicates the Monashee decollement and the double dotted line indicates the Columbia River fault. Base map from British Columbia Ministry of Parks (1989).

1.5 p.11 2.4 p.23
1.6 p.14
1.9 p.16
2.1 p.17
2.3 p.23
3.1 p.33

The compressional shear zone that developed during northeasterly obduction of the superterrane onto the Kootenay terrane is not well exposed in this region and has been affected by the superposition of younger tectonic events. The boundary trends northwest-southeast and in the Okanagan Valley it is intersected by north-northeasterly trending extensional faults of the Okanagan Valley - Eagle River fault system. Eocene volcanic rocks unconformably overlie rocks of the superterrane and those of the Kootenay terrane.

At the town of Armstrong (Figure 6) in the Okanagan Valley, we proceed northward on Route 97A closely following the trace of the Okanagan Valley - Eagle River Tertiary extensional fault system. Eocene volcanic rocks were extruded before, during, and after extensional faulting; some of these relationships are evident in the hill sides to the east of the town of Enderby and will be viewed in the distance as we drive north on Highway 97A. Farther north at Mara Lake and in the vicinity of the town of Sicamous we will examine excellent exposures of middle crustal footwall rocks of the extensional fault system and upper crustal rocks of the hanging wall. We will review the evidence in this region for Tertiary exhumation and illustrate our interpretation of the geometrical links of this system to the extensional fault zone in the southern Okanagan Valley.

From the town of Sicamous we turn east along the Trans-Canada Highway. The footwall rocks of the Okanagan Valley - Eagle River fault system dip gently to the west, and so we cut slowly down section through these high-grade middle crustal gneisses. The focus on this part of the trip will be the change in structural style as we penetrate the footwall rocks of the extensional system. With several stops along the way we will illustrate a transition from the uppermost part of the footwall, in which kinematic indicators suggest a "top-to-the-west" sense of shear to a middle "dead zone", where shear sense indicators are absent or ambiguous, to a lower zone of intense "top-to-the-east" shearing. This lower zone of shearing, the Monashee decollement, marks the tectonic boundary with underlying rocks of the Monashee complex. The panel of middle crustal gneisses has been thrust northeastward over the Monashee complex and tectonically denuded by the westerly directed low-angle normal faulting of the Okanagan Valley - Eagle River fault system. Regional geochronological, petrological, and structural data suggest that the denudation was in part coeval with thrusting on the Monashee decollement. It appears that in the Late Cretaceous and Paleocene the previously accreted superterranes, together with underlying North American crust, were displaced northeastward across the Monashee complex, and in the latter stages of this crustal shortening event the thickened orogen began to collapse.

We will drive east to Revelstoke for the night and return to view exposures of the Monashee complex at the start of DAY 2.

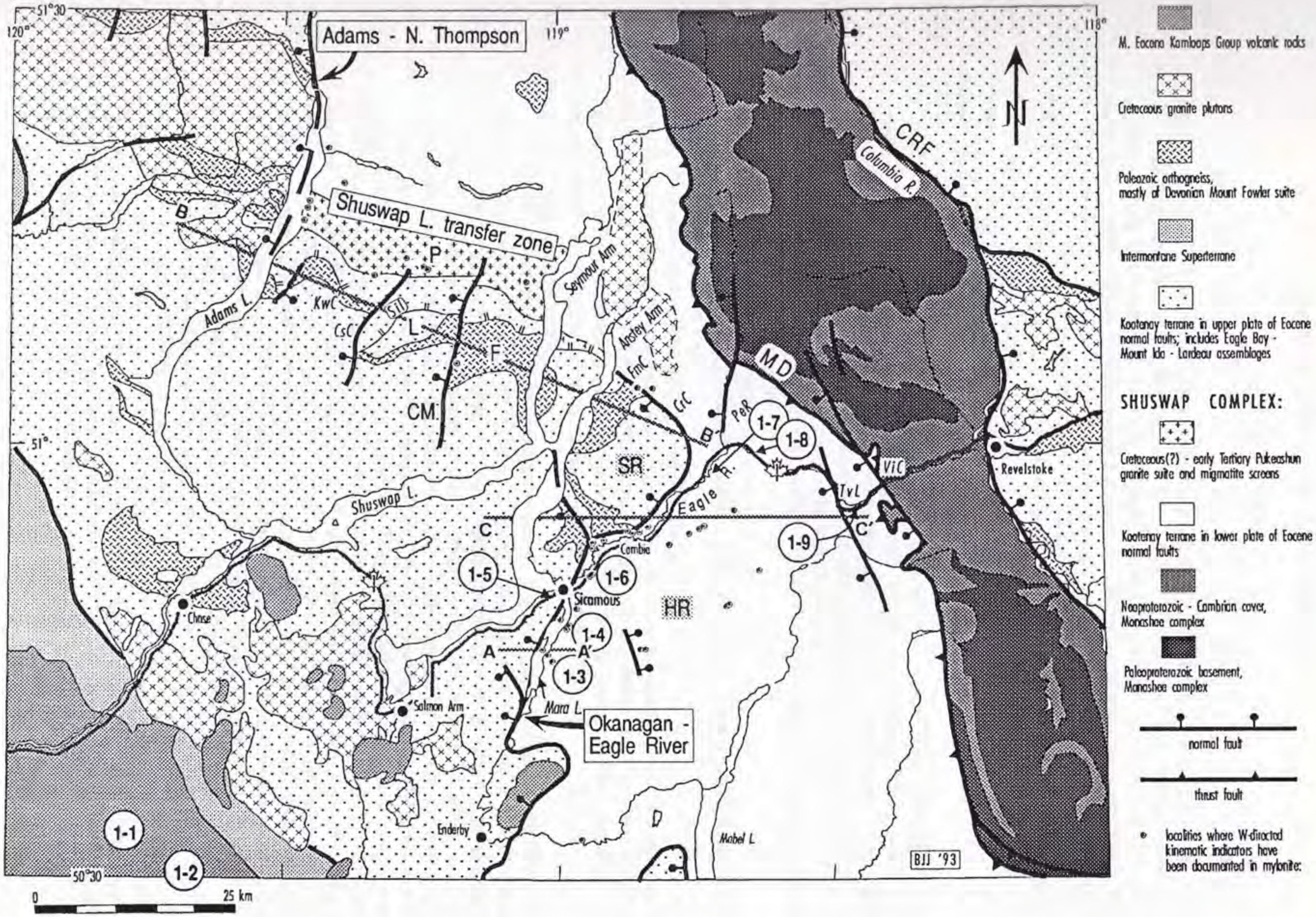
The second day of our trip will take us eastward on the Trans-Canada Highway from the Monashee decollement on the western flank of the Monashee complex across its domal culmination to the eastern flank, which is bound by the easterly dipping Columbia River fault.

At the Revelstoke Dam the hanging wall of the Columbia River fault is well exposed, and the footwall may be viewed across the Columbia River on the western side of the dam. Intensely sheared gneissic rocks in the hanging wall are part of the exposed base of the Clachnacudainn terrane. Recent work has led to reinterpretation of this terrane, and we now consider these strata to be an integral part of the pericratonic Kootenay terrane. During the day we will outline the evidence for this correlation and will consider the tectonic implications. We drive north on Highway 23 in the Columbia River Valley to view exposures of the northern part of the Clachnacudainn terrane, termed the **Clachnacudainn igneous complex**, in the hanging wall of the Columbia River fault. We also visit an excellent locality to examine part of a 500 m thick mylonite zone that overlies the brittle shear zone of the Columbia River fault. We argue that the base of the mylonite zone includes rocks that are characteristic of the footwall of the Monashee decollement; if correct, this puts additional constraints on the magnitude of extensional shearing along the Columbia River fault and implies that the base of the Clachnacudainn terrane rested tectonically on sheared rocks of the Monashee decollement prior to disruption during Eocene extensional faulting. Mylonitic rocks in the Columbia River fault zone have been variously ascribed to Eocene extensional shearing and compressional shearing related to motion on the Monashee decollement. The available data have not yet resolved this controversy so we can have some good discussions on the outcrops.

We then return to Revelstoke and work eastward via the Trans-Canada Highway and Mount Revelstoke National Park summit road to further view the structure and intrusive relationships within the Clachnacudainn terrane. The upper boundary of the terrane is the Standfast Creek fault. This structure has a somewhat controversial background; its interpretation is of course fundamental to the question of whether or not the Clachnacudainn terrane is part of the Kootenay terrane. Based on structural, stratigraphical, petrological, and geochronological arguments we consider the fault to be a minor feature with perhaps a few kilometres of extensional shearing that is most readily accounted for by attenuation of the overturned limbs of westerly verging folds during Mesozoic deformation. From the roadside it will be difficult to convince you that we speak the "truth", but several exposures together with some distant views and supporting laboratory data will give you some meat to chew on. We then return to Revelstoke for the night.

The **third day** takes us north along Highway 23 in the hanging wall of the Columbia River fault, where we are able to view low-grade metasediments of the lower Paleozoic **Lardeau Group** within Kootenay terrane. Westerly verging folds of the **Selkirk fan structure** are exposed in the alpine ridges to our east; these structures are southerly plunging, permitting us to view deeper structural levels as we continue northward. Along the way we take time out to look westward to the Monashee complex of Frenchman Cap and to point out **Downie slide** with its accoutrements related to BC Hydro's stabilization program. We continue beyond the northern limit of the Columbia River fault and rapidly move up grade into middle crustal rocks that are correlated with Proterozoic Windermere of the North American shelf-slope margin. These strata swing northwestward across the Columbia River and wrap around the northern end of the Monashee complex in the hanging wall of the Monashee decollement. Our route takes us to Mica Dam, where we will examine structures of the Selkirk fan within sillimanite-grade Windermere strata. Beyond this point we will be able to look northeastward across the Rocky Mountain Trench and realize that our trip across the Omineca Belt has closed our circular tectonic voyage.

Figure 7. Map for Day 1 with stop locations (circled numbers) and major tectonic elements. Shuswap Lake transfer zone is left step between the en echelon Okanagan - Eagle River and Adams - North Thompson segments of the Okanagan Valley - Eagle River fault system. Circled dots represent localities where reliable indicators of upper-member-to-the-west shear sense have been documented in mylonites. Cross sections A-A', B-B', and C-C' are shown in Figures 8, 10, and 12. HR = Hunters Range; SR = Shuswap Range; CrC = Craigellachie Creek; CsC = Cross Creek; FmC = Four Mile Creek; KwC = Kwikoit Creek; PeR = Perry River; TvL = Three Valley Lake; ViC = Victor Creek; CM = Crowfoot Mountain; F = Mount Fowler; L = Lichen Mountain; P = Pukeashun Mountain; CRF = Columbia River fault; MD = Monashee decollement. Geology compiled by Johnson from Okulitch (1979), Schiarizza and Preto (1987), Johnson (1990, 1993 in preparation), Bardoux (1993), Wheeler (1965), Hoy and Brown (1980), Journeay (1986), Journeay and Brown (1986), Bosdachin (1989), Harrap (1990), Coleman (1989), and Crowley (1992).


Adams - N. Thompson
Shuswap L. transfer zone
Okanagan - Eagle River
CRF
Columbia R.
MD
Adams L.
Shuswap L.
Seymour Arm
Anstey Arm
Eagle R.
Mara L.
Mabel L.
Revelstoke
Sicamous
Cambie
Chase
Salmon Arm
Enderby
CM
SR
HR
B
B'
C
C'
A
A'
P
L
F
D
KwC
CsC
StJ
FmC
CrC
PeR
ViC
TvL
1-1
1-2
1-3
1-4
1-5
1-6
1-7
1-8
1-9
120°
119°
118°
51°30
51°
50°30
0
25 km
BJJ '93
M. Eocene Kamloops Group volcanic rocks
Cretaceous granite plutons
Paleozoic orthogneiss, mostly of Devonian Mount Fowler suite
Intermontane Superterrane
Kootenay terrane in upper plate of Eocene normal faults; includes Eagle Bay - Mount Ida - Lardeau assemblages
SHUSWAP COMPLEX:
Cretaceous(?) - early Tertiary Pukeashun granite suite and migmatite screens
Kootenay terrane in lower plate of Eocene normal faults
Neoproterozoic - Cambrian cover, Monashee complex
Paleoproterozoic basement, Monashee complex
normal fault
thrust fault
localities where W-directed kinematic indicators have been documented in mylonite.

ROAD LOG AND STOP DESCRIPTIONS

DAY 1 OF PART 2

km

0.0 Kamloops; junction of the Trans-Canada Highway (TCH) and Columbia Street. Travel east on the TCH to Highway 97 and take Highway 97 South. We are in **Quesnel terrane** of the **Intermontane Superterrane**, of which the predominant lithology in this region is the volcanic assemblage of the Upper Triassic **Nicola Group**. Unconformably underlying the Nicola Group are Pennsylvanian to Late Devonian limestone and associated clastic rocks of the Harper Ranch Group. Eocene volcanics of the Kamloops Group rest unconformably on the Nicola Group. Numerous northwesterly to west-northwesterly high-angle normal faults have disrupted the section.

52.7 **STOP 1-1**, Monte Lake

A brief stop to view the Eocene volcanic rocks of the **Kamloops Group**.

83.1 **STOP 1-2** (8 km east of the town of Falkland)

Low-grade metasediments of the **Harper Ranch** assemblage, which forms the basement to Quesnel terrane. The origin and evolution of both the basement assemblage and the arc-oceanic rocks of Quesnel terrane remain controversial. There is general agreement that the Late Triassic arc was established outboard of continental North America with a marginal basin between it and the North American continental margin; the relationship of the arc to the North American plate boundary and the magnitude of lateral displacement prior to accretion in Toarcian time remains unclear.

125 Town of Armstrong, continue north on Highway 97A.

138.4 Town of Enderby, hills to the east are capped by Eocene volcanics in the hanging wall of the Okanagan - Eagle River fault

148.3 Cross the Shuswap River; town of Grindrod just ahead.

152.4 Hills to the west are greenschist-grade metavolcanic and metasedimentary rocks (**Mount Ida Group**) in the hanging wall of the **Okanagan Valley - Eagle River fault system**. Outcrops along the road are sillimanite-grade gneisses of the **Shuswap metamorphic complex**. The hanging wall - footwall boundary is not exposed at this locality.

168.4 **STOP 1-3**, Mara Lake viewpoint

The trace of the **Okanagan - Eagle River fault** follows the west shore of Mara Lake (Figure **7**). Metamorphic rocks in the footwall that are exposed in the prominent peninsula across the lake from here include migmatitic garnet-sillimanite-biotite pelite and semipelite mylonites, garnet-hornblende-biotite-quartz-plagioclase gneiss, clinopyroxene amphibolite, marble, and calc-silicate gneiss. The predominant foliation in these rocks, defined by transposed layering and "C" (shear) surfaces, dips about 20° WNW (Figure 8), and a strong mineral stretching lineation plunges westward. The semipelite mylonites exhibit C-S fabric and feldspar porphyroclast systems that indicate west-side-down shear sense. Locally, biotite has been completely replaced by chlorite and hematite, K-feldspars are highly sericitized, and microfractures and veinlets of quartz and hematite are abundant. Retrogression and brittle overprint in the high-grade mylonites are synkinematic, are most pronounced close to the brittle detachment, and are taken as evidence that normal-sense shearing continued as the rocks reached brittle upper crustal levels; crustal extension is therefore considered to have been the cause of much, if not all, of the exhumation of the high-grade rocks of the Shuswap complex.

In the upper plate of the fault at this locality, exposed in scattered outcrops in the Larch Hills (Figure 9), are semipelitic to pelitic quartz-muscovite and garnet-biotite-quartz-muscovite schists, micaceous and feldspathic quartzites, and minor carbonate and mafic schist of the **Silver Creek Formation**. The ages of the Silver Creek and of the footwall rocks are uncertain, but they are thought to correlate with Upper Proterozoic to lower Paleozoic pericratonic strata of the Kootenay terrane (either Windermere or Lardeau - Eagle Bay).

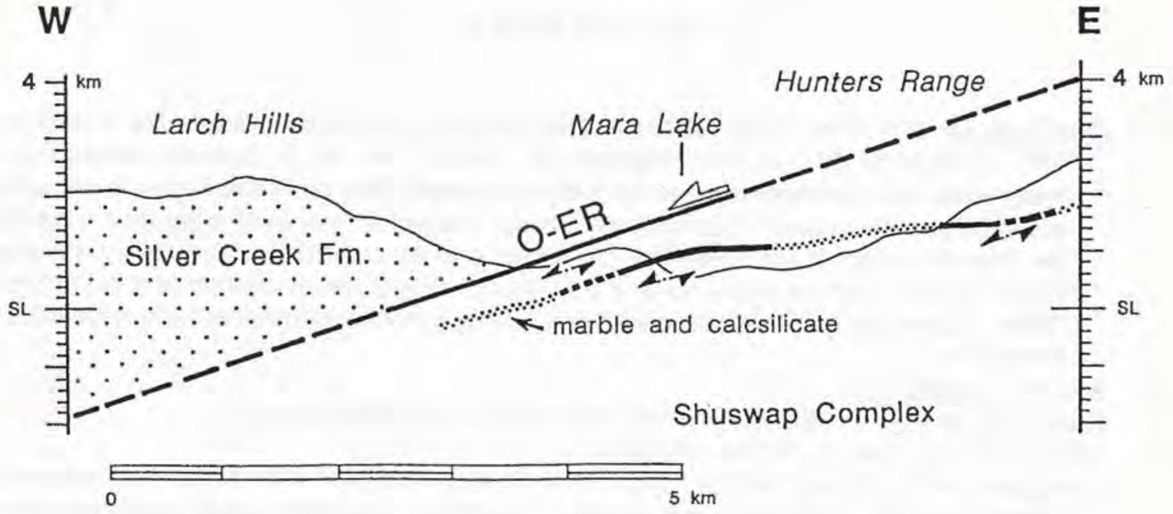


Figure 8. Cross section through the Mara Lake area (A-A' in Figure 7). Okanagan - Eagle River detachment (O-ER) is inferred as being subparallel to the west-dipping mylonitic foliation in the immediate footwall; double half-arrows indicate apparent dips of foliation at localities of documented upper-member-to-the-west shear sense. See descriptions in text. From Johnson (1993 in preparation).

173.1 **STOP 1-4**

Turn right into the quarry at Two Mile Road (sign for the Beach Comber Lodge is ahead on the left side of Highway 97A). At this level in the lower plate (several hundred metres beneath the detachment), the fabric in the rock is deformed by folds that in part predate extensional shearing. We are on the western flank of the **Hunters Range**, where the Shuswap complex has been affected by three recognizable phases of regional synmetamorphic fabric-forming deformations. D1 has transposed gneissic layering into what is now the predominant regional penetrative foliation. D2 has resulted in tight to isoclinal folds with hinge lines that have been variably rotated into parallelism with an east-northeasterly trending stretching lineation in response to Mesozoic-Paleocene thrusting. D3 folds are upright to moderately inclined, typically open, overturned, west-southwesterly verging structures with subvertical to moderately east-northeast-dipping axial surfaces and subhorizontal to gently plunging hinge lines. Sillimanite wraps around the hinges of F3 folds but is not dynamically recrystallized, implying that it was stable during D3. Metapelites locally exhibit an axial-plane S3 cleavage defined by parallel sillimanite and micas. D3 structures are Late Cretaceous or younger. Locally they are cut by discrete west-directed shears that presumably are related to the Okanagan Valley fault system.

Across Mara Lake to the west, the prominent cliffs in the Larch Hills are phyllitic carbonates of the Sicamous Formation, in the upper plate of the Okanagan - Eagle River fault.

Continue north on Highway 97A.

177.2 Junction of Highway 97A and the TCH. Proceed west on the TCH across bridge over the Shuswap River.

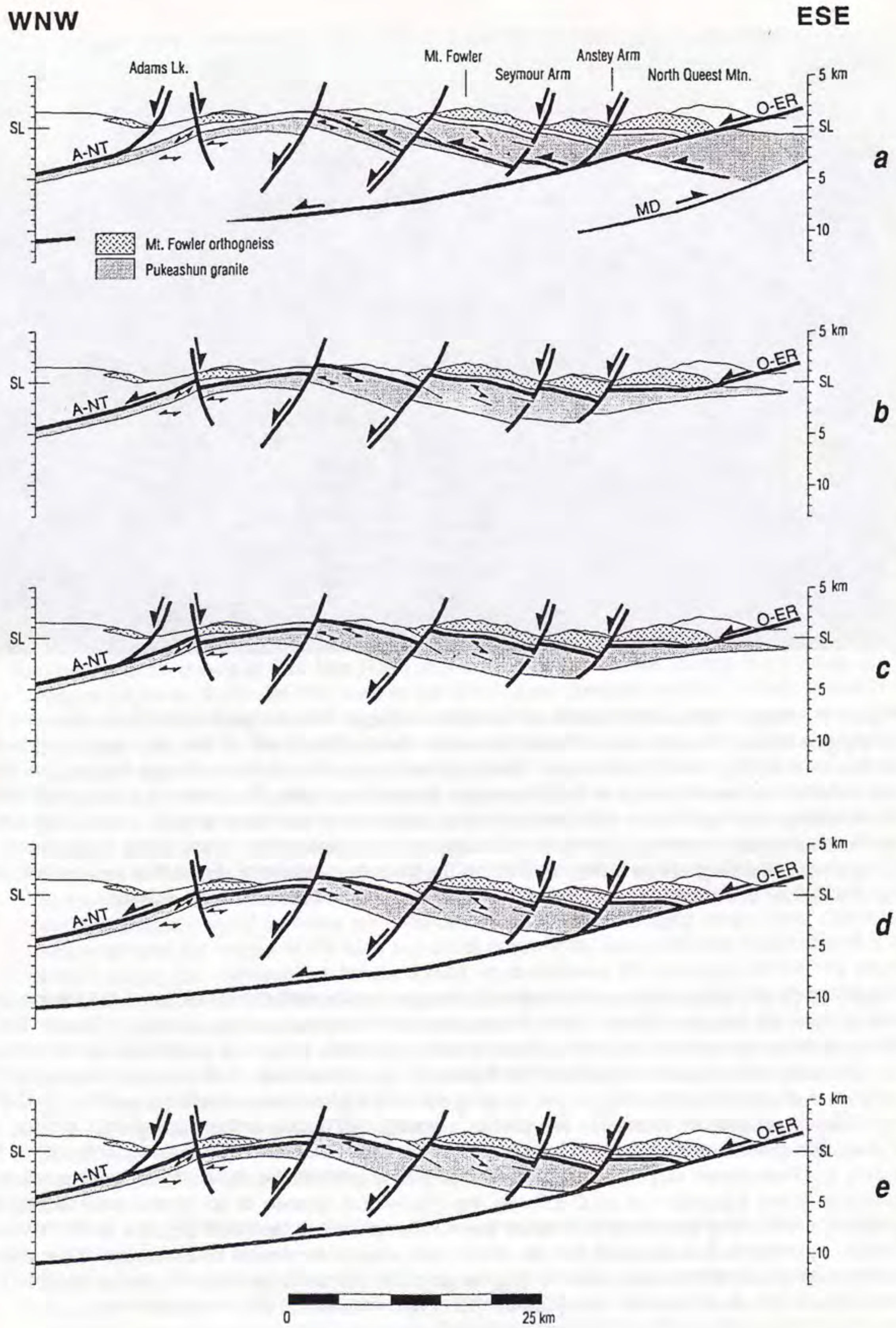
178.4 Immediately after the bridge, take the left-hand turn-off.

179 **STOP 1-5**

Pull off the road on the right side and park at the entrance to the private road. Walk back to the road exposures of fractured upper-plate rocks of the **Sicamous Formation**. There is considerable uncertainty about the tectonostratigraphic significance of these rocks. Originally they were thought to be correlative with the Triassic Slocan Group, which is part of Quesnel terrane. However, correlation with lower Paleozoic strata of the Eagle Bay Assemblage and

Figure 9. Photograph looking southward across the Eagle River valley toward Mara Lake and the Okanagan valley. The section in Figure 8 crosses the southernmost of two prominent peninsulas on the west (right) side of Mara Lake. Both peninsulas and the Hunters Range (east of the lake) are underlain by footwall rocks of the Okanagan - Eagle River fault. The Enderby Cliffs (small hump in left background and Larch Hills (west of Mara Lake) are in the hanging wall. From Mara Lake, the fault trace passes through the town of Sicamous and traverses the lower slopes of the Shuswap Range along the Eagle River valley, well below the trees in foreground. From this perspective, one can be readily convinced that the dip of the fault is less than 30°. Photo by Johnson.

Figure 10 (facing page). Kinematic models for the geometric relationships between the Okanagan - Eagle River (O-ER) and Adams - North Thompson (A-NT) segments of the Okanagan Valley - Eagle River fault system and the Pukeashun leucogranite mylonites, based on geological section across the Shuswap Lake transfer zone (B-B' in Figure 7): (a) Pukeashun mylonites are the product of northwest-directed backthrusting in the hanging wall of the Monashee decollement (MD); (b) O-ER, the Pukeashun granite, and A-NT are part of a contiguous ductile-brittle normal fault system; (c) Pukeashun granite mylonites are in a distal part of the O-ER that has been subsequently cut by the A-NT; (d) Pukeashun mylonites are the excised up-dip part of the A-NT, folded into a roll-over anticline in the hanging wall of O-ER; (e) the Pukeashun granite is an abandoned part of the evolving system that has been excised by the A-NT and incised by the O-ER; this is the favoured model. Representative apparent dips are shown with short lines; double half-arrows indicate upper-member-to-the-northwest shear sense. High-angle brittle faults cut the mylonites and either feed into or cut the brittle detachment in (a), (d), and (e). From Johnson (1993 in preparation).


WNW
ESE
Adams Lk.
Mt. Fowler
Seymour Arm
Anstey Arm
North Queest Mtn.
5 km
SL
O-ER
A-NT
MD
5
10
a
Mt. Fowler orthogneiss
Pukeashun granite
b
c
d
e
0
25 km

Lardeau Group or with the upper Paleozoic Milford Group, each of the pericratonic Kootenay terrane, has been suggested. Regardless of the origin of these rocks, there is a significant contrast in structural style and metamorphic grade between them and the footwall rocks observed at the previous stops.

The **Okanagan Valley - Eagle River fault system** consists of two west-dipping, en echelon, brittle detachment fault segments (Figure 7). The **Okanagan - Eagle River segment** is probably for the most part a single continuous fault. The **Adams - North Thompson segment**, northwest of here, may itself consist of en echelon segments, but this needs to be checked by additional mapping. The uppermost few hundred metres to 2 km of the footwall is a zone of inhomogeneous shear strain, within which mylonites exhibit upper-member-to-the-west kinematic indicators that formed in upper amphibolite facies. These mylonites are interpreted as exhumed former parts of a subhorizontal mid-crustal shear zone, inferred from LITHOPROBE reflection profiles, into which the detachment faults root. Between the en echelon Okanagan - Eagle River and Adams-North Thompson brittle fault segments is the 40-km-wide **Shuswap Lake transfer zone**, a left step in the system within which there is no obvious brittle fault separating footwall from hanging wall, but across which the belt of footwall mylonites continues. Unlike mylonites beneath the en echelon detachment segments, which are mainly migmatitic semipelites, mylonites in the Shuswap Lake transfer zone are predominantly two-mica leucogranites (the **Pukeashun granite suite**). These granites were at least partly syntectonic and must have served to localize strain and facilitate crustal extension. The mylonitic foliation in the granite has been warped into a broad antiform that is interpreted as resulting from isostatic rebound during tectonic denudation. The geometric relationships between folded mylonites and en echelon brittle detachments can be explained by kinematic models that invoke progressive warping and abandonment of the shear zone and excisement of the hanging wall during extension (Figure 10).

Apparent dips of seismic reflectors in the middle and lower crust imaged on LITHOPROBE profile 19 (Figure 11) outline a fold geometry of similar scale to the broad folds of mylonitic foliation in the Pukeashun granite. Because the deformation of the granite is considered to be synextensional, some of the deep crustal reflection geometry is probably related to extension.

We will have lunch at the beach site in <u>Sicamous</u> and then return to the TCH.

179.6 On the TCH proceed east.

183.5 **STOP 1-6** (Figure 12)

Pull off and park at the east end of the long road cut. High-grade footwall rocks here include paragneiss, migmatitic garnet-sillimanite-biotite schist, some biotite-hornblende and calc-silicate gneisses, and lots of pegmatite. The pegmatite is strained and is concordant with the layering in the other rocks. The migmatites are mylonitic and display a number of excellent indicators of west-directed shear. These include C-S fabric, asymmetrical extensional shear bands, and feldspar porphyroclast systems. The peak metamorphic mineral assemblage grt-sil-bt-pl-Kfs-qtz is synkinematic with west-directed shearing. Ductile shearing in the footwall of the Okanagan Valley fault system to the south is known to have occurred in the Middle Eocene, mylonitic synextensional leucogranites to the northwest are Early Eocene or possibly older. Monazites from the pegmatite at this outcrop have given Late Cretaceous U-Pb dates, interpreted as representing growth during a protracted Cretaceous to Paleocene or heating history.

Across the Eagle River to the north are hanging-wall rocks of the **Eagle Bay Assemblage**, which are at least in part equivalent to the lower Paleozoic Lardeau Group. They are cut by Devonian granodiorite orthogneiss -- we will see equivalents of this tomorrow in the Clachnacudainn terrane. The Eagle Bay was metamorphosed in greenschist to lower amphibolite facies (staurolite occurs in some units across the river from here) in the Mesozoic.

Continue east on the TCH, deeper into the footwall of the Okanagan - Eagle River fault.

204.3 Crossing the Eagle River.

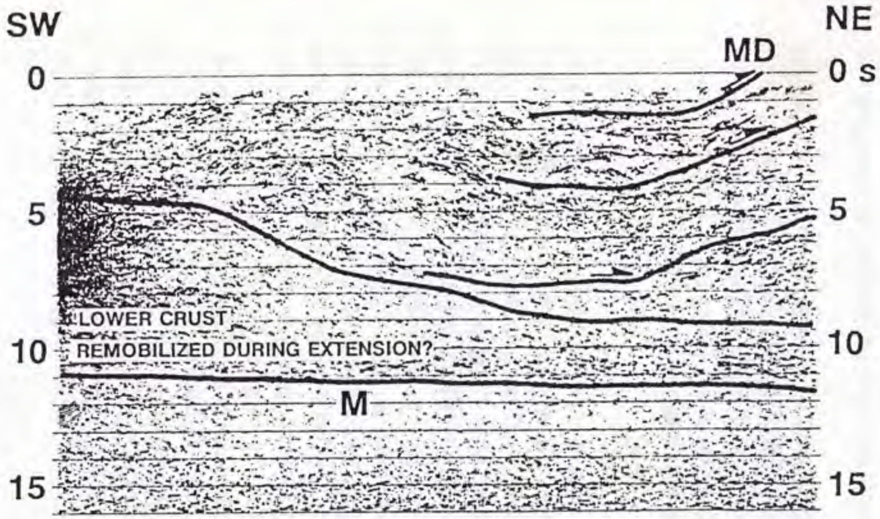


Figure 11. Migrated and coherency filtered reflection data from LITHOPROBE line 19. Numbers correspond to two-way travel times in seconds. Heavy lines highlight inferred geometry of the Moho (M), east-directed thrusts (e.g., Monashee decollement: MD), and the approximate upper limit of a zone of apparent east-dipping reflections that may represent lower crust remobilized by lateral ductile flow during Eocene extension. Strongly layered subhorizontal reflections in the upper crust near the southwest end of profile (~1-4 s) may represent mylonitic foliation that is either part of the footwall of the Okanagan Valley - Eagle River fault system or part of the older east-directed thrust system, arched during extension. From Johnson (1991).

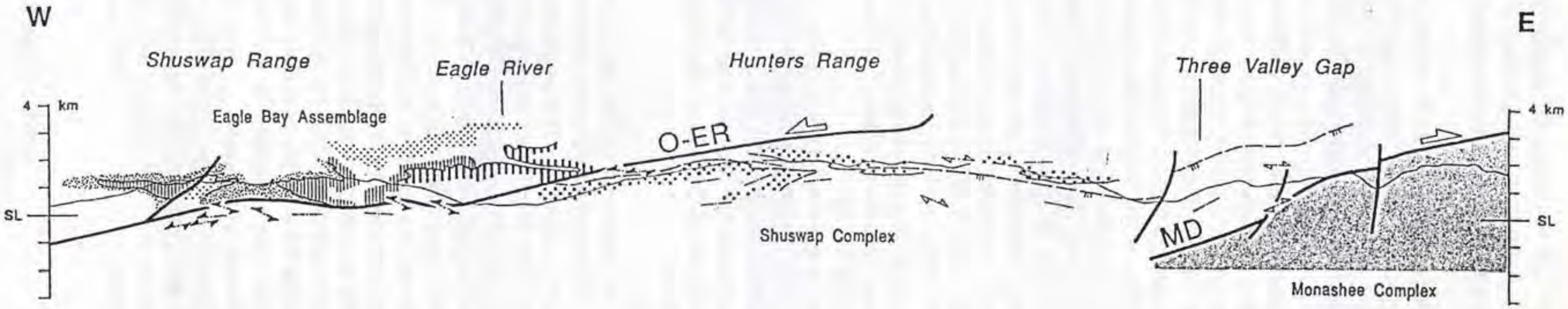


Figure 12. East-west section adjacent to the Eagle River and Trans-Canada Highway (C-C' in Figure 7). The Okanagan - Eagle River detachment (O-ER) juxtaposes medium-grade rocks of the Eagle Bay Assemblage against the high-grade Shuswap complex. The Monashee complex, the deepest exposed structural level within the Shuswap core complex, contains Early Proterozoic basement rocks and forms the footwall to the Monashee decollement (MD). Foliation of rocks in the structural panel between MD and O-ER is regionally subhorizontal; the double half-arrows indicate shear sense documented from mylonitic fabrics, their shafts represent apparent dips of foliation. Mylonites with upper-member-to-the-west fabrics (solid arrows) occur within the upper kilometre of the Okanagan - Eagle River fault, whereas upper-member-to-the-northeast fabrics related to thrusting (open arrows) occur closer to the Monashee decollement. The sillimanite-K-feldspar isograd (dashed line with triple ticks on high-grade side) is offset by one of several high-angle normal faults near Three Valley Gap. From Johnson (1993 in preparation).

205.1 **STOP 1-7**

Pull into parking area for the "**last spike**". We will take a few moments to view this historic site and then take a look at some "dead zone" exposures in the TCH road cuts. Most of the rocks that we have passed since our last stop are diorite to granodiorite gneisses and pegmatite. They are well foliated but only in some places have a weak to moderate hornblende lineation that trends southwest, in contrast to the strong west to west-northwesterly trending stretching lineation characteristic of mylonitic rocks in the immediate footwall of the Okanagan - Eagle River fault. The rocks along the highway here are biotite-hornblende quartz diorite gneisses, they are coarse-grained for the most part and not mylonitic, and there is no obvious shear sense.

Continue east on the TCH.

211.7 **STOP 1-8**

Just west of Crazy Creek Bridge. Quartz diorite gneiss is weakly foliated and well lineated. The gneiss is cut by unstrained pegmatite and mafic dykes. There are also concordant and strained pegmatites. Hornblende from this outcrop has given a $^{40}Ar/^{39}Ar$ plateau age of 56.5 ± 3.1 Ma (Johnson 1993 in preparation), representative of cooling ages obtained from the footwall of the Okanagan - Eagle River fault in the Hunters Range. Hanging wall rocks have given more complicated hornblende age spectra, generally reflecting cooling below the closure temperature of hornblende to ^{40}Ar loss (about 500°C) in the Cretaceous. The age of the metasedimentary sequence of the Hunters Range remains speculative, with regional mapping suggesting that Late Precambrian Windermere strata are likely correlatives. The orthogneiss at this locality has been collected for U-Pb dating, but results are not yet available.

Continue east on the TCH.

231.4 **STOP 1-9**

Three Valley Gap Motel and Restaurant. Park in the motel parking area. If it is not too late we will spend some time looking at the excellent roadside exposures, but we will return tomorrow morning to review our interpretation of these complex rocks.

The strata of the Hunters Range, which we have driven through since leaving the town of Sicamous, are now structurally above us. Regional mapping (Johnson 1990, 1993 in preparation) indicates that a high-angle, down-to-the-west normal fault separates that assemblage from the gneisses viewed in the cliffs at this locality (Figure 12).

Boudins up to 13 m long of amphibolite in semipelitic garnet-sillimanite-biotite-K-feldspar-quartz paragneiss are spectacularly exposed in this long road cut along Three Valley Lake. These rocks generally have been regarded as being equivalent to the Horsethief Creek Group of the Late Proterozoic Windermere Supergroup, but recent isotopic studies do not support this correlation. In particular, U-Pb and Sm-Nd data produced by David Parkinson (1991, 1992) and by Dick Armstrong (1991) suggest that the mafic rocks preserved as boudins are at least 1.5 Ga old.

Mineral assemblages within the amphibolite boudins include hornblende and plagioclase with lesser amounts of quartz, clinopyroxene, orthopyroxene, ilmenite, and locally garnet (Nicholls and Stout, 1986). This granulite assemblage is only preserved within the boudins. Nearby pelitic gneisses contain quartz-biotite-garnet-sillimanite. Ghent (1976), Ghent et al. (1977), and Nicholls et al. (1988) estimate a pressure of 6.1 kbar and a temperature of 700°C for the crystallization of this assemblage. Parkinson (1992) interpreted a U-Pb zircon lower intercept age from the amphibolite boudins of 73.4 ± 1.7 Ma as representing the time of peak metamorphism. Hornblende $^{40}Ar/^{39}Ar$ age spectra from the amphibolites have patterns suggestive of excess ^{40}Ar and possible episodic reheating, with probable final closure ages (corresponding to temperatures of about 500°C) of about 55-60 Ma (Johnson, 1993 in preparation).

The transposed layering and boudinage distribution point to a complex structural history that includes intense folding and shearing with easterly vergence. The gneisses are cut by steeply dipping to vertical basalt and lamprophyre dykes with northerly trends. These dykes commonly have chill margins and were probably emplaced during Eocene extension and exhumation.

Regional mapping has demonstrated that these probable Early to Middle Proterozoic gneisses are structurally underlain by intensely sheared pegmatitic zones that permeate a transposed metasedimentary assemblage of unknown age. The sheared rocks dip westerly and have a stretching lineation with northeasterly to easterly trend. Mylonitic fabrics are observed in thin section that are generally annealed and in which shear sense is predominantly upper member to the east; discrete zones that are usually unannealed indicate an upper-member-to-the-west shear sense. Similarly sheared pegmatites at a structurally higher level at Eagle Pass Ridge have yielded a Paleocene age based on U-Pb zircon and monazite analyses (Johnson, 1993 in preparation). These results are in close agreement with geochronological constraints determined by Carr (1992) for the time of synkinematic emplacement of pegmatite and leucogranite at the southern end of the Monashee complex. It appears that contractional upper-member-to-the-east shearing was in progress during the Paleocene, and by Eocene time the predominant deformation was extensional and westerly directed.

Continue east on the TCH to the town of Revelstoke, where we will spend the night.

DAY 2 OF PART 2

From Revelstoke return west on the TCH to Three Valley Gap to view STOP 1-9 in the light of day and to review our understanding of the rocks at this locality. Resume the road log of DAY 1 at 231.4 km and continue east on the TCH.

km

235.8 **STOP 2-1** (Figures 13-18)

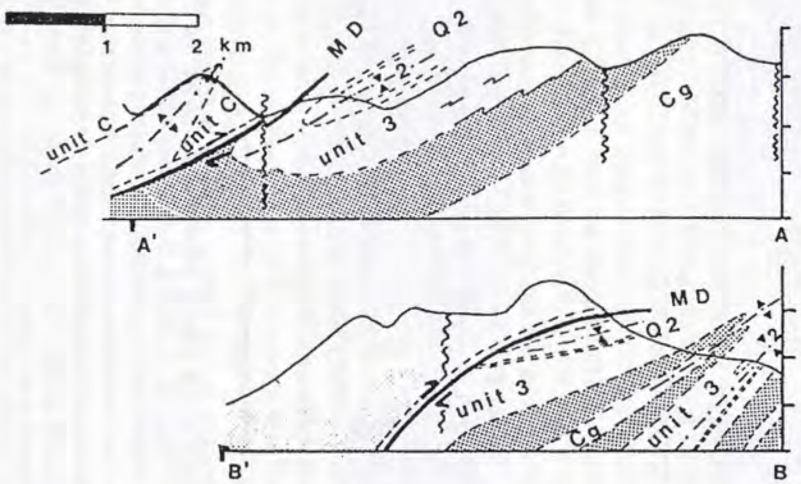
Pull into the parking area at Victor Lake (the picnic site has been closed for some strange reason and parking is just east of the old picnic ground).

The map of Figure 7 shows that a high-angle westerly dipping normal fault, the **Victor Creek fault**, crosses the TCH at this locality. Rocks in the hanging wall of the normal fault are interpreted as part of the highly sheared assemblage that structurally underlies the amphibolite-bearing gneisses viewed at Three Valley Gap. To the east in the footwall of the normal fault are exposed metasediments readily correlated with cover gneisses of the **Monashee complex**. In alpine regions to the north and south of the TCH it can be demonstrated that the normal fault is a minor feature with a maximum throw of no more than 1000 m. Where this fault does not intervene, the Monashee complex cover gneisses are in sheared contact with the overlying western metamorphic assemblage; this major shear zone is known as the **Monashee decollement**. Fabrics related to the shear zone may be viewed in the road cuts on the north side of the TCH. The majority of kinematic indicators give an upper-member-to-the-east sense of shear. The quartzite exposures with included amphibolite boudins, together with the overlying and underlying calc-silicate and semipelitic metasediments, are correlated with the **cover gneisses** of the Monashee complex. The age of this assemblage is not well constrained, but the basal part of the succession is intruded by syenitic rocks that yield a Late Proterozoic age, and the upper part is as young as Cambrian based on a model lead age (Hoy and Godwin 1988) and possibly includes rocks of Devonian age (Robert Scammell and Randy Parrish, personal communication, 1993). The basement gneisses unconformably underlying the cover gneisses are known to be as old as Early Proterozoic. As pointed out earlier there are uncertainties concerning the ages of the metasediments in the hanging wall of the Monashee decollement; however, at the northern end of the Monashee complex the footwall metasediments are tectonically overlain by highly sheared middle crustal rocks that extend upwards into strata correlated with Late Proterozoic assemblages of the Windermere Supergroup. Based on these regional arguments the Monashee decollement has thrust older strata of Precambrian age onto younger rocks of lower Paleozoic age.

If the Early to Middle Proterozoic age for the Three Valley Gap assemblage is correct then the shear zone has penetrated basement rocks and transported them eastward onto the cover gneisses of the Monashee complex.

SYMBOLS

- Geological contacts: defined, approximate, inferred.
- Monashee Decollement:defined, approximate, inferred.
- Late fractures and normal faults with minor displacement
- Axial surface traces: anticline, syncline.
- Oc Carbonatites
- Lake and stream



LEGEND

ALLOCHTHONOUS COVER

- D — sillimanite bearing semi-pelitic schist, quartzo-feldspathic paragneiss, hornblende-garnet gneiss, laced with pegmatite.
- C — quartzite, diopsidic marble, quartzo-feldspathic paragneiss, orthogneiss, laced with pegmatite.
- quartzo-feldspathic paragneiss, sillimanite bearing semi-pelitic schist, calc-silicate gneiss, diopside bearing quartzite, quartzite, with amphibolite boudins.
- highly strained shear zone with chaotic and fragmented remnants of footwall stratigraphy.

MONASHEE SEQUENCE:

- 5 — sillimanite/kyanite schist, calc-silicate gneiss, marble
- Q2 — Q2 quartzite: quartzite with thin biotitic interlayers and local amphibolite boudins.
- 3 — calc-silicate gneiss, impure marble, sillimanite/kyanite bearing schist, local carbonatites.
- basal quartzite: muscovite-tourmaline bearing quartzite.

CORE GNEISS

- Cg — mixed paragneiss: biotite-hornblende gneiss, calc-silicate gneiss.

Figure 13. Cross sections illustrating the truncation of phase-two folds by the Monashee decollement. From Bosdachin and Harrap (1988).

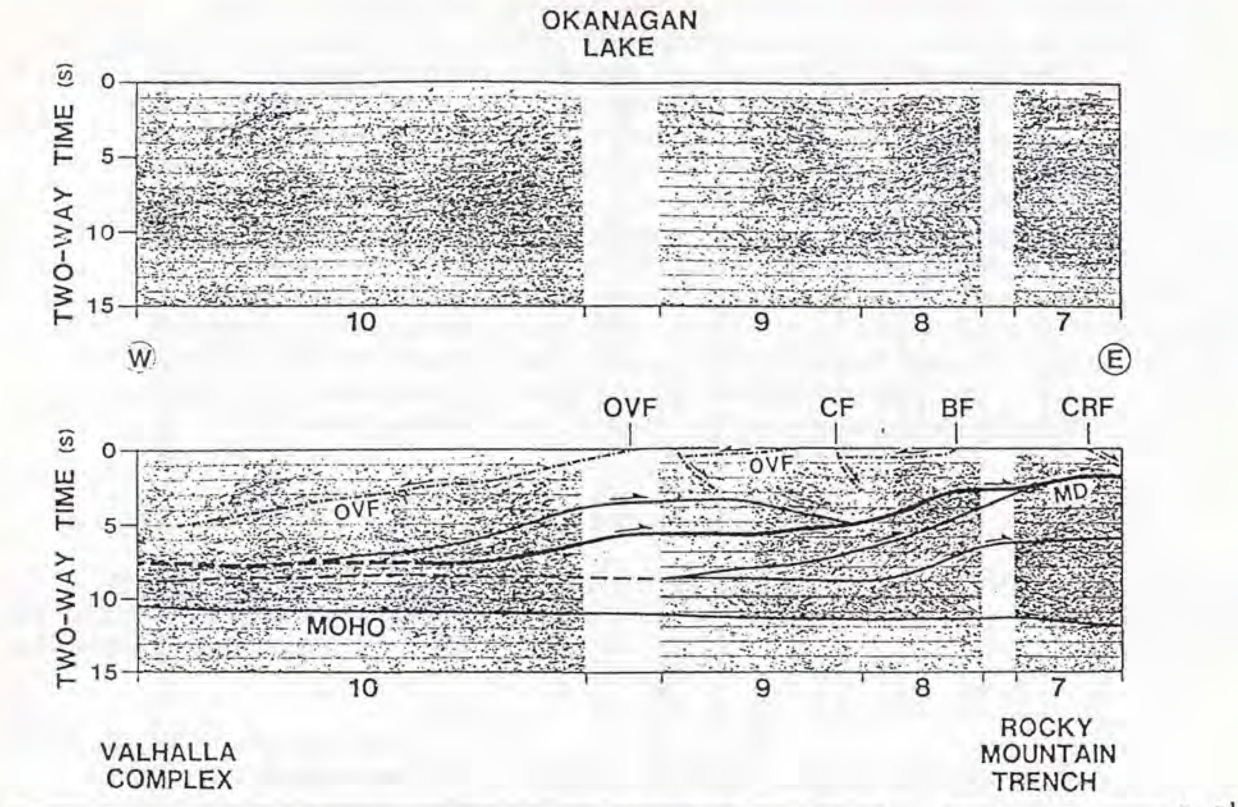


Figure 14. Top panel: LITHOPROBE seismic reflection data across the Omineca Belt (lines 1-5, 7-9) and part of the Intermontane Belt (line 10). Data are migrated and coherency filtered and are shown with no vertical exaggeration for a velocity of 6.0 km/s. Bottom panel: structural interpretation. Shaded pattern represents crystalline basement interpreted as being of NA cratonic origin. Position of Moho in lines 1 and 2 is based on refraction data. NBR (near-basement reflector) is the sole thrust to the Rocky Mountain Belt, which lies east of the Rocky Mountain Trench. NBR and Monashee decollement (MD) are shown as bold lines to emphasize inferred correlation across Slocan Lake normal fault (SLF). Eocene normal faults are shown as alternating long and short dashes: BF = Beaven fault, CF = Cherryville fault, CRF = Columbia River fault, OVF = Okanagan Valley fault, VS = Valkyr shear zone. For location of lines, see Figure 2. From Brown et al. (1992).

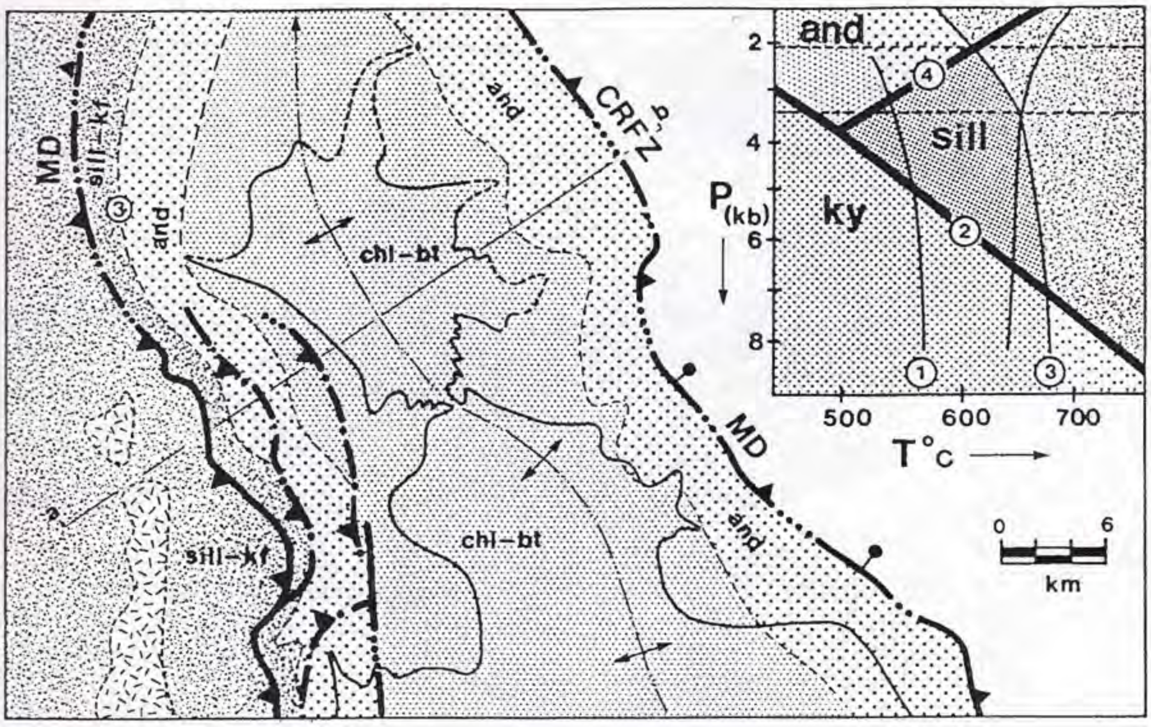


Figure 15. Simplified regional metamorphic map of northern Frenchman Cap dome showing distribution of M2 metamorphic zones and metamorphic isograds, and their relationship to major folds and faults. Refer to idealized P-T phase diagram (inset) for stability fields of metamorphic zones. From Journeay (1986).

Stratigraphic correlation of the cover gneisses along the length of the Monashee complex together with structural mapping reveal that the shear zone of the Monashee decollement cuts gradually upwards through its footwall from southwest to northeast in the direction of transport.

The significance of the Monashee decollement cannot be evaluated simply by viewing these roadside exposures, but it is clear that we have travelled eastward through a panel of middle crustal rocks, of which the upper part is bound by the westerly directed shear zone of the Okanagan Valley - Eagle River extensional fault system and the lower part is bound by an easterly directed shear zone, the Monashee decollement (Figure 12). These easterly directed structures continue down into the deepest exposed levels of the Monashee complex but are most intense within a zone of approximately 2 km thickness that straddles the stratigraphic and metamorphic discontinuity of the decollement.

The metamorphic changes in the vicinity of the TCH have not been exhaustively studied. The most obvious change is the appearance in the cover gneisses of the Monashee complex of metastable kyanite, which is absent in the overlying sillimanite + K-spar gneisses, but even this is difficult to demonstrate on the highway (Ed Ghent reports that the last visible kyanite has been carried away by enthusiastic rock hounds). To the north of us in the alpine exposures of **Frenchman Cap,** Murray Journeay has done a superb job of mapping out the metamorphic relationships. Figure 15 is a simplified diagram of some of his mapping, which illustrates the presence of low-pressure, high-temperature (Buchan) assemblages in the footwall of the Monashee decollement that have been superimposed on older Barrovian assemblages. The Buchan assemblages indicate that the footwall rocks were metamorphosed at bathozone 4 conditions, and the distribution of isograds implies a thermal inversion. This inversion is considered by Journeay to be a result of the emplacement of the overlying thrust sheet. The age of this period of thrusting and related development of the thermal inversion have been

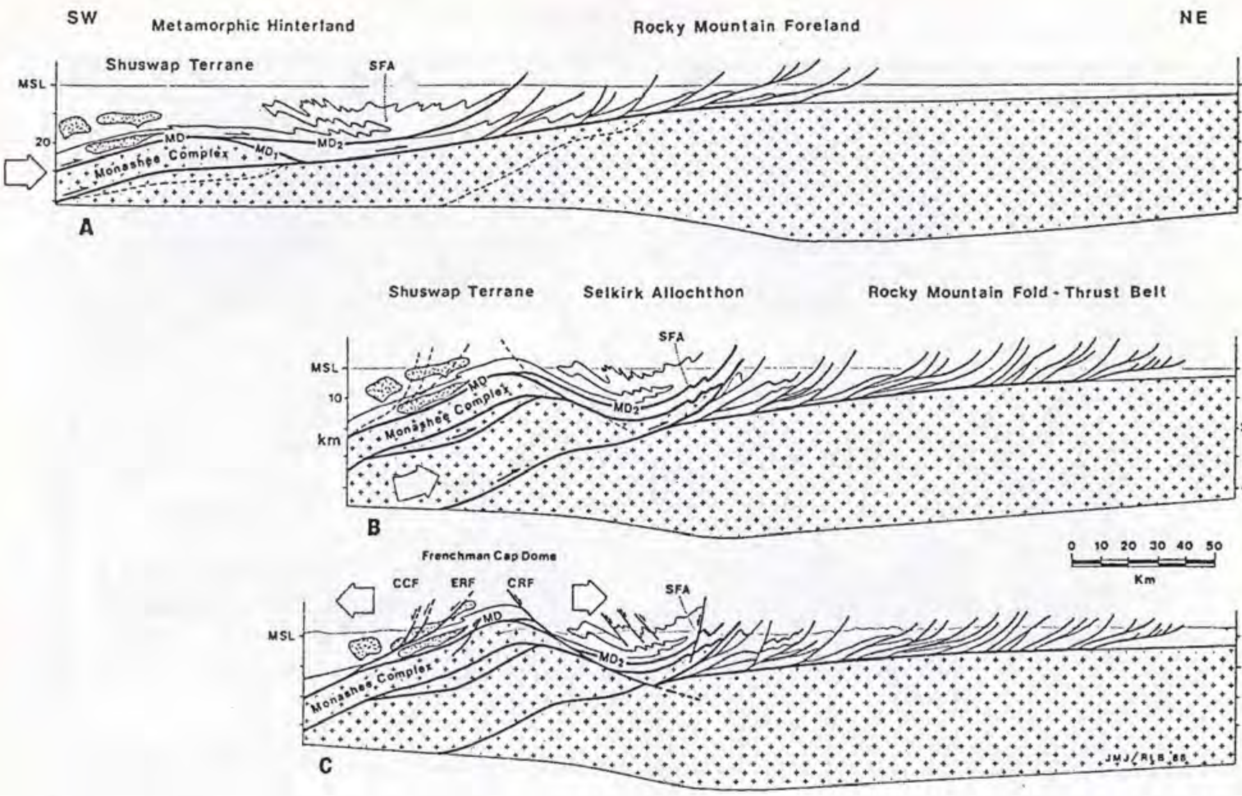


Figure 16. Cross section and sequence diagram for Late Cretaceous to Eocene evolution of southern Omineca Belt and Rocky Mountain Belt. A: Mid to Late Cretaceous thrusting on Monashee decollement (MD2); B: Late Cretaceous to Paleocene development of crustal duplex and associated uplift of Monashee complex; C: Paleocene to Eocene uplift and extension of structural culmination. Crosses delimit crystalline basement; dashed pattern indicates Late Cretaceous granitic intrusions. SFA = Selkirk fan axis, for reference. CCF = Craigellachie Creek fault; ERF = Eagle River fault; CRF = Columbia River fault. From Brown and Journeay (1987).

estimated by Journeay to be latest Cretaceous to Paleocene. This estimate is supported by U-Pb geochronology from the Frenchman Cap region and elsewhere from within the Monashee complex and the overlying thrust sheet. The peak of metamorphism and associated shearing on the Monashee decollement are best constrained at the southern end of the complex, where dating by Sharon Carr of a series of pegmatites and leucogranites together with regional mapping have placed these events between 58 ± 0.3 Ma and 59 ± 0.3 Ma (Carr 1992). Her results together with work by Vicki McNicoll place the most recent shearing on the Monashee decollement in latest Paleocene time. Preservation of the thermally inverted metamorphic assemblages in the footwall of the decollement implies rapid exhumation, presumably by tectonic denudation. Since it is known that extension on the Okanagan Valley - Eagle River fault system was under way by the earliest Eocene we can develop a model in which the thrust sheet that was emplaced eastward over the Monashee complex became gravitationally unstable in the final stages of its emplacement and its upper part was thrown into extension. More recent work by Robert Scammell points to tectonic denudation that was in progress as early as Late Cretaceous time, implying that easterly advance of the thrust sheet was accompanied by extension. We interpret these data in terms of critical taper theory and suggest that gravitational collapse of the orogen was initiated during the culminating stages of crustal thickening. Reduction in convergence rates of the North American and Kula-Farallon plates appears to have coincided with termination of thrusting on the Monashee decollement;

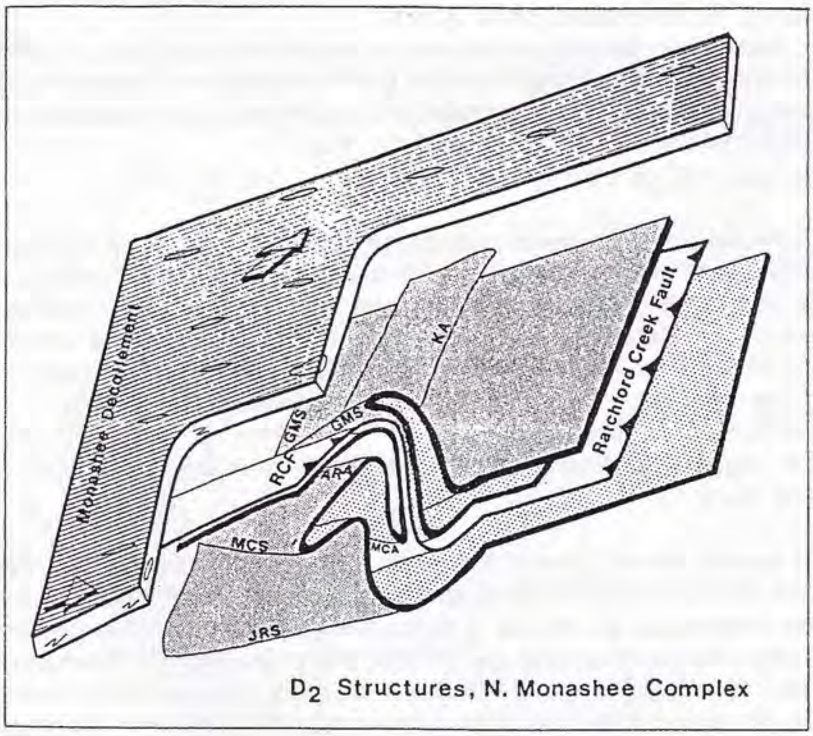


Figure 17. Schematic diagram illustrating the inferred geometry and kinematics of F2 cross-folds along the west flank of Frenchman Cap dome, and their relationship to early-stage mylonitic shear zones of the Monashee decollement (MD1) and older F1 fold closures of the Monashee complex. North is toward the top of the diagram. From Journeay (1986).

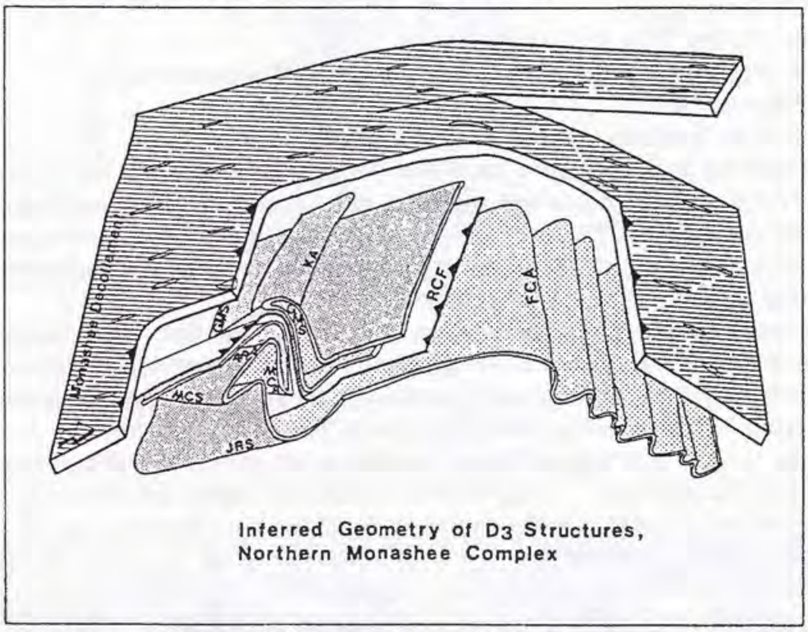


Figure 18. Schematic diagram illustrating the inferred geometry and kinematics of F3 folds and their relationship to late-stage mylonitic shear zones of MD2 within the northern Monashee complex. Major F3 folds include the Monashee antiform (labelled here as FCA), and the Pettipiece Pass fold set. From Journeay (1986).

establishment of a more oblique transpressive setting is thought to have influenced the orientation of the extensional shear zones.

The Monashee decollement appears to be a middle crustal shear zone that linked upper crustal shortening in the Rocky Mountain Belt to deeper level crustal shearing in the Omineca and Intermontane belts. This interpretation is supported in the subsurface by seismic reflection data from LITHOPROBE (see Figures 4, 11, 14).

Continue east on the TCH.

248.4 **STOP 2-2**

Pull into the parking area on the left side of the Highway. (This locality is just east of the power line that crosses the TCH and adjacent to a saw mill on the south side of the Highway.)

The sillimanite-grade calc-silicates and minor pelitic rocks exposed here are **cover gneisses of the Monashee complex**. They are well foliated, but compositional layering is clear and there is no indication of mylonitization. Strata now dip gently east, and we have crossed the culmination to the eastern flank of the complex.

Continue east on the TCH.

249.7 Junction with Highway 23 South. Turn left at the junction into the side road that swings back toward the west.

250.4 **STOP 2-3**

The road is usually closed beyond this point. Park on the side of the road. View the road exposures and then walk into the quarry just to the north of the road.

These exposures are typical of the calc-silicates of the **cover gneiss sequence of the Monashee complex**. Here they are sheared and mylonitized, but transposed bedding may be recognized. Kinematic indicators in the mylonitic rocks give an upper-member-to-the-east sense of shear. The age of the shear fabric at this locality is not known. Projection of the Monashee decollement lies above the erosion surface at this point, but the folds and some of the shear fabrics in these exposures may be a result of strain induced during emplacement of the overlying thrust sheet. However, the intensity of this deformation increases to the east as the footwall of the Eocene **Columbia River normal sense shear zone** is approached; much of the mylonitic fabric in these exposures may therefore be a result of this extensional event.

Calcareous layers contain diopside-quartz assemblages, and fibrolite + kyanite occur in the pelitic interlayers.

Return to the TCH and continue east.

252.2 Junction with Highway 23. Turn left on Highway 23 and proceed north.

256.1 **STOP 2-4** (Figures 19-22)

Turn into the visitor parking area for the Revelstoke Dam.

Revelstoke hydro-electric dam was completed in 1982 by BC Hydro. During various stages of construction the site was exposed, and Larry Lane, while working on his Ph.D. thesis and as site geologist for BC Hydro, was able to record the three-dimensional structure of the bedrock of the site. Figure 22 is a photograph of the exposed **Columbia River fault zone** as seen during an early stage of construction.

The west abutment and foundation of the concrete dam comprise pelite, calc-silicate, quartzite, and carbonate of the **cover gneisses of the Monashee complex**. The pelitic rocks contain sillimanite oriented in an east-southeasterly trending extension lineation or in radiating clusters lying in the foliation. Relict kyanite is kinked, bent, corroded, and partly altered to andalusite. Large quartzite units are mylonitic; thin quartzite units in the pelitic layers are incompletely recrystallized. Highly strained carbonate layers are dark grey to black mylonite; the less strained protolith is white coarse-grained marble. The road cut for Highway 23 at the dam crest exposes **garnetiferous amphibolite boudins** in sillimanite-bearing pelitic and semipelitic metasediments, cut by abundant pegmatite. The unit is underlain just below the dam crest by highly sheared cover gneisses of the Monashee complex. Interpretation of this tectonic boundary is based on the presumed correlation of the amphibolite-bearing unit with **Windermere strata**. If this correlation is correct, the contact marks easterly directed thrusting of these rocks over the cover gneisses of the Monashee complex on the **Monashee decollement**. Superimposed on this early shear zone is a 400 m thick ductile-brittle zone that

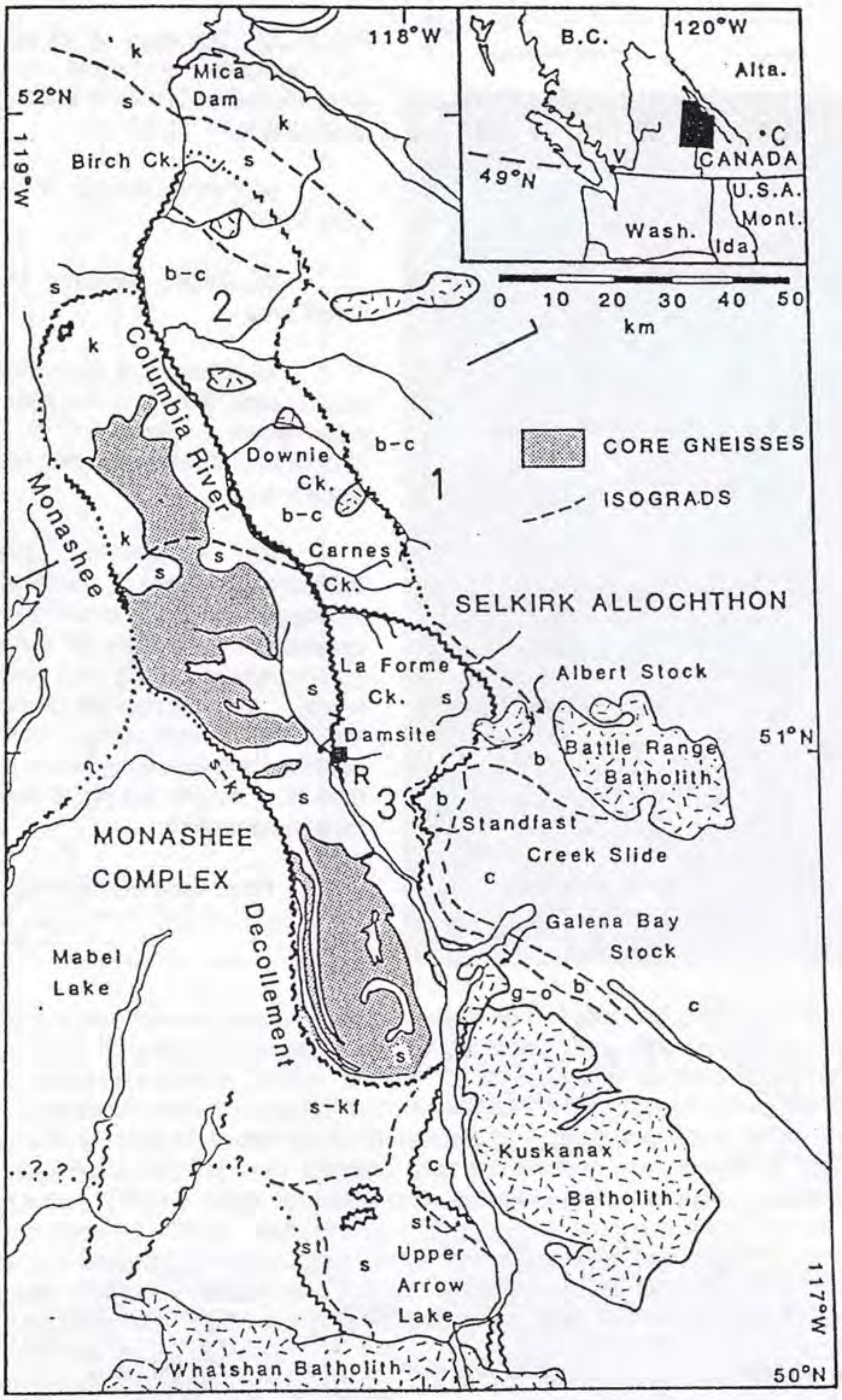


Figure 19. Map showing simplified geologic elements, southeastern British Columbia. Key to metamorphic grades: c, chlorite; b, biotite; b-c, biotite-chlorite; g-o, garnet oligoclase; st, staurolite; k, kyanite; s, sillimanite; s-kf, sillimantite - K-feldspar. Key to cities: C, Calgary; R, Revelstoke; V, Vancouver. Key to numbers: 1, Illecillewaet slice; 2, Goldstream slice; 3, Clachnacudainn slice. From Lane and Brown (1987).

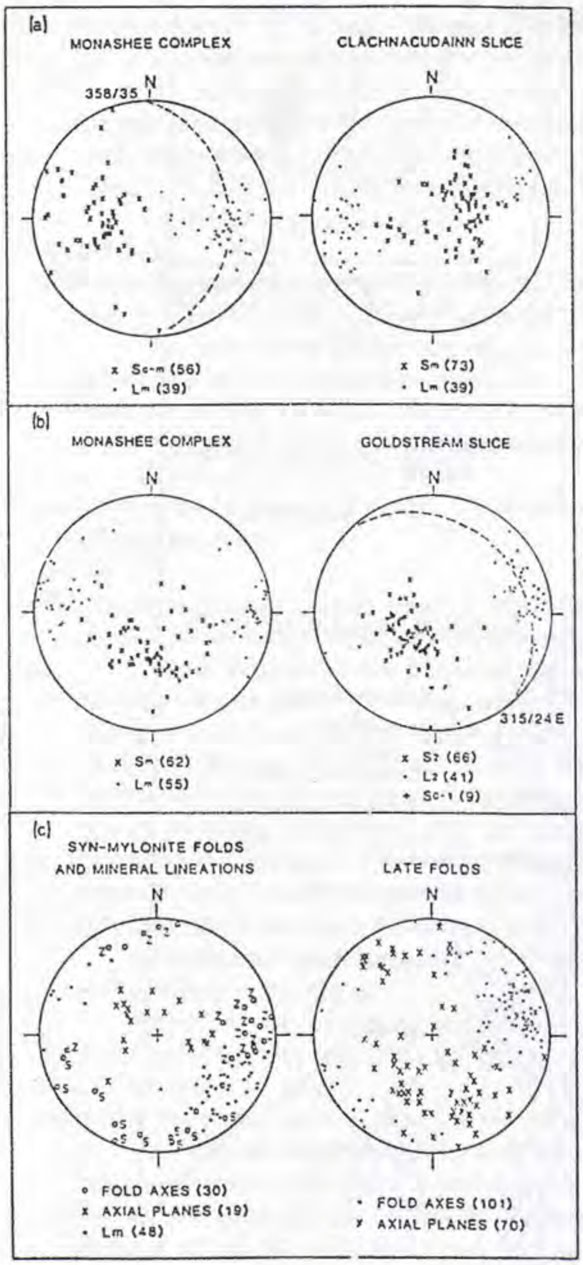


Figure 20. Summary of the fabric elements and kinematic indicators typical of the mylonitic footwall rocks of the Columbia River fault zone.

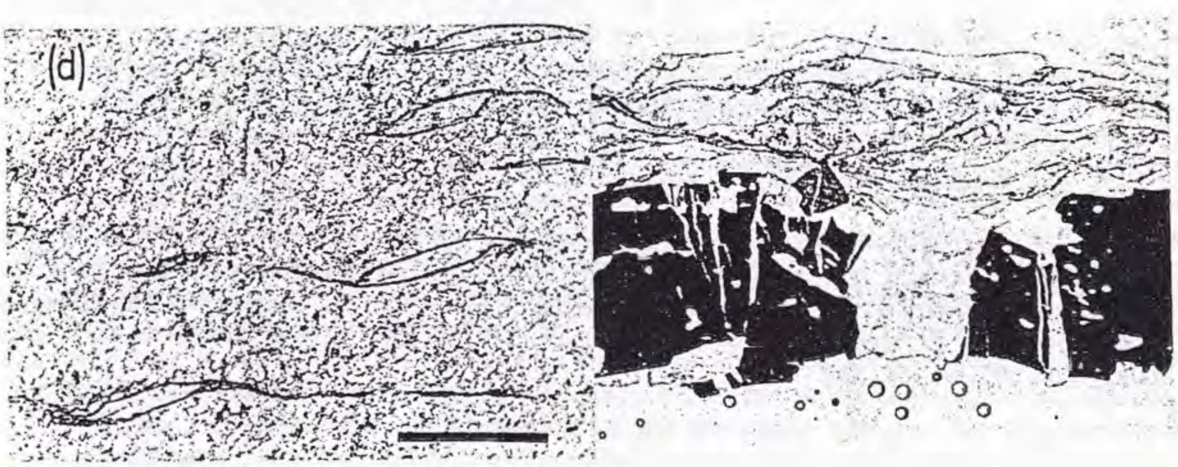
(a) Fabric attitudes of the Revelstoke Dam area.

(b) Fabric attitudes of the Carnes Creek area.

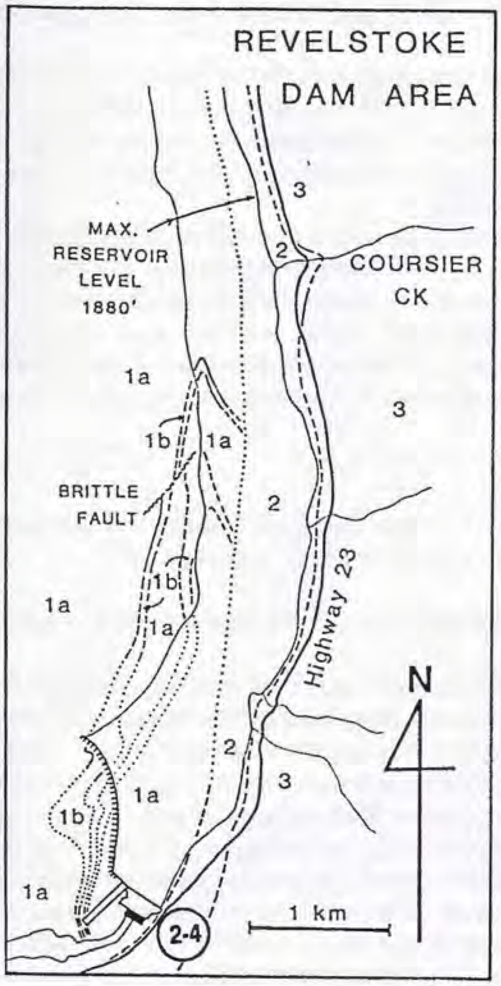
(c) Attitudes of syn-mylonite and late-ductile folds from the Revelstoke dam site excavations. Rotation of syn-mylonite structures indicates hanging wall displaced eastward.

(d) Asymmetric microstructures indicative of sense of displacement. Right micrograph shows clockwise rotation of tourmaline fragment by 45° (based on axis of maximum absorption) and low-angle shear bands. Left micrograph shows muscovite "fish" and c'-fabric tails. Both views look northward in plane light. Scale bar represents 0.08 in. (2 mm) in left photo and 0.02 in. (0.5 mm) in right photo.

From Lane and Brown (1987).



←Figure 21 ↓Figure 22



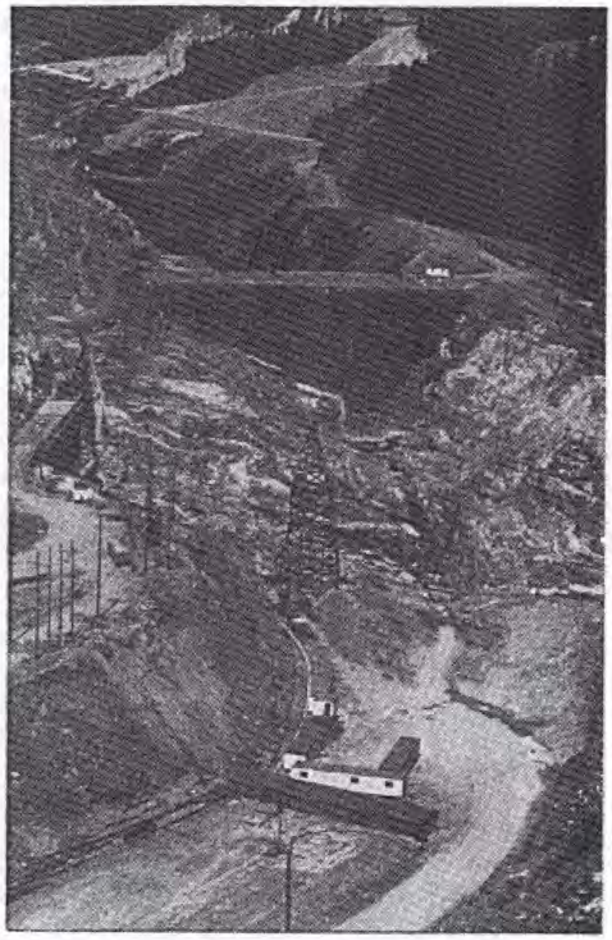


Figure 21. Revelstoke dam site area. Units: 1, Monashee complex; 1a, pelite, calc-silicate, minor marble; 1b, quartzite; 2, tectonic lozenge of silimanite pelite and semipelite, amphibolite boudins, and pegmatite; 3, quartz-monzonite pluton of the Clachnacudainn igneous complex, contains protomylonitic to mylonitic microstructures. Tectonic affiliation of unit 2 is uncertain but is tentatively related to Monashee complex, based on Rb-Sr isotopic characteristics (Lane, 1984) and lithologic similarity to amphibolite-bearing units exposed near the northwestern margin of the Monashee complex (Scammell, 1985). Large quartzite units are defined in the dam site area based on excavations and diamond drilling. North-closing folds in flooded ground north of the dam have east-plunging axes and are syn-mylonitic. The western band of quartzite approximates western limit of mylonitic textures. Contacts between units 1, 2, and 3 are tectonic. Slope between powerhouse and spillway exposed folds that deform mylonitic fabrics. From Lane and Brown (1987).

Figure 22. View looking north of Revelstoke dam site during construction. The Columbia River fault zone is completely exposed; in the foreground on the west bank are highly contorted mylonitic calc-silicate, pelite, and quartzite cover gneisses of the Monashee complex. These units extend to the east bank where they become brecciated and are locally reduced to clay gauge. The uppermost exposure in the extreme east of the photograph is similar to the structurally higher unit currently exposed on Highway 23 adjacent to the east abutment of the dam. This unit is tectonically overlain by members of the Clachnacudainn igneous complex. (Photo taken by Brown, July 1980; see also Read and Brown, 1981.)

was developed during extensional deformation associated with the Eocene Columbia River normal fault. Intense fracturing, clay gouge generation, and hydrothermal alteration have affected this zone.

The principal displacement shear and intense alteration adjacent to it occur in the rocks of the Monashee complex, which were temporarily exposed during construction of the dam and other facilities (see Lane, 1984). Alteration consists of chloritization of biotite and garnet, principally adjacent to the fractures. Where alteration is most intense, illite, kaolinite, sericite, and carbonate replace plagioclase and mafic minerals.

Within the fault zone lamprophyre dykes have been observed that cut all ductile fabrics but are disrupted by brittle shears. The lamprophyres are not dated at this locality, but they occur regionally and render Eocene cooling ages. The southern continuation of the Columbia River fault has been dated as Early Eocene (see Parrish et al., 1988), and this age includes the formation of mylonitic fabrics in its footwall. Estimates of displacement on the Columbia River fault range from as little as 1 km to as much as 30 km. We will pursue this uncertainty at later stops in our journey.

Continue north on Highway 23.

258.2 **STOP 2-5**

Turn left off the Highway and walk back down the road to view exposures above the dam site.

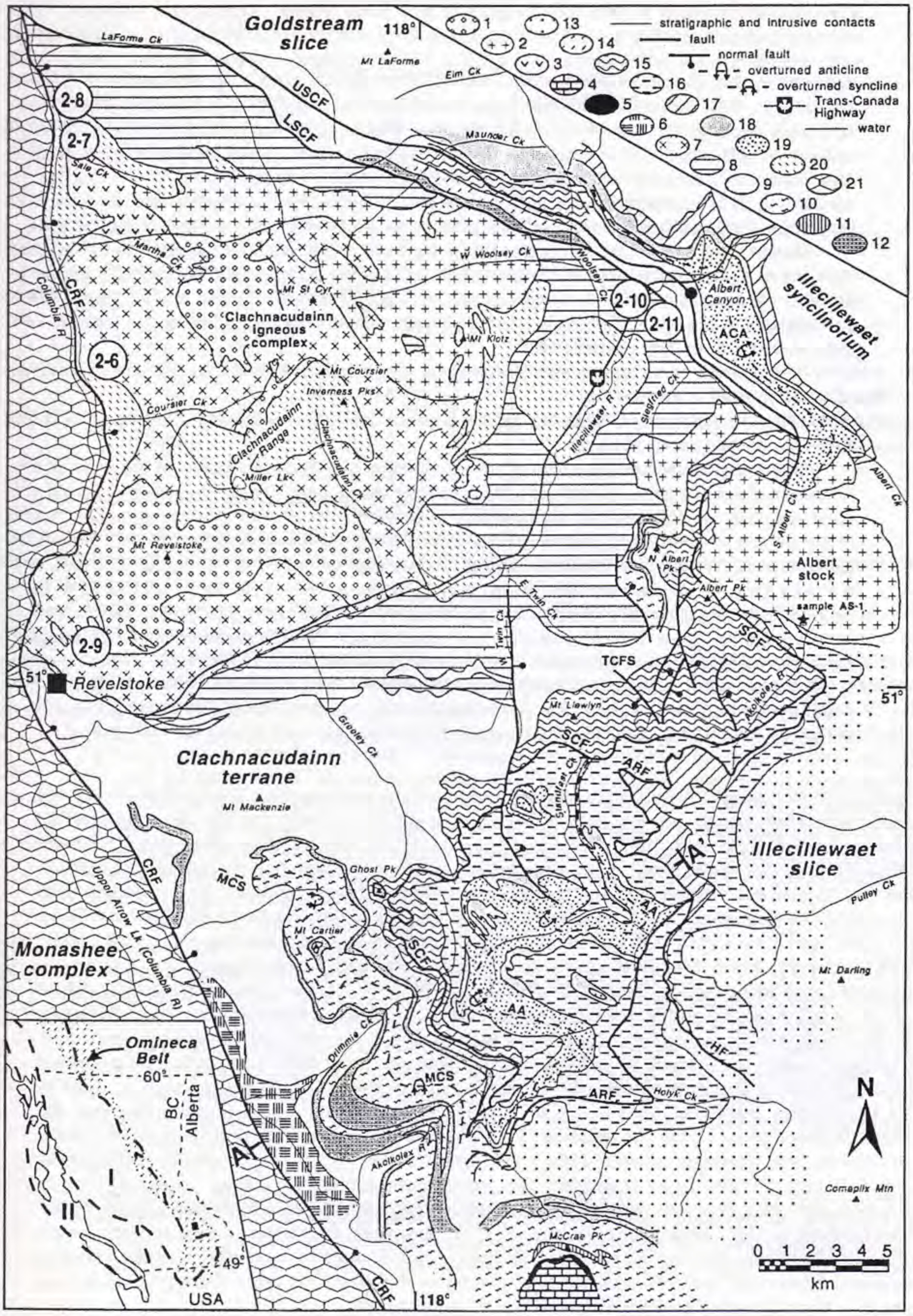
After lunch at the nearby picnic area we will continue north on Highway 23.

265.6 **STOP 2-6, Clachnacudainn igneous complex**

Pull off to left into rest area. Road cut is across Highway 23 from the rest area and continues north to St. Cyr Creek.

In this road cut there are a few of the numerous granitoids of multiple age that have undergone variable amounts of ductile deformation in the **Clachnacudainn igneous complex**. The complex dominates the northern portion of the **Clachnacudainn terrane** and intrudes the base of the overlying **Illecillewaet slice of the Selkirk allochthon** (Figure 23). We use known and inferred granitoid ages, intrusive relationships, contact metamorphic effects, and probable emplacement depths of granitoids gained from hornblende barometry to contend that peak regional metamorphism, regional ductile deformation, and displacement between the terrane and Illecillewaet slice on the **Standfast Creek fault** occurred prior to the mid-Cretaceous, possibly during the Middle Jurassic. We also contend that the complex is the main aspect of the terrane that differentiates it from the rest of the Selkirk allochthon east of the Monashee complex; other regions have a greater abundance of granitoids (such as the Battle Range batholith), but none apparently have as much variety in age or composition. A prolonged igneous centre, which may be a counterpart of the Clachnacudainn igneous complex, occurs in the Selkirk allochthon west of the Monashee complex, in the Seymour Range (Parrish, 1992). Although the recent work has resulted in data that have significant bearing on our interpretation of the terrane, much additional field and geochronological study is required to fully reveal the magmatic, metamorphic, and deformational history of the complex.

The Clachnacudainn igneous complex is mostly composed of the following five granitoids or groups of granitoids of similar age (all of which will be seen today): (1) **Devono-Mississippian Clachnacudainn gneiss** (356 ± 6 Ma U-Pb zircon age from Parrish, 1992); (2) variably foliated diorite and leucogranite of post-Devono-Mississippian to pre-mid-Cretaceous age; (3) mid-Cretaceous granitoids (U-Pb zircon ages from Crowley, 1992, of 104 ± 1 Ma on quartz monzonite that forms the main body of the **Albert stock**; from Lane, 1984, of 99 Ma on megacrystic K-feldspar granite from the <u>Columbia River valley</u>; and from R.L. Armstrong, UBC data file, of the mid-Cretaceous on megacrystic K-feldspar granite from along <u>Sale Creek</u>); (4) Late Cretaceous leucogranite (71 ± 1 Ma U-Pb zircon age from Parrish, 1992); and (5) post-Late-Cretaceous leucogranite and pegmatite. Granitoids in this road cut include variably foliated diorite, strongly lineated (hornblende lineation plunges gently to the west) and slightly to moderately foliated granodiorite and granite, variably foliated leucogranite, and pegmatite. The heterogeneity in the state of deformation and composition of the granitoids seen here is typical of the complex. Because none of these granitoids has been dated geochronologically, relationships seen elsewhere are used to suggest that those with deformation fabrics are post-


Goldstream slice
118°
Mt LaForme
LaForme Ck
Elm Ck
USCF
LSCF
Maunder Ck
1
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21
stratigraphic and intrusive contacts
fault
normal fault
overturned anticline
overturned syncline
Trans-Canada Highway
water
2-8
2-7
Sale Ck
Martha Ck
W Woolsey Ck
Woolsey Ck
Mt St Cyr
Clachnacudainn igneous complex
Mt Klotz
2-10
2-11
Albert Canyon
ACA
Illecillewaet synclinorium
CRF
Columbia R
2-6
Mt Coursier
Inverness Pks
Coursier Ck
Clachnacudainn Range
Clachnacudainn Ck
Miller Lk
Illecillewaet R
Siegfried Ck
Albert Ck
S Albert Ck
Mt Revelstoke
N Albert Pk
Albert Pk
Albert stock
sample AS-1
E Twin Ck
W Twin Ck
2-9
51°
Revelstoke
TCFS
SCF
Akolkolex R
Mt Llewlyn
Greeley Ck
Clachnacudainn terrane
Mt Mackenzie
ARF
Standfast Ck
Illecillewaet slice
Pulley Ck
MCS
Ghost Pk
Mt Cartier
AA
Upper Arrow Lk (Columbia R)
Monashee complex
Mt Darling
Omineca Belt
60°
BC
Alberta
AL
Drimmie Ck
HF
Holyk Ck
N
Comaplix Mtn
McCrae Pk
49°
USA
118°
0 1 2 3 4 5
km

Devono-Mississippian to pre-mid-Cretaceous and those without fabrics are younger. The variably foliated (possibly syntectonic) diorite could be older than Early Cretaceous if it is coeval with the hornblende biotite diorite with a 127 ± 5 Ma hornblende cooling date that Lane (1984) sampled in the Columbia River valley about 3 km to the north. If this diorite is indeed syntectonic, then determining its age would better constrain the timing of the main deformation and peak regional metamorphism in the terrane. It is possible that some of the deformation evident in this road cut is coeval with the relatively minor post-Late-Cretaceous ductile deformation that occurred in the Mount Revelstoke area (such as at STOP 2-9). All fabrics are considered to be associated with deformation events within the Clachnacudainn terrane, and they apparently predate shearing related to east-directed motion at the base of the terrane.

Marble that is intruded by pegmatite is exposed at the southern end of this road cut. Screens of metasedimentary and metavolcanic rocks in the complex are lithologically similar to those in the southern half of the terrane that Read and Thompson (1980) and Crowley (1992) correlated with the lower Paleozoic Lardeau Group, yet no firm correlation of the screens has been made due to their discontinuity.

274.3 **STOP 2-7, Mylonite zone within mid-Cretaceous megacrystic K-feldspar granite at base of the Clachnacudainn terrane**

Pull off to right at Hathaway Creek road (called Spikers Creek by the locals). Outcrops are in the small quarry just south of road.

This exposure is part of a 500 m thick **east-directed mylonite zone** at the base of the Clachnacudainn terrane. Murphy (1980), working along Sale Creek (less than 1 km to the southeast, Figure 24), mapped the downward transition from undeformed megacrystic granite in the terrane to mylonitized granite at the base. A sample of the undeformed granite from Sale Creek was dated as mid-Cretaceous by R.L. Armstrong (U-Pb zircon age, UBC data file), and a similar looking granite from the Columbia River valley a few kilometres to the north of here was dated at 99 Ma by Lane (1984). The mylonitic metasedimentary rocks in the lowest portion of this mylonite zone include quartzite and calc-silicate - pelite assemblages that suggest correlation with the **cover gneisses of the Monashee complex**. Below these mylonitic rocks is the brittle shear zone of the **Columbia River fault**. These relationships suggest that the post-mid-Cretaceous mylonite zone lies in the hanging wall of the Columbia River fault and that the sheared boundary between the Clachnacudainn terrane and Monashee complex is

Figure 23 (facing page). Map of the Clachnacudainn terrane and overlying Illecillewaet slice of the Selkirk allochthon based on mapping by Thompson (1972), Gilman (1972), Zwanzig (1973), Hakkinen (unpublished data, 1977), Read and Wheeler (1976), Sears (1979), Read and Thompson (1980), Read (unpublished data, 1982), and Crowley and Brown (submitted for publication). Box in inset map locates this map with respect to the Omineca Belt and superterranes I (Intermontane) and II (Insular) of Monger et al. (1982). Normal faults (circle on the hanging wall) are the Columbia River fault (CRF) and Twin Creek fault system (TCFS). Other faults are the Akolkolex River fault (ARF), Holyk fault (HF), lower Standfast Creek fault (LSCF), Standfast Creek fault (SCF), and upper Standfast Creek fault (USCF). Major westerly verging folds are the Akolkolex anticline (AA), Albert Canyon anticline (ACA), and Mount Cartier syncline (MCS). Cross section A-A' is shown in Figure 25. Map units are (1) mostly Late Cretaceous leucogranite, (2) mostly mid-Cretaceous granitoids, (3) mid-Cretaceous megacrystic K-feldspar biotite granite, (4) Upper Mississippian to Pennsylvanian or Permian Milford Group limestone, (5) Milford Group conglomerate, (6) mixed Late Devonian to Late Cretaceous granitoids, (7) variably foliated biotite hornblende diorite of uncertain age, (8) Devono-Mississippian biotite hornblende Clachnacudainn gneiss, (9) undifferentiated Lower Cambrian to Late Devonian Lardeau Group, (10) limestone unit in the Broadview Formation of the Lardeau Group, (11) Broadview Formation, (12) Jowett Formation of the Lardeau Group, (13) quartz grit unit of the Index Formation of the Lardeau Group, (14) "upper" Index Formation, (15) "middle" Index Formation, (16) "lower" Index Formation, (17) Lade Peak Formation of the Lardeau Group, (18) Lower Cambrian Badshot Formation, (19) Upper Proterozoic to Lower Cambrian Hamill Group, (20) metasedimentary rocks of uncertain age, (21) Early Proterozoic to lower Paleozoic Monashee complex. From Crowley and Brown (submitted for publication).

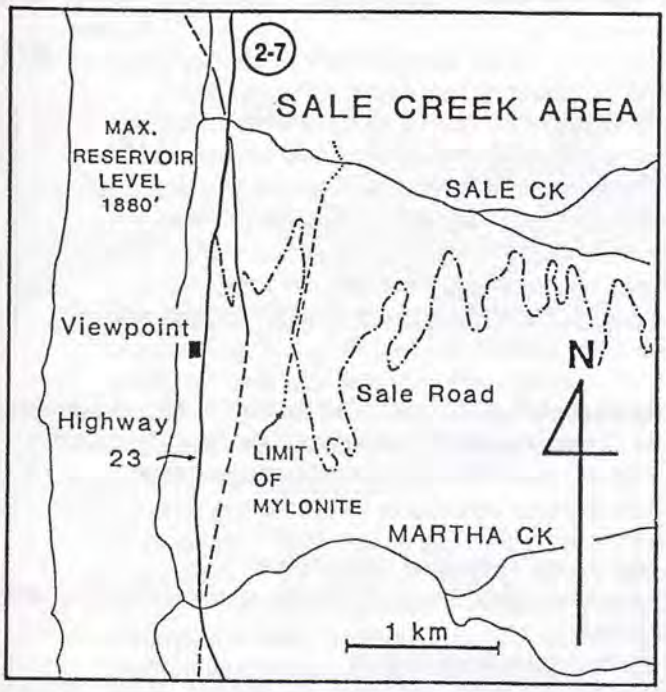


Figure 24. Locality map of Sale Creek - Hathaway Creek area. See stop 2-7 for explanation. From Lane and Brown (1987).

correlative with the Monashee decollement.

275.7 **STOP 2-8, Devono-Mississippian Clachnacudainn gneiss crosscut by undeformed mid-Cretaceous granite**

Turn left into gravel lot. Road cut is across Highway 23 from the gravel lot and continues north for a few hundred metres.

The strongly deformed biotite hornblende orthogneiss seen here crosscut by undeformed megacrystic K-feldspar granite is interpreted as correlating with the **Devono-Mississippian Clachnacudainn gneiss** at Albert Canyon (U-Pb zircon age from Parrish, 1992, STOP 2-11) based on compositional and fabric similarities. The crosscutting megacrystic K-feldspar granite is interpreted as correlating with the mid-Cretaceous granite that is mylonitic at the base of the terrane (previous stop). Both of these granitoids are crosscut by undeformed leucogranite.

Clachnacudainn gneiss with a fabric of similar intensity as seen here is crosscut by undeformed granitoids of known and inferred mid-Cretaceous age at all levels of the terrane. These relationships indicate that regional ductile deformation, peak regional metamorphism, and displacement on the **Standfast Creek fault** or other ductile shear zones within the Clachnacudainn terrane occurred prior to the mid-Cretaceous.

Turn around and head south on Highway 23 toward Revelstoke.

299.2 Turn left at junction of Highway 23 and the TCH.

300.4 Turn right onto the summit road in Mount Revelstoke National Park.

304.1 Undeformed leucogranite and variably deformed (from weak to moderate ductile fabric over a 20 m interval) megacrystic K-feldspar granite (looks similar to mid-Cretaceous granite that was seen at previous stop) are intrusive into highly deformed tan clean quartzite, pelite, semipelite, and minor amphibolite. The metasedimentary rocks are most likely correlative with lower Paleozoic strata that we mapped in the southern part of the Clachnacudainn terrane. These rocks are cut by 0.1-0.5 m thick gouge zones, which could be related to the underlying Columbia River fault.

304.4 Psammite, quartzite, and marble.

305.0 Quartzite, pelite, and semipelite with concordant, thin (less than 1 m) sheets of foliated granite. Lineated leucogranite crosscuts the foliated granite and metasedimentary rocks. This deformed leucogranite is possibly Late Cretaceous because it looks similar to the leucogranite on top of Mount Revelstoke that Parrish (1992) dated at 71 ± 1 Ma (U-Pb zircon age). See the next stop

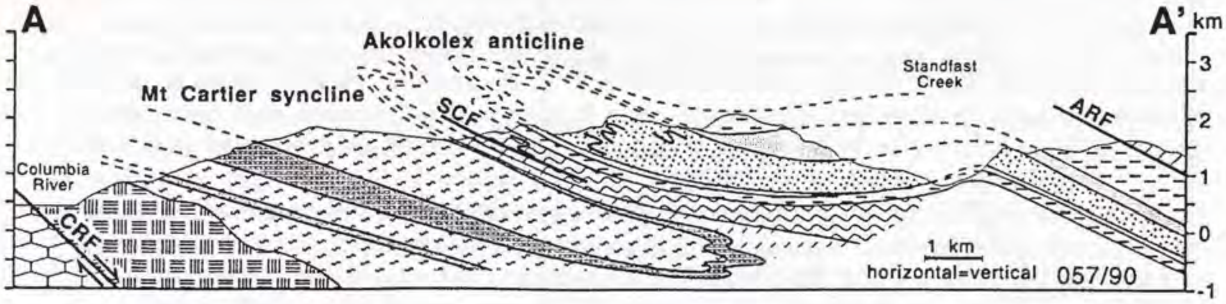


Figure 25. Cross section south of Ghost Peak showing the Akolkolex anticline, Mount Cartier syncline, Columbia River fault (CRF), Standfast Creek fault (SCF), and Akolkolex River fault (ARF). See Figure 23 for location and legend. From Crowley and Brown (submitted for publication).

for the interpretation of this possibly post-Late-Cretaceous deformation.

305.6 Foliated diorite with sheets of concordant and discordant lineated granite, all of which are crosscut by undeformed leucogranite and pegmatite.

306.2 **STOP 2-9, Localized minor post-Late-Cretaceous deformation**

Pull off to right into the Revelstoke Lookout parking area. WE ARE IN MOUNT REVELSTOKE NATIONAL PARK -- PLEASE DO NOT HAMMER THE ROCKS OR TAKE ANY SAMPLES.

Directly opposite the parking area there is lineated leucogranite that is crosscut by undeformed pegmatite dykes. The leucogranite is possibly Late Cretaceous because it has the same composition and fabric as the leucogranite on top of Mount Revelstoke that Parrish (1992) dated at 71 ± 1 Ma (U-Pb zircon age). Just downhill from the parking area there is a foliated granitoid that looks similar to the mid-Cretaceous megacrystic K-feldspar granite that was seen as undeformed in the previous stop, as well as lineated leucogranite and foliated pegmatite of unknown age. This apparently **post-Late-Cretaceous deformation** (termed D4) is interpreted as relatively minor (compared to the main phase of deformation, D2) because the intrusive contacts of the granitoids only affected by D4 are at high angles to their D4 fabrics and to older fabrics in the strongly deformed country rocks; presumably the contacts would have been transposed into parallelism with the D4 fabrics upon a moderate amount of shearing. D4 is also considered to be of only local significance because granitoids of known and inferred mid-Cretaceous age outside of the Mount Revelstoke area (such as the Albert stock and megacrystic granite) do not contain any ductile fabrics and they cut the deformation observed in the country rocks.

The presence of voluminous Late Cretaceous and younger granitoids in the only area of the Clachnacudainn terrane that has undergone D4 suggests that it was restricted to a zone that was thermally weakened by these young granitoids. D4 could be coeval with motion at the base of the terrane, yet the east-dipping mylonite zone at STOP 2-7 is at high angles to the fabrics in these granitoids (steeply south-dipping foliations and moderately to steeply southwest-plunging lineations).

Turn around and head down the summit road to the TCH.

311.8 Proceed east on the TCH.

328.9 East gate of Mount Revelstoke National Park. Dominant peak to the east is North Albert Peak, most of which is intruded by satellite bodies from the main body of the 104 ± 1 Ma Albert stock. Marble layers and intervening siliceous clastic layers in the cliffs south of North Albert Peak (headwaters of East Twin Creek) are in the upper part of the Clachnacudainn terrane and are correlated with the **"middle" Index Formation (marble unit)** by Crowley and Brown (submitted for publication).

342.4 **STOP 2-10, Clachnacudainn gneiss crosscut by deformed and undeformed leucogranite dykes**

Pull off the TCH to right into rest area.

Leucogranite dykes that originally lay within the shortening field of the D2 strain ellipsoid are deformed here into Z-folds with northwesterly trending hinge lines and northeast-dipping axial surfaces that parallel the fabric (S2) in the Clachnacudainn gneiss. Dykes that originally lay within the extending field are boudinaged. Undeformed dykes crosscut S2 at high angles. Determining the ages of the dykes would obviously constrain the age of deformation at this level of the Clachnacudainn terrane. These relationships are seen up close in the road cut opposite the TCH from the rest area and they are seen at a distance by looking southeast across the Illecillewaet River at the blasted rock faces along the Canadian Pacific Railway. This locality is near Stop 2-6 of Price et al. (1985). See description of the next stop for further discussion of the tectonic significance of the gneiss.

343.4 Brittle strike-slip fault within the Clachnacudainn gneiss. Post-mid-Cretaceous faults such as these are quite common throughout the terrane.

344.2 Bridge over Illecillewaet River

344.5 Cataclastic garnet biotite muscovite schist (locally with pseudomorphs of staurolite according to Price et al., 1985) that is approximately at the fault mapped by Wheeler (1963, 1965) in the lower limb of the westerly verging **Albert Canyon anticline** (Wheeler, 1963, 1965; Zwanzig, 1973). Price (1986) placed the eastern branch of the Standfast Creek fault (termed the upper **Standfast Creek fault** in Figure 23) at this fault. We consider displacement on this fault to be insignificant because identical lithologies that we correlate with the Index Formation of the **Lardeau Group** crop out on both sides of the northwest continuation of this fault in the generally well exposed Clachnacudainn Range (see Figure 25). Zwanzig (1973) mapped garnet- and staurolite-grade rocks in the hanging wall of this fault.

344.6 Turn right onto Albert Canyon Road (road is in sight of signs for Canyon Hot Springs Resort).

345.3 Continue south toward the railway tracks.

345.7 Turn right just before the tracks and continue on small road on the north side of tracks.

345.9 Bridge over Albert Creek

346.8 Bear left at fork in road

347.0 **STOP 2-11, Clachnacudainn gneiss**

Park and cross the railway tracks to the quarry on the south side.

Parrish (1992) sampled **Clachnacudainn gneiss** with 356 ± 6 Ma zircons (U-Pb age) in this quarry. The gneiss forms a 0.5 km thick sheet that is underlain by metasedimentary rocks of unknown affinity in the Woolsey Creek window (Gilman, 1972) and overlain by metasedimentary and metavolcanic rocks that we correlate with the lower Paleozoic Lardeau Group (Figure 23). Price et al. (1985) stated that the gneiss grades to a mylonitic gneiss toward the contact with the overlying metasedimentary rocks, and Price (1986) placed the western branch of the Standfast Creek fault (termed the **lower Standfast Creek fault** in Figure 23) at the contact.

Parrish et al. (1988) inferred that the gneiss is the footwall mylonite of the Standfast Creek fault. They used a discrepancy in K-Ar mica cooling dates across the fault (reported in Read and Brown, 1981; Lane, 1984; and Parrish et al., 1988) to infer that a large temperature difference between the terrane and the Illecillewaet slice in the Eocene was due to ductile extension on the fault. In their model the fault accommodated the large-magnitude Eocene extension that is apparently absent on the underlying Columbia River fault (absent in comparison to estimates of up to 30 km of displacement on the segment to the south).

We contend that since all of the Eocene mica cooling dates in the terrane were obtained from or near Late Cretaceous and younger granitoids in the Clachnacudainn igneous complex (Late Cretaceous leucogranite from Mount Revelstoke (Parrish, 1992) and crosscutting leucogranite and pegmatite are examples), then the cooling dates only signify that these granitoids heated the country rocks above the mica closure temperature until the Eocene. Data from the Albert stock, which lies in an area apparently devoid of these young granitoids, indicate that adjacent rocks in the upper part of the terrane cooled below the biotite K-Ar closure temperature at 83 Ma (D.A. Archibald, unpublished data, reported in Price et al., 1985). In addition, the presence of andalusite in the well defined contact aureole (Sears, 1979) and hornblende barometry data (Crowley and Ghent, manuscript in preparation) require that this part of the terrane was exhumed to relatively shallow crustal levels (at or below the aluminosilicate triple point) by the mid-Cretaceous. We therefore contend that present cooling data should not be used as evidence suggesting that the entire terrane was part of the Shuswap metamorphic complex and tectonically denuded in the Eocene; data from the intrusive-free southern part of the terrane should be obtained before a cooling history is proposed.

Additional evidence that indicates that Parrish et al.'s inference is incorrect include the following: (1) the contact between the Clachnacudainn gneiss and overlying metasedimentary rocks is crosscut by the undeformed dykes that are continuous and assumed to be coeval with the 104 ± 1 Ma main body of the Albert stock south of the TCH and by undeformed granitoids of inferred mid-Cretaceous age in many places north of the highway; (2) there is no strain gradient in the gneiss away from the contact; (3) the gneiss contains xenoliths of the country rock; and (4) there are gneissic dykes within the country rocks.

In this quarry the strong northeast-dipping gneissosity is transected by slickensides and veins of pseudotachylite. This brittle deformation is post-mid-Cretaceous and most likely of minor tectonic significance because similar brittle faults crosscut the Albert stock but do not significantly offset it. The siliceous dyke in the quarry that crosscuts the brittle faults is the only granitoid observed in the terrane that post-dates these young features.

The Hamill Group quartzite and Badshot Formation marble in the well exposed cliffs north of the TCH outline the core of the westerly verging **Albert Canyon anticline**. The highly appressed nature of this anticline is similar to the **Akolkolex anticline** to the south, which is shown in the cross section in Figure 25. We interpret both of these anticlines as westerly verging, syn- to late-peak-metamorphic, second-phase folds that post-date the Albert stock. Work to the northeast of here in the **Illecillewaet synclinorium** by Colpron and Price (1993) suggests that westerly verging folds of the same generation formed during emplacement of Middle Jurassic plutons.

Return to Revelstoke for the night.

383.4 Junction of Highway 23 and the TCH. Turn right into parking area for the Frontier Motel.

DAY 3 OF PART 2

km

383.4 Junction of Highway 23 and the TCH. Drive north on Highway 23.

422.2 Turn right at Carnes Creek Road.

423.0 **STOP 3-1** (Figures 26-27)

Pull into parking spot on left side of the road. Green calcareous phyllites are part of the **Jowett Formation of the lower Paleozoic Lardeau Group**. These phyllites are exposed here in the hanging wall of the Columbia River fault. Walk down the road toward Highway 23 where mylonitic gneisses are exposed in the footwall. Protolith is uncertain but possibly is Devonian orthogneiss of the Clachnacudainn terrane. Note the high degree of silicification.

Here the Columbia River fault and Standfast Creek fault merge and the Clachnacudainn igneous complex is pinched out in the shear zone. Below flood level, mylonitic rocks of semipelite and amphibolite tectonically overlie metasediments of the Monashee complex. These rocks are similar to the amphibolite-bearing gneisses that we observed above Highway 23 at the Revelstoke dam site; our suggested correlation is with rocks of the Late Proterozoic Windermere Supergroup, and we place them in the hanging wall of the Monashee decollement. This admittedly tenuous correlation suggests that hanging-wall rocks of the Monashee decollement are preserved as discontinuous lenses within the shear zone of the Columbia River fault. The implication of this is that thrusting along the Monashee decollement carried Windermere stratigraphy northeastward over the Monashee complex, and then down-to-the-east normal faulting on the Columbia River fault dissected and greatly attenuated both hanging-wall

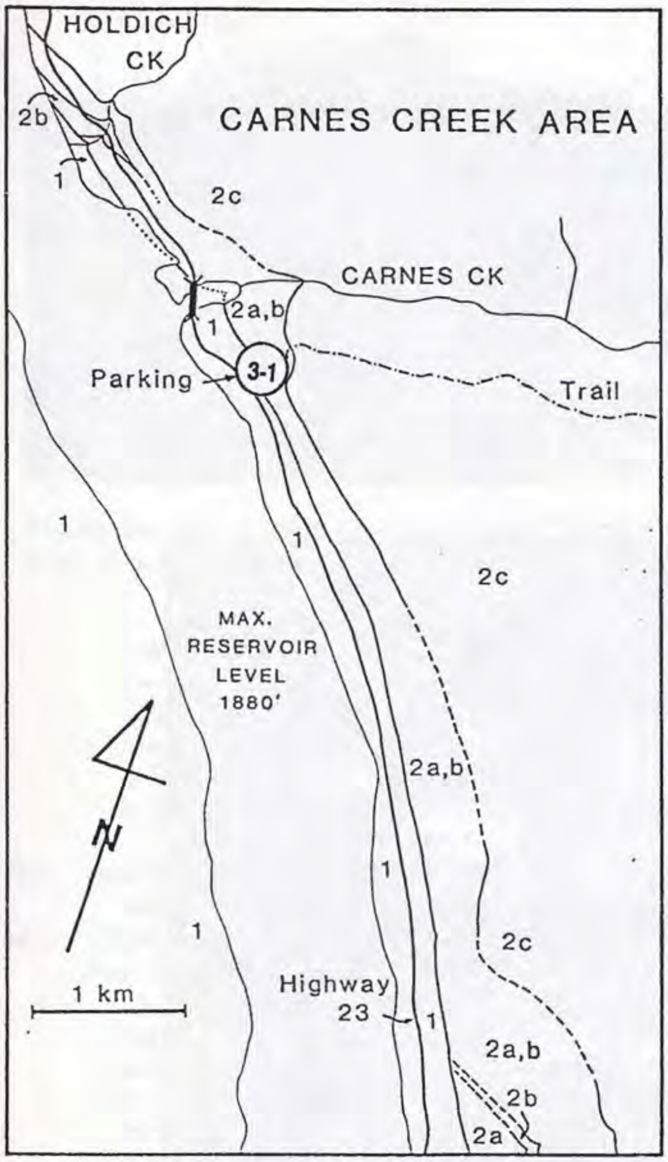


Figure 26. Locality map of Carnes Creek area. Units: 1, Monashee complex pelite, calc-silicate, and minor marble; 2, Goldstream slice, Selkirk allochthon; 2a, calcareous tuff, Jowett Formation (late Paleozoic Lardeau Group); 2b, lensoid dolomitic marble, Jowett Formation; 2c, siliceous phyllites, locally graphitic, and interbedded psammite, Index Formation (Lardeau Group). Rocks of unit 1 reached sillimanite-muscovite grade of metamorphism, while unit 2 rocks reached middle greenschist grade (biotite in 2c, actinolite in 2a). Tectonic contact between units 1 and 2 truncates a carbonate unit near Holdich Creek. Eocene brittle faulting and hydrothernal activity have intensely altered many of the exposures along the highway road cuts. Contacts are dashed where inferred. From Lane and Brown (1987).

and footwall rocks of the decollement. Further support for this notion will be demonstrated as we travel northward to Mica Creek where amphibolite-bearing semipelitic rocks of the Windermere Supergroup emerge from beneath the footwall of the Columbia River fault as displacement on the fault dies out.

Return to Highway 23 and continue north.

425.2 Carnes Creek bridge

426.7 Road cuts of black graphitic phyllite are of **Index Formation of the Lardeau Group**.

430.2 Keystone Basin road

445.6 **STOP 3-2**

Pull off the road just before reaching the bridge across Downie Creek. View to the east is of Lardeau Group and intrusive granitic sheets in the slopes of Downie Peak. An east-west trending pluton of unknown but probable Late Cretaceous age lies in the slopes to our north and is responsible for the contact metamorphic assemblages that may be viewed in roadside exposures. From this vantage point we will discuss the structures that have been mapped in the Selkirk Mountains to the east. The **Selkirk structural fan** dominates the geometry of the

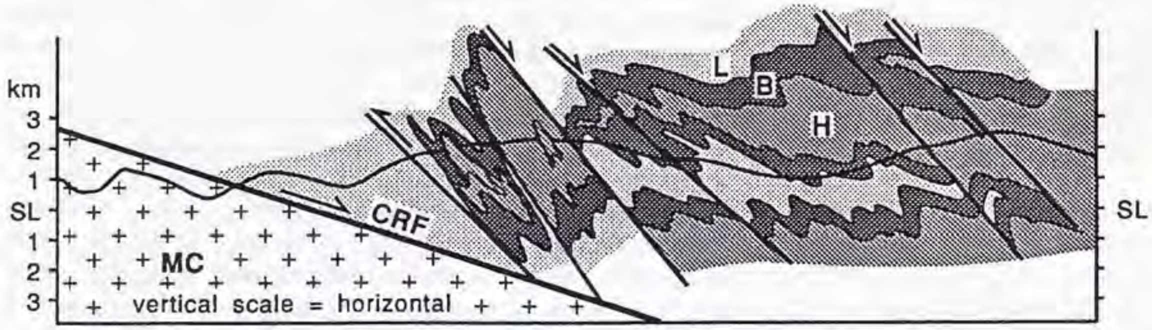


Figure 27. Cross section, Downie Creek Map Area 82 M/8, GSC Open File 2414 (Brown, 1991; see also Brown and Lane, 1988). L = Lardeau Group, B = Badshot Formation, H = Hamill Group, MC = Monashee complex, CRF = Columbia River fault. See Figure 28 for location of section.

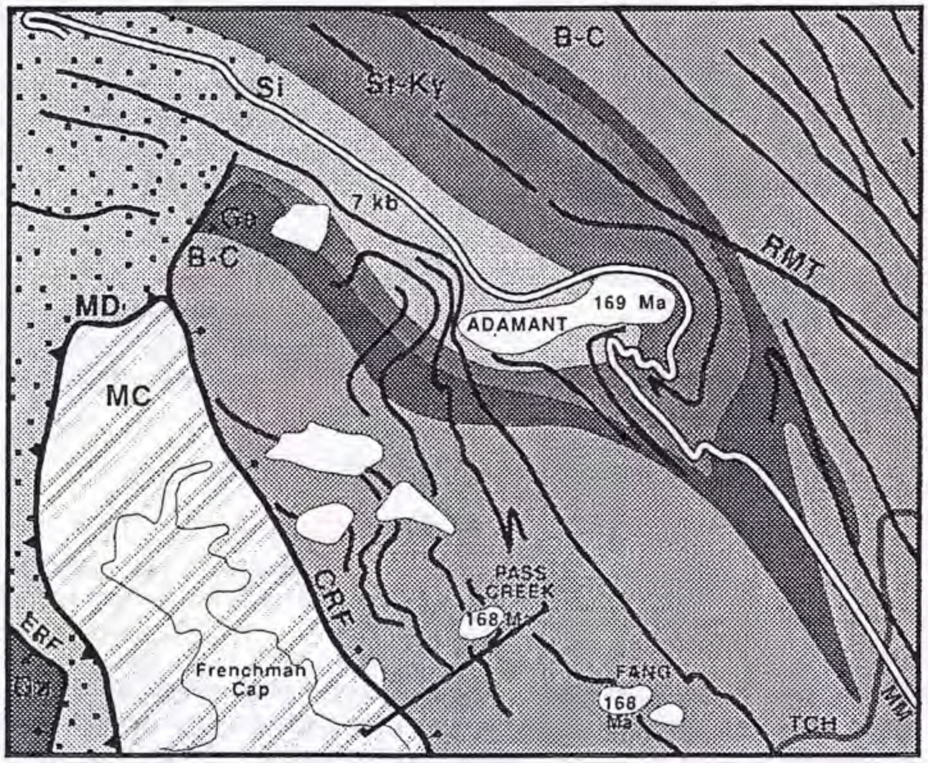


Figure 28. Sketch map outlines metamorphic relationships in the Selkirk and Monashee mountains and illustrates apparent continuity of isograds eastward across the Rocky Mountain Trench into the Rocky Mountain Belt. Pass Creek and Fang plutons postdate the deformation illustrated in Figure 27 and have been dated as Middle Jurassic by the U-Pb zircon method (see Brown et al., 1992). The age assigned to the Adamant pluton is the time of peak metamorphism in that region and may be only a minimum age for the emplacement of the pluton (Shaw, 1980). Areas of black dots and diagonal stripes were at amphibolite-grade in the early Tertiary; the remainder of the region was exhumed to upper crustal conditions by Late Jurassic time. The white band (MM) is the middle marble unit of the Windermere Supergroup. RMT = Rocky Mountain Trench, CRF = Columbia River fault, MD = Monashee decollement, ERF = possible branch of Eagle River fault, MC = Monashee complex. Pressure of 7 kbar from Leatherbarrow (1981). Isograd distribution compiled from Wheeler (1965), Leatherbarrow (1981), and Simony et al. (1980).

Figure 29. View looking west towards the Downie slide showing the prominent scarp boundaries. From Brown and Psutka (1980).

region; to the west of the fan the major folds and faults verge to the west. These structures are part of a fold and thrust belt that developed along the length of the hinterland of the Canadian Cordillera in Jurassic time. At this time the Selkirk fan was situated approximately 300 km to the west adjacent to the present eastern boundary of the Coast Belt. (Please refer to Figures 2-5, 27, and 28, and Open File Map of Downie Creek (Brown, 1991); additional references are in the Bibliography of the Field Guide.)

Continue northward on Highway 23.

439.9 Roadside exposures of two-mica granite that is unstrained. Adjacent metasediments exhibit amphibolite-grade contact metamorphism.

444.6 **STOP 3-3**

Pull off the road on the left side. View of **Downie slide and stabilization work by** BC **Hydro.**

The slide mass is composed of pelitic and semipelitic schists that lie on the northeastern flank of Frenchman Cap gneiss dome in the Shuswap metamorphic complex. The slide was first recognized by Dick Armstrong in 1956 during reconnaissance mapping of this section of the river valley for a possible dam site. Recognizing the potential hazards it posed for future hydroelectric developments along the river, BC Hydro initiated an intensive exploration program that involved collecting ground-water data, monitoring slope movements, defining the subsurface by drilling and seismic methods, and undertaking remedial measures in the form of drainage tunnels and drain holes to increase the stability of the slope (see Meidal, 1979; Brown and Psutka, 1980; Figures 29-31). Currently the slide is continuously monitored, and data are linked directly to computers in Vancouver.

457.1 Road to Goldstream Mine. We will not be visiting the mine, but the trip leaders will be pleased to discuss the geological setting of this producing copper property.

Continue on Highway 23.

464.0 Bridge over the Goldstream River. Road exposures along the route are of **Lardeau Group.** The massive grey marble is in the **upper part of the Index Formation.**

474.2 View looking northwest to Hoskins Creek. We are looking toward the **north end of the Monashee complex** (Figure 32). The Monashee decollement emerges from beneath the hanging wall of the Columbia River fault in the Columbia River valley and swings westward to wrap around the northern margin of the Monashee complex. The high-grade strata in the hanging wall of the Monashee decollement extend southeastward into the Selkirk Mountains where they are correlated with the North American shelf-slope Windermere assemblage of Late Proterozoic to Cambrian age.

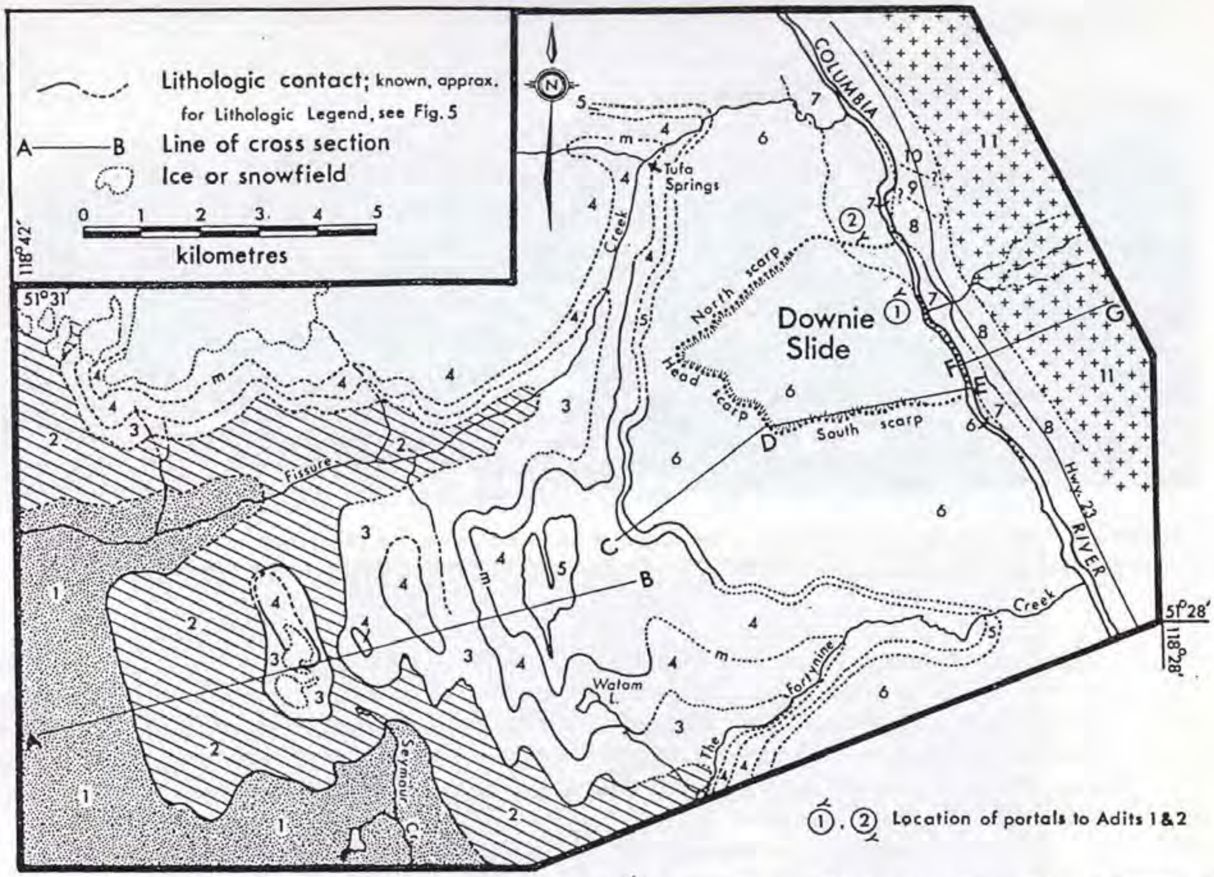


Figure 30. Stratigraphic map of the Downie slide area (see Figure 31 for legend). From Brown and Psutka (1980).

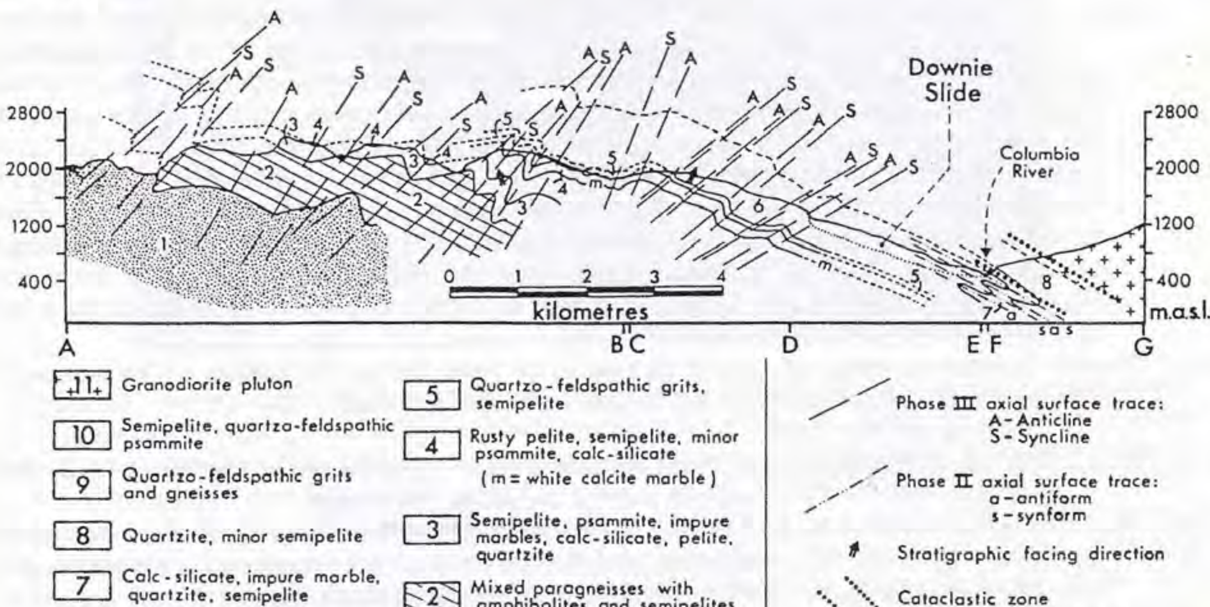


Figure 31. Combined stratigraphic and structural cross section through Pettipiece Ridge. From Brown and Psutka (1980).

485.1 Junction with Bigmouth Road. Continue on Highway 23.

496.3 Settlement of Birch Creek. Here the Columbia River fault loses displacement as it swings eastward up the slopes of Birch Creek and evidence of brittle shearing and stratigraphic disruption is lost. Sillimanite-grade rocks of the **semipelite and amphibolite member (SPA) of the Windermere assemblage** emerge from beneath the footwall of the Columbia River fault as displacement across the fault decreases northward.

501.6 **STOP 3-4**

Pull off the road on the left side. **SPA** is well exposed, and its metamorphic grade and structural complexity are evident. Regional mapping places this panel in the inverted limb of a major westerly verging fold nappe, the Scripp Nappe.

Continue north on Highway 23.

505.5 **STOP 3-5, Mica Dam**

Park in visitors' area and proceed to the view point to observe the folded strata exposed in the cut of the dam spillway and view at a distance the geology of the surrounding hills.

The description for this and the final stop has been **abstracted from Ghent, Simony and Brown (1990)**; Philip Simony has agreed to help us describe the relationships that he and his students have worked so hard to establish in this region. The photo in Figure 33 of the structure in the spillway was taken by Dick Armstrong and, shortly after his death, was found in his files and sent to RLB. Please refer to Figures 34-39 (from Ghent et al. 1990) for an overview of the geology of the region.

An overturned sequence from the **SPA** through the marble unit into the pelite unit on the overturned limb of the large phase-one **Scripp nappe** (see Figures 35 and 36) can be viewed in the roadside section between the boat landing on Kinbasket Lake and Mica Dam. The SPA is here in the core of the northeasterly verging **Mica Creek antiform**, which plunges to the southeast. At the hinge of this fold there is extensive small-scale F3 folding. The effect of this folding on the marble is best seen on the east wall of the spillway of the dam and in a small fold pair to the north of Forestry Road Junction. Ed Ghent estimates temperature in these rocks to have peaked at 620 ± 25 degrees at a pressure of 6.5 ± 0.5 kbar.

A southeast-side-down transverse normal fault passes by the west abutment of the dam and then follows the northwest shore of the lake out to the trench. To the northwest of the fault, in the Mt. Nagle massif, we see the broad and complex core of the Mica Dam antiform composed of rocks of the SPA unit in upper kyanite zone with a lot of migmatite and pegmatite (see Figure 36). On the southeast side of the fault the core of the antiform has been dropped about 1500 m relative to the northwest side, and we see the geology depicted in Figure 36 (looking southeast).

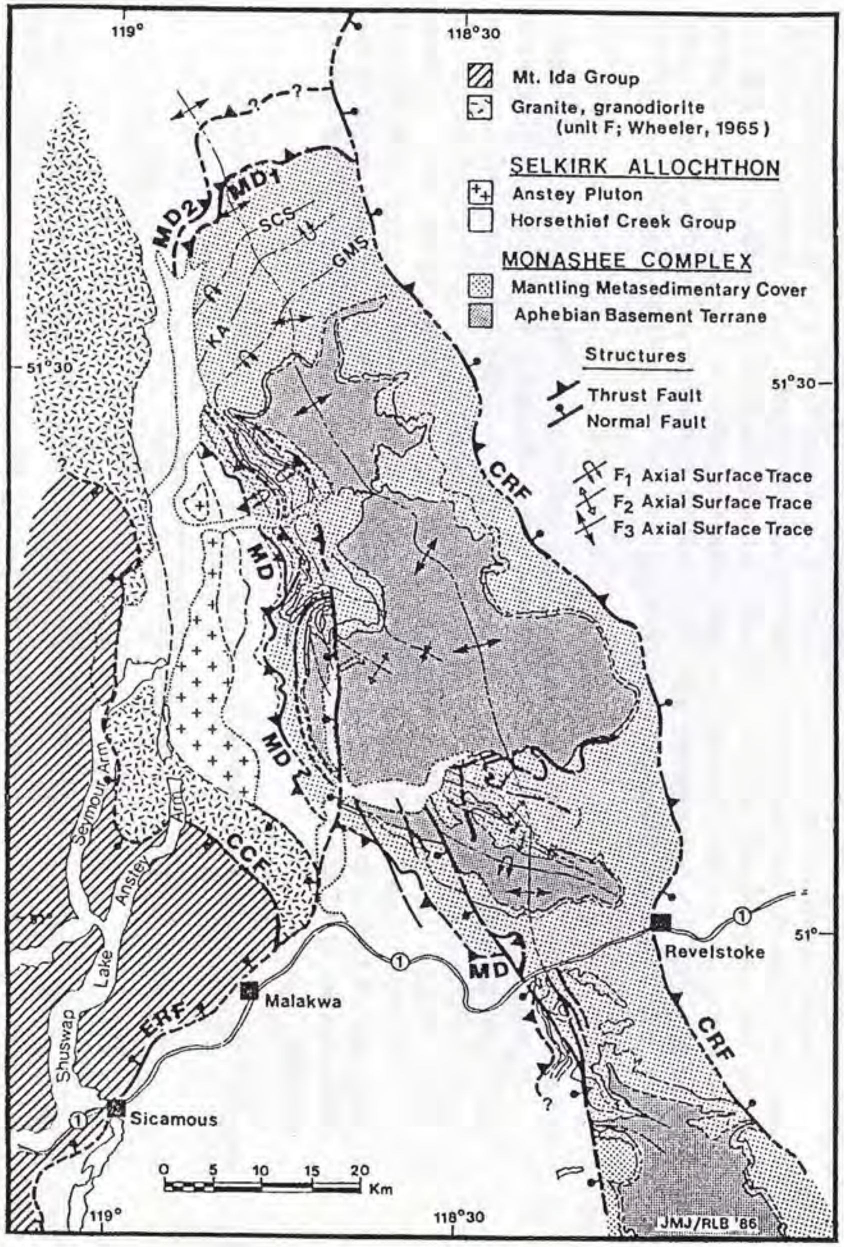
506.0 **STOP 3-6**

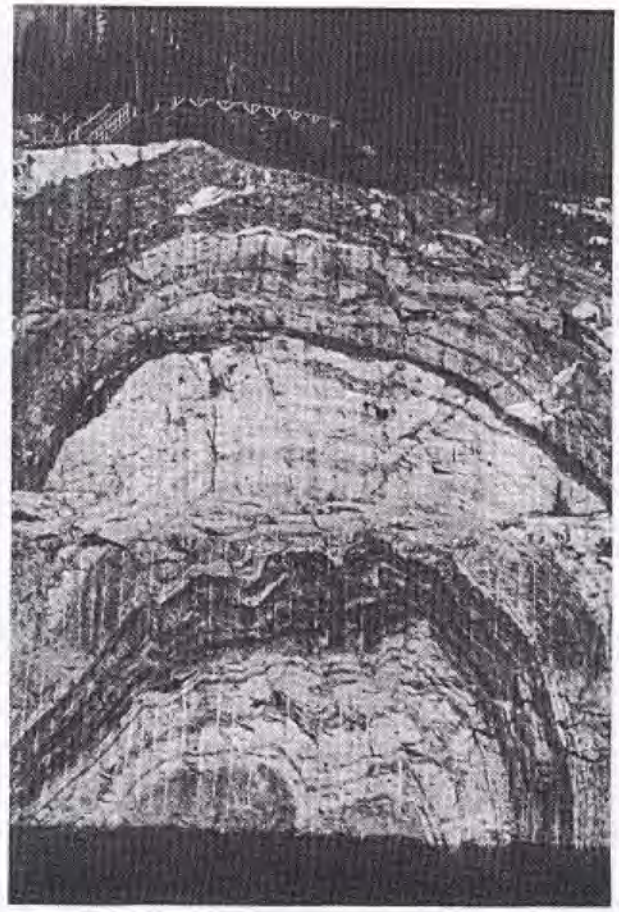
View east across the **Rocky Mountain Trench to the Main Ranges of the Rocky Mountain Belt**.

If the weather is clear, one has a good view to the northeast, across the trench, toward the southwest flank of the **Porcupine Creek anticlinorium** (Figure 39). The garnet isograd passing by Mt. Molson and behind Mt. Dainard is the same isograd as can be observed well to the south at Rogers Pass on the TCH (we will travel this way on our return journey this afternoon).

The highest grade sillimanite and staurolite zone extends across the front of the Molson Ridge and in front of the marble cliffs of Mt. Dainard. These cliffs and the grey peaks farther north consist of Middle Cambrian marble, pelite, and quartzite preserved in the Dainard syncline.

END Return to Revelstoke (1.5 h of temperate driving).





↑**Figure 33.** Photo of spillway at Mica Dam (R.L. Armstrong).

←**Figure 32.** Detail of Frenchman Cap dome and adjacent areas. Major bounding faults of northern Monashee complex and adjacent Selkirk allochthon. Bounding faults include high- and low-pressure shear zones of Monashee decollement (MD1 and MD2, respectively), Eagle River fault (ERF), Craigellachie Creek fault (CCF), and Columbia River fault (CRF). SCS = Sibley Creek syncline; KA = Kirbyville anticline; GMS = Grace Mountain syncline. From Brown and Journeay (1987).

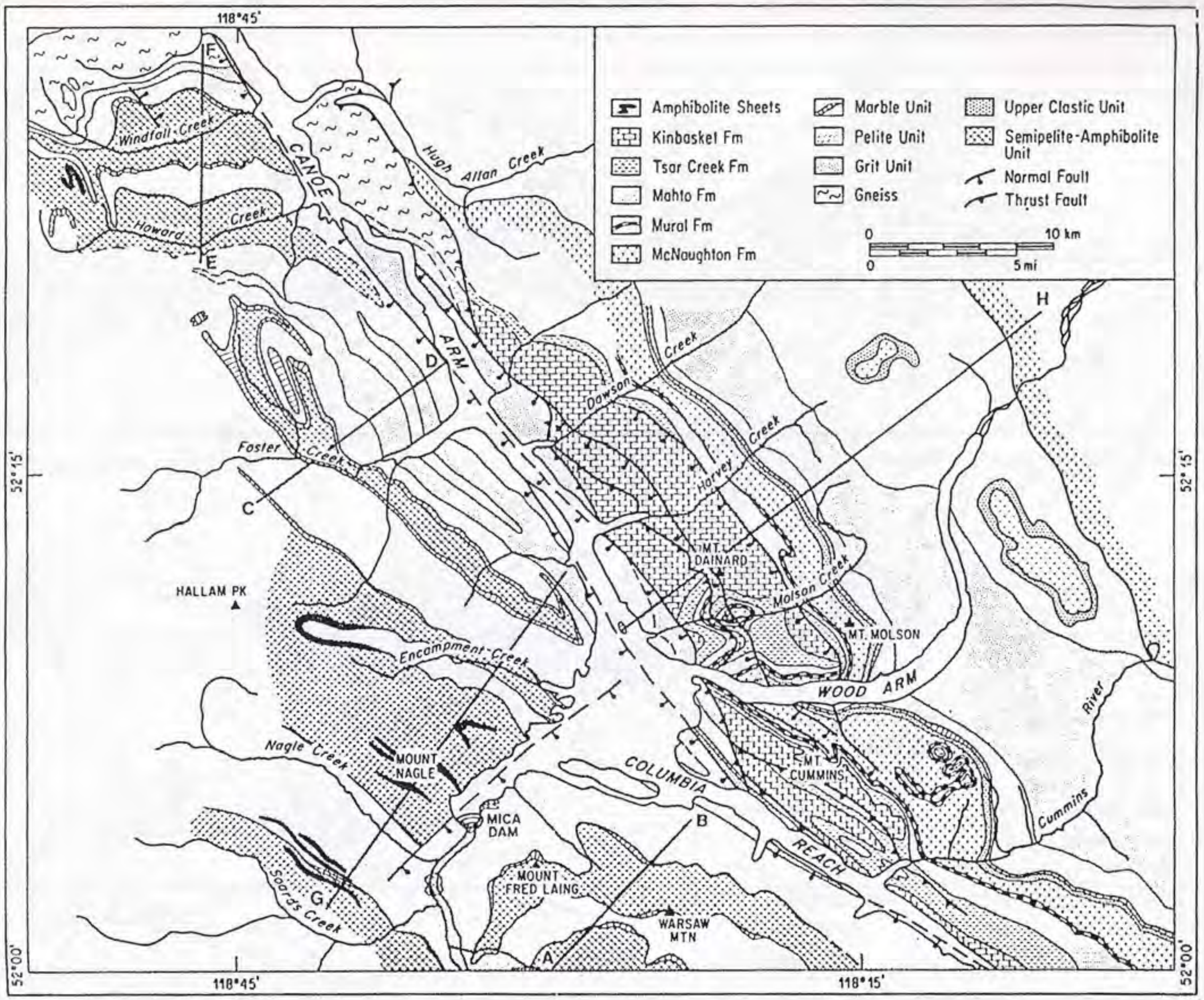


Figure 34. Generalized geologic map of southern Canoe River area. From Simony et al. (1980).

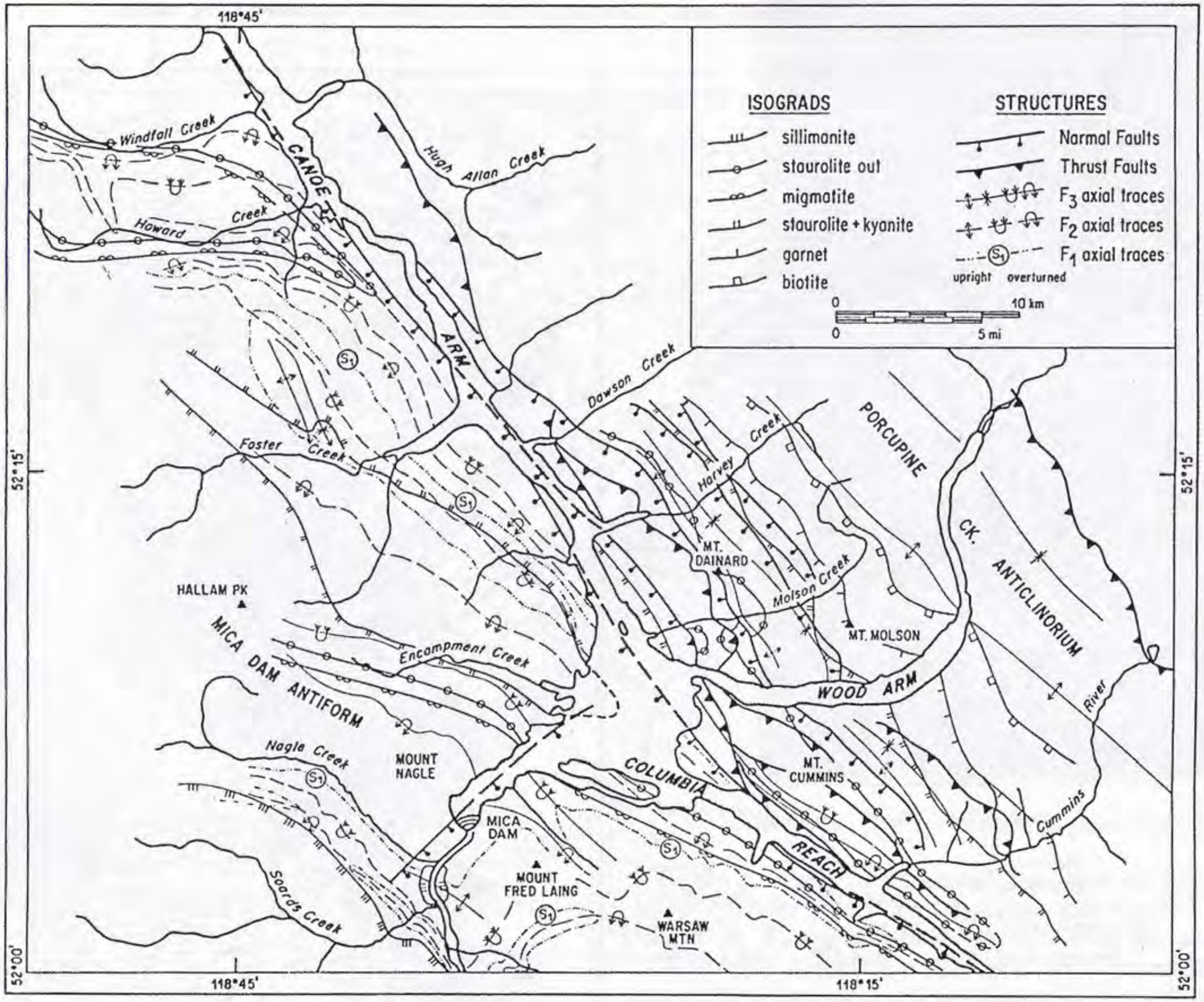


Figure 35. Generalized map of metamorphic isograds and major structures in southern Canoe River area. From Simony et al. (1980).

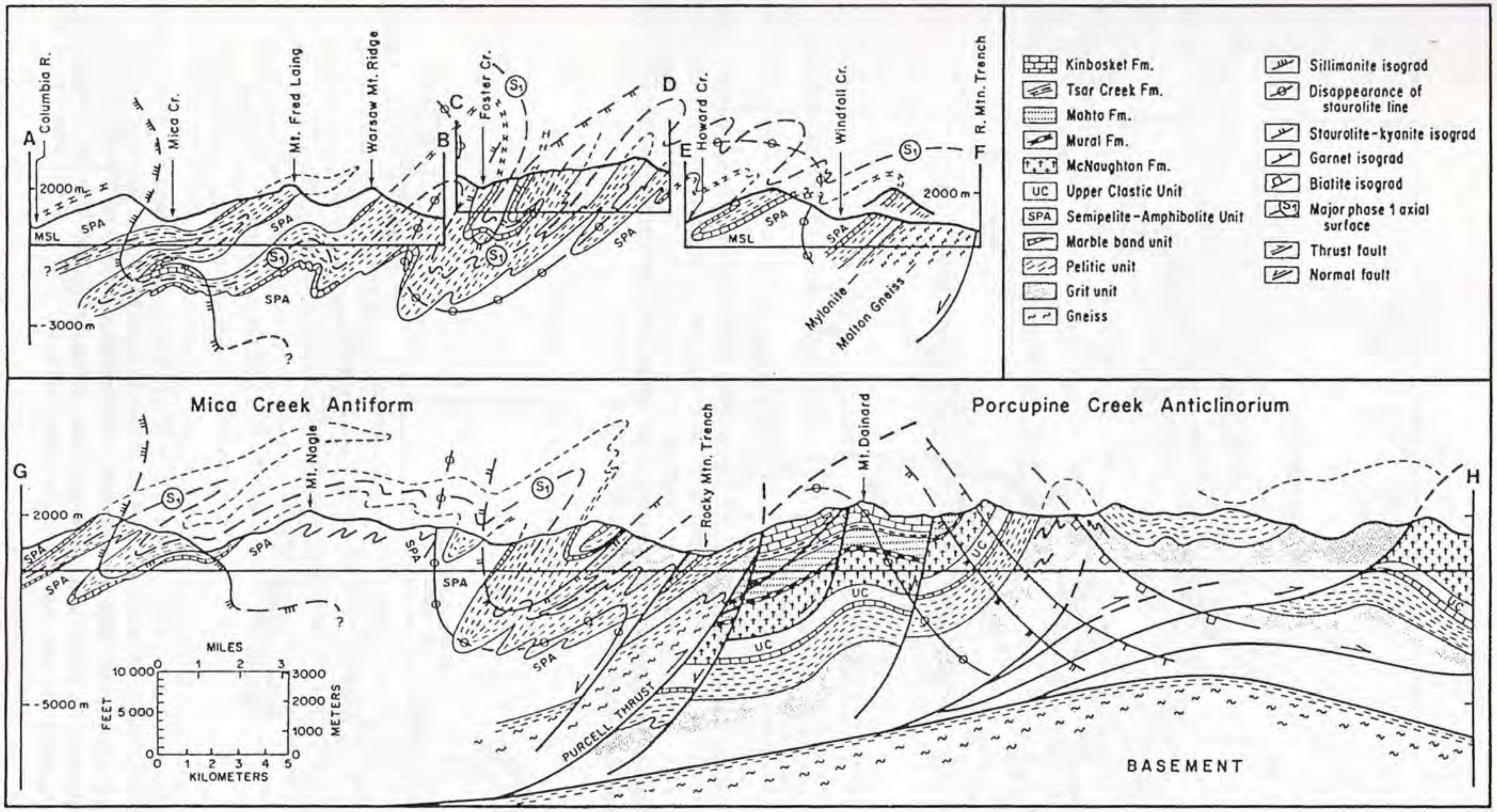


Figure 36. Cross sections illustrating structure of southern Canoe River area. A-B, C-D, and E-F form a composite section to illustrate relationships of structures from Mica Creek to Malton gneiss. The sections are linked by common structural and stratigraphic elements, and all the geology shown is derived by axial projection form the map in Figure 34, which also shows the locations of the cross sections. From Simony et al. (1980).

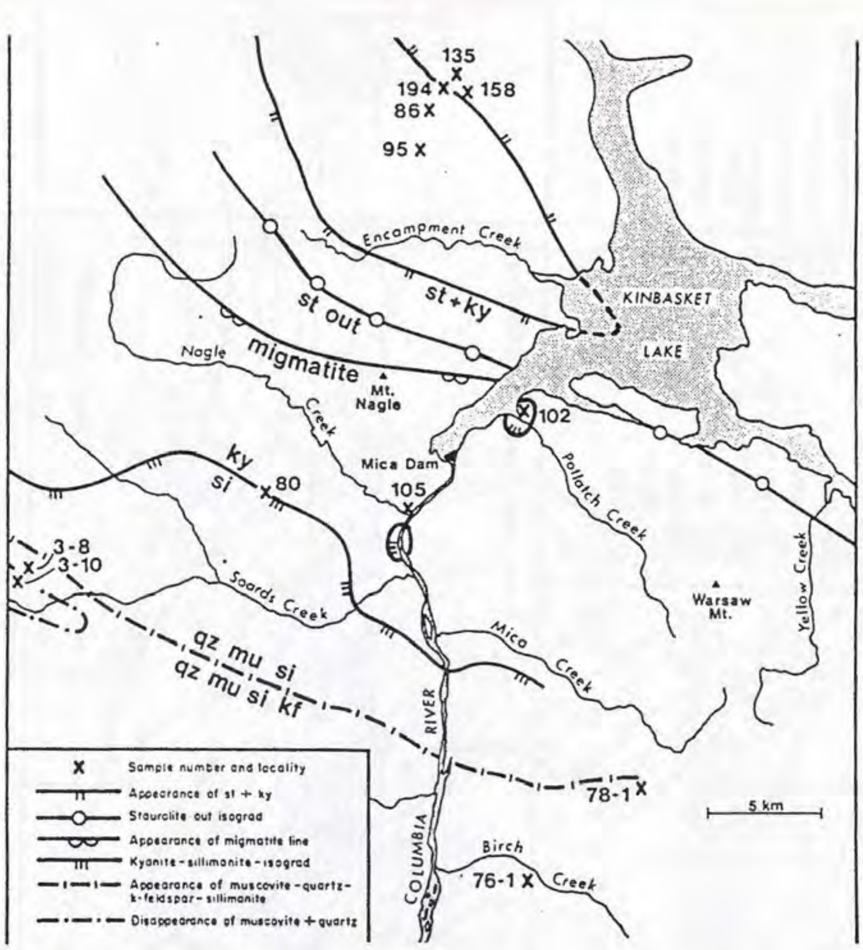


Figure 37. Metamorphic isograd map of the Mica Creek area. Sample numbers on map refer to samples studied by Bowman and Ghent (1985). From Ghent et al. (1990).

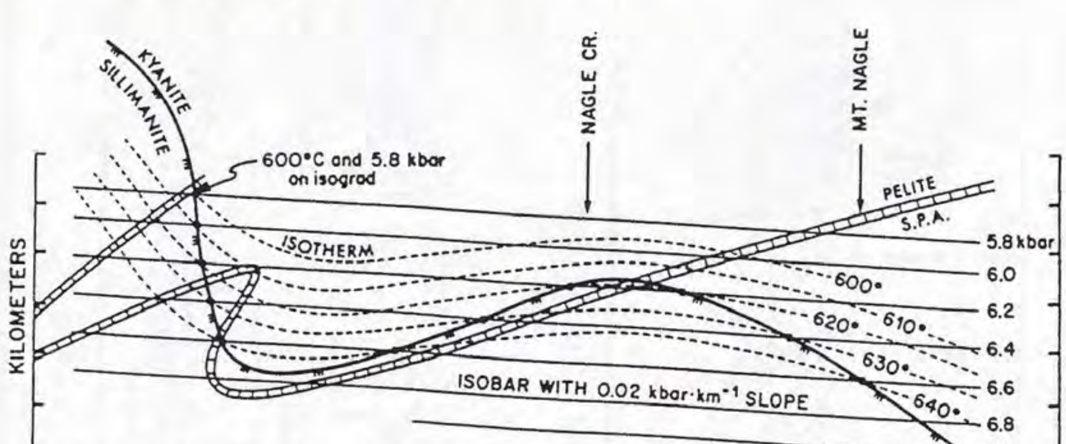


Figure 38. Kyanite-sillimanite isograd, isotherms, and isobars (at 2.0 kbar) interval, southwest of Mica Dam, with the effects of F3 deformation removed. The marble marker (brick symbol) separates the lower pelite from the overlying up-side-down semipelite-amphibolite unit (SPA). From Ghent et al. (1990).

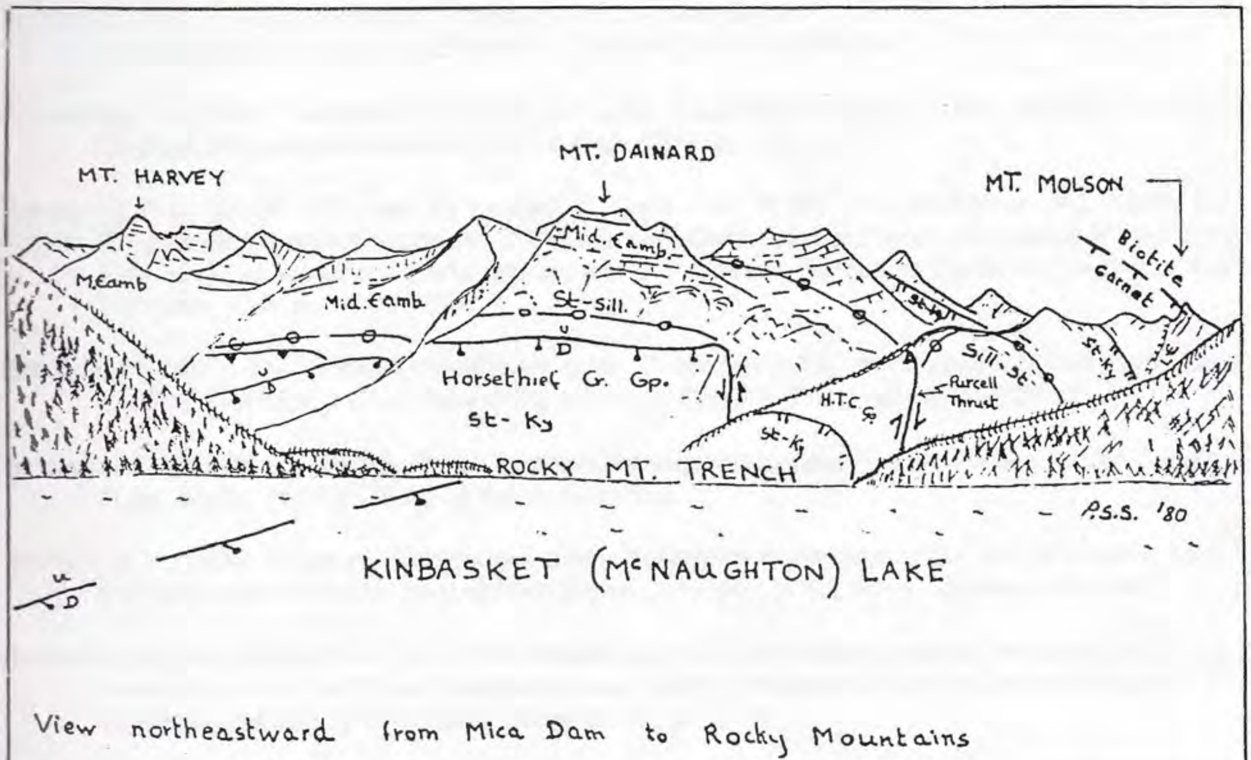


Figure 39. View northeastward from Mica Dam toward the Rocky Mountains showing the configuration of the isograds and the stratigraphy and structure. Horsethief Creek Group in hanging wall of Purcell thrust; L Camb = Lower Cambrian quartzite; M Camb = Middle Cambrian carbonates. Mineral abbreviations are st = staurolite, sill = sillimanite, ky = kyanite. From Ghent et al. (1990).

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Crustal structure and early Tertiary extensional tectonics of the Omineca belt at 51°N latitude, southern Canadian Cordillera[1]

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Abstract: A crustal cross section through the Omineca belt at the latitude of the Trans-Canada Highway has been drawn to satisfy available surface geological information and Lithoprobe seismic data from this part of the Cordilleran hinterland. Palinspastic restoration of Tertiary normal-sense shear zones leads to the conclusion that the Omineca belt at latitude 51°N was extended in the Eocene by approximately 45 km, 20–25% of the width of the belt. It is shown that the Okanagan – Eagle River fault, which defines the western margin of the Shuswap metamorphic core complex, is likely to have accommodated approximately 30 km of displacement. Restoration of this fault and of 15 km displacement on the Columbia River fault (eastern margin of the Shuswap complex) juxtaposes upper-crustal rocks with similar stratigraphic, structural, and metamorphic characteristics and indicates that the crust was over 50 km thick prior to Eocene extension. Comparison of the crustal geometry in the present and restored sections suggests that extensional strain was partitioned such that the upper crust was most highly attenuated above the central Shuswap complex, whereas the lower crust was most greatly stretched beneath the Intermontane and western Omineca belts.

Résumé : Une coupe crustale au travers le Domaine d'Omineca, à la latitude de la route Transcanadienne, a été dressée en harmonisant les données de la géologie de surface disponibles à celles des levés sismiques du projet Lithoprobe dans cette partie de l'arrière-pays de la Cordillère. La restitution palinspastique des zones de cisaillement distensif du Tertiaire mène à la conclusion que le Domaine d'Omineca, à la latitude 51°N, a subi à l'Éocène une extension d'environ 45 km, l'équivalent de 20 à 25% de sa largeur actuelle. Il semble que la faille d'Okanagan – Eagle River, qui définit la bordure occidentale du Complexe métamorphique de Shuswap, ait pu vraisemblablement accommoder près de 30 km de déplacement. La restauration de cette faille, accompagnée d'un déplacement sur la faille de Columbia River de 15 km (bordure orientale du Complexe de Shuswap), juxtapose des roches de croûte supérieure exhibant des similitudes stratigraphiques, structurales et métamorphiques, et en plus indique que la croûte avait une épaisseur de plus de 50 km avant son étirement à l'Éocène. Un examen comparatif de la géométrie crustale des coupes actuelles avec les coupes reconstituées suggère que les forces d'étirement furent réparties de manière à créer un amincissement maximal de la croûte supérieure au-dessus de la région centrale du Complexe de Shuswap, tandis que l'étirement maximum de la croûte inférieure s'est manifesté sous le Domaine intermontagneux et la partie occidentale du Domaine d'Omineca.
[Traduit par la rédaction]

Introduction

A new crustal section through the southern Omineca belt of British Columbia draws upon previously published data and incorporates results from our recent study of the early Tertiary Okanagan Valley fault system on the western margin of the Shuswap metamorphic core complex. The section illustrates the structural style resulting from a long and complex history of contractional orogeny followed by extensional tectonic exhumation of the Shuswap complex and serves as the basis for a palinspastic restoration of the extensional structures that considers regional metamorphic, thermochronological, and structural data. Results of the restoration are compared with previous estimates of extension, interpretations of preextension crustal geometry, and hypotheses regarding processes of low-angle normal faulting and crustal extension.

Geological setting

Five distinct morphogeological belts parallel the length of the Canadian Cordillera (Gabrielse et al. 1991) (Fig. 1*a*). The Foreland belt is characterized by the thin-skinned thrust and fold belt of the Rocky Mountains, in which Proterozoic to Upper Jurassic platformal and miogeoclinal strata that were deposited on the rifted western margin of the ancestral North American continent, together with synorogenic continental foreland basin strata, were translated northeastward and shortened by at least 200 km between the latest Jurassic and early Tertiary (Price and Mountjoy 1970; Price 1981). The Omineca belt is the exhumed metamorphic–plutonic hinterland to the Foreland belt. It contains metamorphosed equivalents of Proterozoic and Paleozoic miogeoclinal strata, exhumed basement culminations, slivers of accreted terranes, and Paleozoic to Tertiary plutons. West of the Omineca belt

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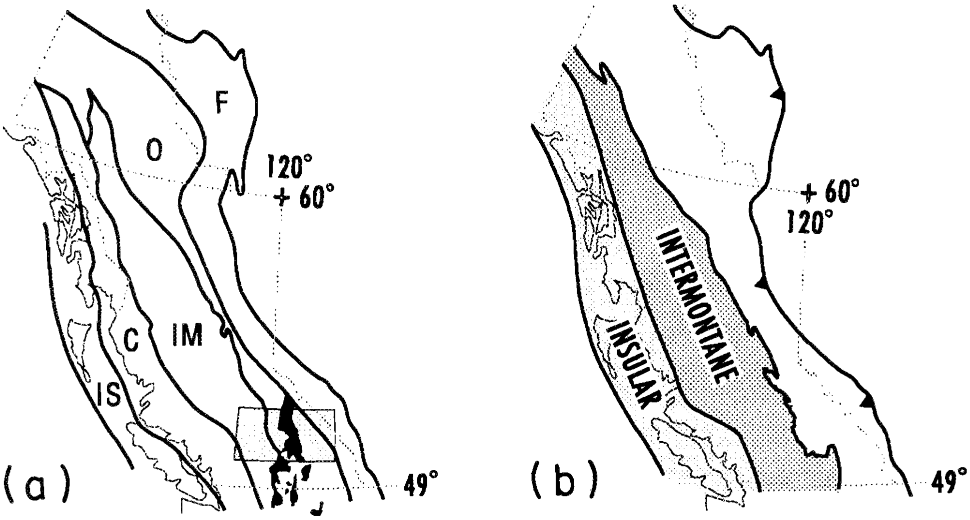
Fig. 1. (*a*) Morphogeological belts of the Canadian Cordillera. IS, Insular; C, Coast; IM, Intermontane; O, Omineca; F, Foreland. (*b*) Composite superterranes of the Cordillera in Canada and the northwestern United States. From Gabrielse et al. (1991).



are the Intermontane, Coast, and Insular belts, which, for the most part, are made up at the present erosion surface of Paleozoic to Early Jurassic island-arc and oceanic terranes. These terranes were amalgamated to form the composite Intermontane and Insular superterranes (Fig. 1*b*), which were accreted to the western margin of ancestral North America either successively during the Early Jurassic through Early Cretaceous (Monger et al. 1982; Gabrielse and Yorath 1991) or en masse in the Jurassic (van der Heyden 1992).

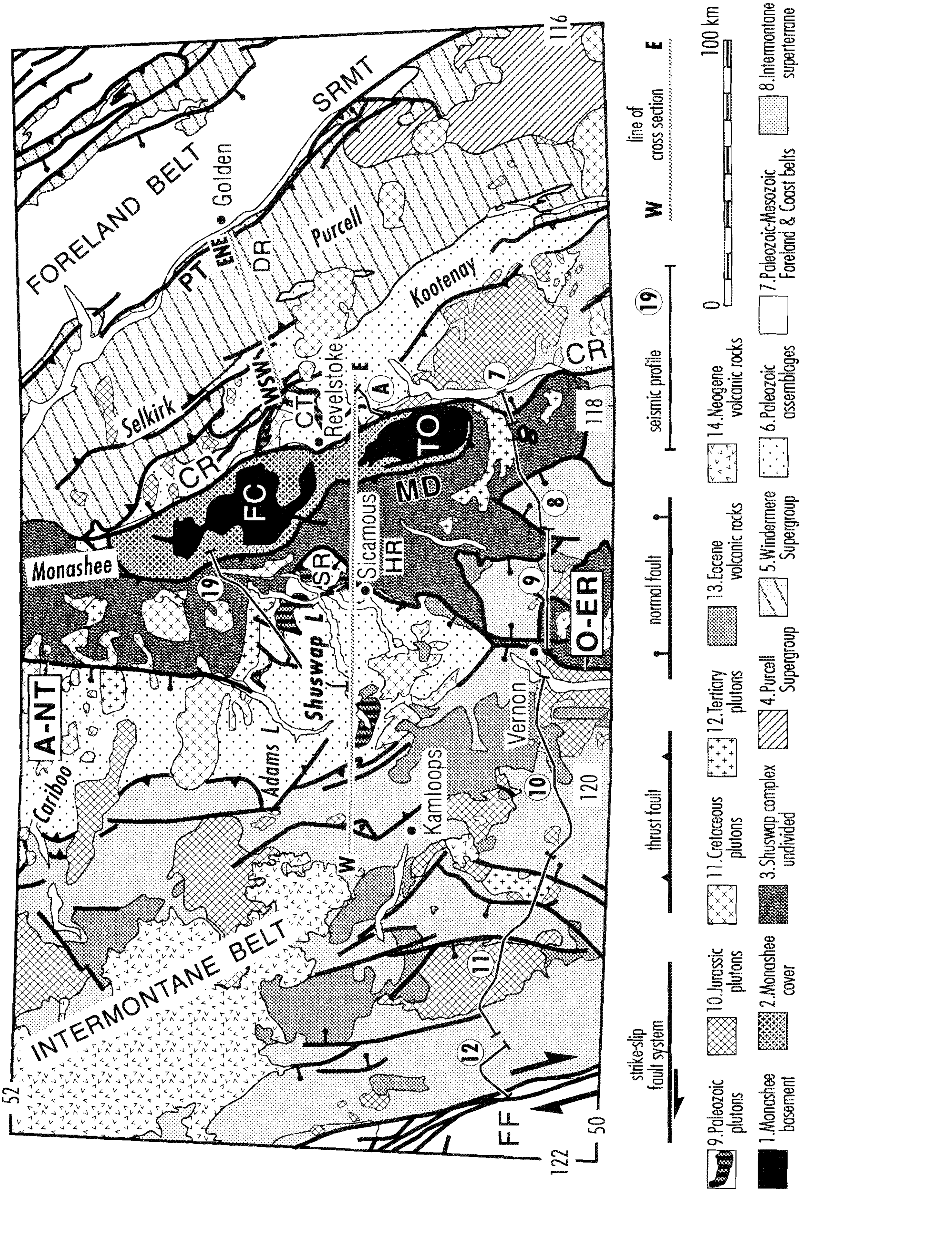
Accretion of the Intermontane superterrane in the Early and Middle Jurassic involved large-scale northeast-directed thrusting along the suture, followed or accompanied by southwestward thrusting and backfolding along and inboard of this boundary in the Omineca belt (Struik 1981; Brown et al. 1986, 1993; Price 1986; Rees 1987; Murphy 1987). Further convergence from the Late Jurassic to early Tertiary was accommodated by northeast-directed thrusting and folding with attendant metamorphism in the Omineca belt (Simony et al. 1980; Price 1981; Brown et al. 1986; Carr 1995; Parrish 1995) and by thin-skinned thrusting and folding in the Foreland belt (Price and Mountjoy 1970; Price 1981). Large-scale dextral strike-slip faulting occurred during the mid-Cretaceous through early Tertiary (Gabrielse 1985). Extensional collapse of the southern Omineca belt occurred in the early Tertiary, toward the end of crustal contraction and orogenic thickening and overlapping with strike-slip faulting.

Crustal extension of the southern Omineca belt resulted in tectonic exhumation of high-grade metamorphic rocks from beneath low- to moderate-angle Eocene normal fault systems. The exhumed footwalls of the normal fault systems constitute a structural and metamorphic culmination in south-central British Columbia and adjacent Washington known as the Shuswap metamorphic complex (Fig. 1*a*). A composite of several smaller, northerly elongate, domal culminations that are each either partly or entirely bounded by outward-dipping Eocene normal faults, the Shuswap complex is the largest metamorphic core complex in the North American Cordillera (Coney 1980; Armstrong 1982). Of particular importance among the Eocene normal fault systems are the west-side-down Okanagan Valley system (Tempelman-Kluit and Parkinson 1986), which bounds the Shuswap complex on the west, and the east-side-down Columbia River – Slocan Lake – Champion Lake system (Read and Brown 1981; Parrish 1984; Corbett and Simony 1984), which defines the eastern boundary of the complex (Fig. 2). The initial geometry of the Tertiary normal faults, the amount of displacement that has occurred along them, and the thickness of the crust before extension are here addressed by means of a crustal cross section and preextension palinspastic restoration.

Trans-Canada Highway transect, surface geology

Figure 3*a* shows an interpretation of the present structure of the Omineca belt in a vertical cross section (see Fig. 2 for location). The section is a composite of two segments: segment W–E extends along latitude 50°55′N from the eastern Intermontane belt to the Selkirk Mountains, crossing the western Omineca belt and the Shuswap complex subparallel to the direction of early Tertiary extension; and segment WSW–ENE crosses the northern Selkirk and Purcell mountains perpendicular to older compressional structures, where the effects of extension have been negligible. The surface geological data described below form the basis on which the upper crust in this cross section has been drawn.

The Shuswap complex is bounded on the east at Revelstoke by the east-dipping Columbia River fault and on the west at Sicamous by the west-dipping Okanagan – Eagle River fault, both of which are early Tertiary normal faults. The deepest structural level exposed within the Shuswap complex is the Monashee complex, a basement-cored thrust window bounded by the Monashee décollement and truncated on its east side by the Columbia River fault. High-grade metamorphic rocks of the Three Valley and Hunters Range assemblages lie above the Monashee décollement and below the Okanagan – Eagle River fault in the western part


FORELAND BELT
INTERMONTANE BELT
Golden
Revelstoke
Sicamous
Kamloops
Vernon
Selkirk
Purcell
Kootenay
Monashee
Cariboo
Adams L
Shuswap L
SRMT
PT
ENE
DR
WSW
CR
CT
FC
TO
MD
HR
SR
A-NT
O-ER
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122
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118
116
strike-slip fault system
thrust fault
normal fault
seismic profile
line of cross section
W E
0
100 km
1.Monashee basement
2.Monashee cover
3.Shuswap complex undivided
4.Purcell Supergroup
5.Windermere Supergroup
6.Paleozoic assemblages
7.Paleozoic-Mesozoic Foreland & Coast belts
8.Intermontane superterrane
9.Paleozoic plutons
10.Jurassic plutons
11.Cretaceous plutons
12.Tertiary plutons
13.Eocene volcanic rocks
14.Neogene volcanic rocks

Fig. 2. Tectonic assemblage map of the Omineca belt and adjacent parts of the Intermontane and Foreland belts between 50° and 52°N latitude. Cross sections W–E and WSW–ENE are shown in Fig. 3. Seismic reflection profiles include 7–12 and 19 of Lithoprobe (Cook et al. 1992) and the Akolkolex River transect (A) of Cook (1986). Trans-Canada Highway (shown in Fig. 4) passes through Golden, Revelstoke, Sicamous, and Kamloops. 1, Paleoproterozoic basement of Monashee complex; 2, Proterozoic to Paleozoic cover of Monashee complex; 3, undivided metamorphic rocks of Shuswap complex above Monashee décollement (includes equivalents of 4–7); 4, Purcell Supergroup (Mesoproterozoic); 5, Windermere Supergroup (Neoproterozoic); 6, Paleozoic strata in hanging walls of major Eocene normal faults (includes Hamill, Badshot, Lardeau, Eagle Bay, Silver Creek, Tsalkom, and Sicamous; some rocks adjacent to west side of Shuswap complex may be of Neoproterozoic age); 7, Paleozoic and Mesozoic strata of Foreland belt (east of SRMT) and undifferentiated rocks of Coast belt (west of FF); 8, Intermontane superterrane (Devonian–Jurassic; includes Slide Mountain, Quesnellia, and Cache Creek terranes, Jurassic overlap assemblages, and Cretaceous volcanic assemblages); 9, Paleozoic granodioritic to dioritic gneiss; 10, Jurassic granodiorite, quartz monzonite, quartz diorite; 11, Cretaceous granite, granodiorite; 12, Paleocene – Early Eocene granite; 13, Middle Eocene volcanic and sedimentary rocks (Kamloops Group); 14, Neogene volcanic rocks. A–NT, Adams – North Thompson segment of Okanagan Valley fault system; CR, Columbia River fault; CT, Clachnacudainn terrane; DR, Dogtooth Range; FC, Frenchman Cap culmination; FF, Fraser fault system; HR, Hunters Range; MD, Monashee décollement; O–ER, Okanagan – Eagle River segment of Okanagan Valley fault system; SR, Shuswap Range; SRMT, southern Rocky Mountain Trench; TO, Thor–Odin culmination.

of the Shuswap complex. Low- to medium-grade rocks are juxtaposed against the Shuswap complex on both its eastern and western flanks.

Monashee complex and Monashee décollement

Paleoproterozoic gneisses inferred as being parautochthonous North American basement (Armstrong et al. 1991) are exposed to the south and north of the Trans-Canada Highway in, respectively, Thor–Odin and Frenchman Cap culminations of the Monashee complex (Fig. 2). A cover sequence of quartzite, metapelite, calcsilicate gneiss, marble, and amphibolite that represents a continental platform and rift succession (McMillan 1973; Scammell and Brown 1990 and references therein) of Neoproterozoic to possibly mid-Paleozoic age (Parrish and Scammell 1988; Höy and Godwin 1988; Scammell and Parrish 1993) overlies the basement unconformably. The top of the Monashee complex is marked by the Monashee décollement, a major ductile thrust zone up to 1 km thick characterized by annealed mylonitic gneisses (Read and Brown 1981; Journeay and Brown 1986; Brown et al. 1992). Mylonitic fabrics within the zone indicate a northeast-directed sense of displacement (i.e., upper member of the shear couple to the northeast) (McNicoll and Brown 1995 and references therein).

Three Valley and Hunters Range assemblages

The structural panel between the Monashee décollement and the Okanagan Valley fault system (Figs. 2, 4) consists mainly of migmatitic gneisses and pegmatite that have been thrust northeastward over the Monashee complex. Carr (1991, 1992) has called the rocks at this regional structural level the "middle crustal zone" in reference to the crustal depth at which they were deformed and metamorphosed. Within this zone, voluminous leucogranites and pegmatites were emplaced during the transition between compressional orogeny and extensional collapse of the southern Omineca belt (Carr 1992; Scammell 1993). Along the Trans-Canada Highway transect, rocks in this zone preserve excellent structural evidence for both northeast-directed compressional and west-directed extensional shearing, both at upper amphibolite facies. The gneisses have been assigned to two assemblages, the Three Valley and the Hunters Range assemblages.

The Three Valley assemblage is characterized by semi-pelitic paragneisses with large boudins of amphibolite and by less abundant pelitic schist and calcareous psammite. These rocks generally have been regarded as equivalent to the Neoproterozoic Windermere Supergroup, but recent isotopic studies cast doubt on this correlation. In particular, U–Pb zircon data of Parkinson (1992) from the amphibolite boudins suggest an age of at least 1.5 Ga, much older than Windermere rocks and somewhat older than the known U–Pb zircon age of sills that intrude the Mesoproterozoic Belt–Purcell Supergroup (1468 ± 2 Ma, Anderson and Davis 1995). In addition, a Sm–Nd model age of 2.0 Ga for the amphibolite (Parkinson 1992) and extremely high initial $^{87}Sr/^{86}Sr$ ratios from the paragneiss and amphibolite of 0.913 biotite and 0.734 hornblende (Armstrong et al. 1991) reflect crustal contamination or a crustal source and support a pre-Windermere age.

The Hunters Range assemblage is a succession of migmatitic garnet–sillimanite–biotite schist, quartzofeldspathic paragneiss, amphibolite, marble, calcsilicate gneiss, and biotite–hornblende granodioritic to dioritic gneiss that structurally overlies the Three Valley assemblage (Figs. 3, 4). This succession, which is tentatively correlated with Windermere strata (Johnson 1994), forms a structural pile with a minimum thickness of ~5 km, characterized by regionally subhorizontal foliation and lacking any major internal structural breaks (Fig. 3*a*).

Two mylonitic zones with opposing shear sense

The main fabric elements of the Three Valley assemblage are an annealed mylonitic foliation, into which layering has been transposed, and a west-southwest-trending mineral stretching lineation. Asymmetrical shear structures indicate relative northeastward movement of the upper plate, consistent with thrusting associated with the Monashee décollement. Up structural section in the Hunters Range, the foliation persists; the lineation (mean trend 065°) is well developed in relatively weak rocks such as migmatitic schist and paragneiss but is only weakly to moderately developed in stronger rocks. Non-coaxial shear fabrics are rare except in pegmatites in the northeastern part of the range, which commonly are heterogeneously mylonitic and locally display winged feldspar porphyroclasts and asymmetrical extensional shear bands indicative of northeast-directed shear. At the top of the "middle crustal" panel, in the immediate footwall of the Okanagan – Eagle River fault, mylonitic paragneisses exhibit nonannealed C–S fabrics, winged feldspar porphyroclasts, asymmetrical extensional shear bands, and oblique foliations in dynamically recrystallized quartz aggregates that consistently indicate westward movement of the upper plate (Johnson 1994). A strong stretching lineation defined by sillimanite and quartz–feldspar aggregates trends westward (mean trend 275°) and is interpreted as the direction of movement associated with normal-sense shearing, in contrast to the northeast-trending lineation related to thrusting at deeper levels. Cataclastic zones near the brittle detachment of the Okanagan – Eagle River fault display slickensides with west-directed chlorite fiber lineations parallel to the stretching lineation and are taken as evidence that normal-sense shearing continued as the rocks reached brittle upper-crustal levels.

Both the northeast-directed and the west-directed mylonites are defined by sillimanite-bearing assemblages, and no overprinting relationships have been observed between them. Therefore, although west-directed extensional shearing clearly outlasted northeast-directed thrusting, the onset of extensional shearing and the final stages of thrusting may be closely associated in time.

Early Tertiary normal faults

Okanagan Valley fault system

The Okanagan Valley fault system consists of two west-dipping, en echelon, ductile–brittle normal fault segments and an intervening transfer zone (Figs. 2, 4). The Okanagan – Eagle River segment is delineated for the most part by a single continuous low-angle detachment fault. The Adams – North Thompson segment may consist of en echelon segments. Mylonites exhibiting west-directed kinematic indicators occur within the uppermost few hundred metres to 2 km of the footwall of the system (Bardoux 1985, 1993; Parkinson 1985; Journeay and Brown 1986; Tempelman-Kluit and Parkinson 1986; Johnson 1989, 1990, 1994). Between the major en echelon fault segments is the Shuswap Lake transfer zone, a 45 km wide left step in the system within which there is abundant evidence for low-angle ductile displacement and limited evidence for high-angle brittle or ductile–brittle strike-slip transfer (Johnson 1994).

Columbia River fault

The Columbia River fault forms the northeastern boundary of the Shuswap complex (Fig. 2). The ductile–brittle fault zone is characterized by east-dipping mylonitic foliation, within which asymmetrical shear fabrics consistently indicate east-directed shear sense (Brown and Murphy 1982; Lane 1984*a*; Lane et al. 1989; Parkinson 1992), and by discrete brittle shears with slickenfiber lineations that indicate east-side-down normal-sense slip and minor dextral strike-slip reactivation (Lane 1984*a*, 1984*b*). The fault may spatially coincide with the arched Monashee décollement along the northeastern margin of the Monashee complex (Read and Brown 1981). Annealed mylonite within the fault zone has been interpreted as having formed during early stages of thrusting on the décollement (Lane et al. 1989), whereas younger nonannealed fabrics defined by greenschist-facies mineral assemblages are considered to be related to normal-sense displacement on the Columbia River fault (Parrish et al. 1988; Carr 1992; Parkinson 1992; McNicoll and Brown 1995).

Rocks in the hanging walls of early Tertiary normal faults

Northern Purcell and Selkirk mountains

Rocks known to be part of the ancestral North American miogeoclinal succession occur in the eastern part of the southern Omineca belt in the Cariboo, northern Monashee, Selkirk, and Purcell mountains and in the Kootenay Arc, an arcuate fold belt south of the Trans-Canada Highway (Fig. 2). Of importance to this investigation are the dominantly coarse clastic and pelitic units of the Neoproterozoic Windermere Supergroup, the overlying quartzite-dominated Hamill Group, Lower Cambrian marble of the Badshot Formation, and the Cambro-Ordovician(?) Lardeau Group, which consists of graphitic phyllite, chlorite schist, calcareous phyllite, marble, and impure quartzite (Fyles and Eastwood 1962; Read and Wheeler 1976).

In the Dogtooth Range of the northern Purcell Mountains, southwest-dipping panels of Windermere and Hamill Group are imbricated by northeasterly directed thrusts (Kubli and Simony 1994). These structures steepen westward and give way to southwesterly overturned folds and northeast-dipping faults (Brown and Tippett 1978). The westernmost Selkirks consist of Hamill, Badshot, and Lardeau strata intruded by the Devono-Mississippian Clachnacudainn orthogneiss (Parrish 1992), folded by tight, recumbent, southwest-verging nappes and metamorphosed to garnet zone and higher grade (Crowley and Brown 1994 and references therein). Southwest-vergent folding, thrusting, and metamorphism in the Selkirk Mountains occurred in the Middle Jurassic (Brown and Tippett 1978; Colpron and Price 1993). Open folds and crenulation cleavage were superimposed on these structures before emplacement of mid-Cretaceous granitic plutons (Crowley and Brown 1994).

Western Omineca belt

In the hanging wall of the Okanagan – Eagle River fault are garnet–mica schists, impure quartzites, and minor carbonate and mafic schist of the Silver Creek assemblage, which are thought to correlate with either Neoproterozoic or lower Paleozoic strata (Windermere–Hamill or Lardeau) (Okulitch 1979; Johnson 1989, 1990). Above and in probable faulted contact with the Silver Creek assemblage are discontinuous metabasites of the Tsalkom Formation and a thick succession of phyllitic marble and calcareous phyllite of the Sicamous Formation. These rocks are probably equivalent to lower Paleozoic strata of the Lardeau Group and Eagle Bay assemblage (Schiarizza and Preto 1987; Johnson 1990), although correlations with the Triassic Slocan Group have been suggested (Campbell and Okulitch 1973).

The Eagle Bay assemblage, consisting of quartzite, mica schist, marble, calcsilicate schist, phyllite, and metabasite, is located northeast of and structurally above the Sicamous Formation. These strata range in age from Lower Cambrian or older to Mississippian and are equivalent to the Hamill–Badshot–Lardeau succession in the Selkirk Mountains (Okulitch 1979; Schiarizza and Preto 1987; Johnson 1994).

Fig. 3. Crustal cross section through the Omineca belt (*a*) and palinspastic restoration of Tertiary normal faults (*b*). Sources of data for (*a*) are as follows: Intermontane belt (Monger and McMillan 1989); western Omineca belt (Okulitch 1979); Shuswap Range and Hunters Range (Johnson 1994); Monashee complex (Read and Klepacki 1981; Harrap 1990); western Selkirk Mountains (Crowley and Brown 1994; Sears 1979; Brown et al. 1993); eastern Selkirk Mountains (Monger et al. 1985; Brown et al. 1993); Dogtooth Range (Monger et al. 1985); subsurface (Cook et al. 1992; Brown et al. 1992; Cook 1986). See Fig. 2 for location.

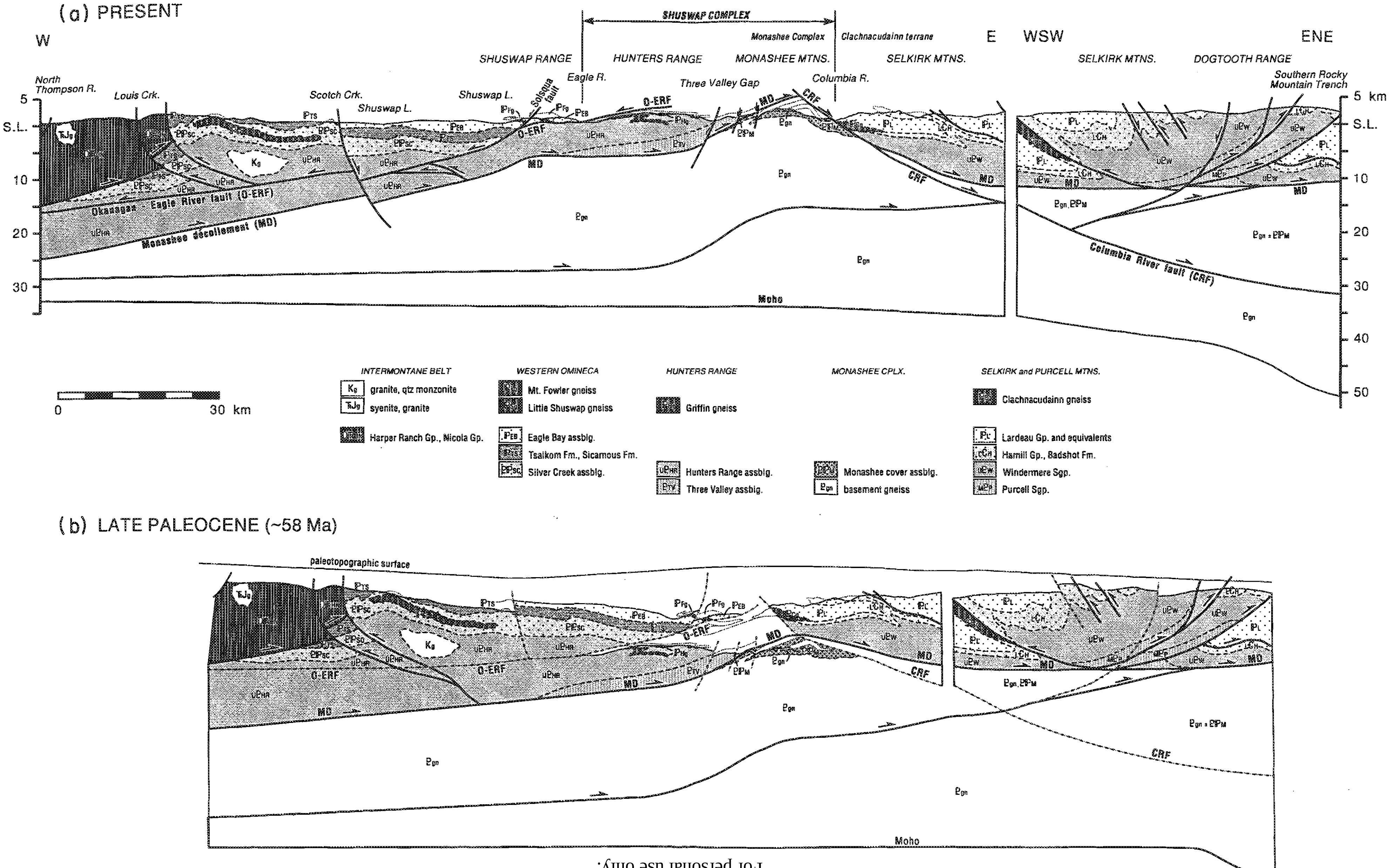
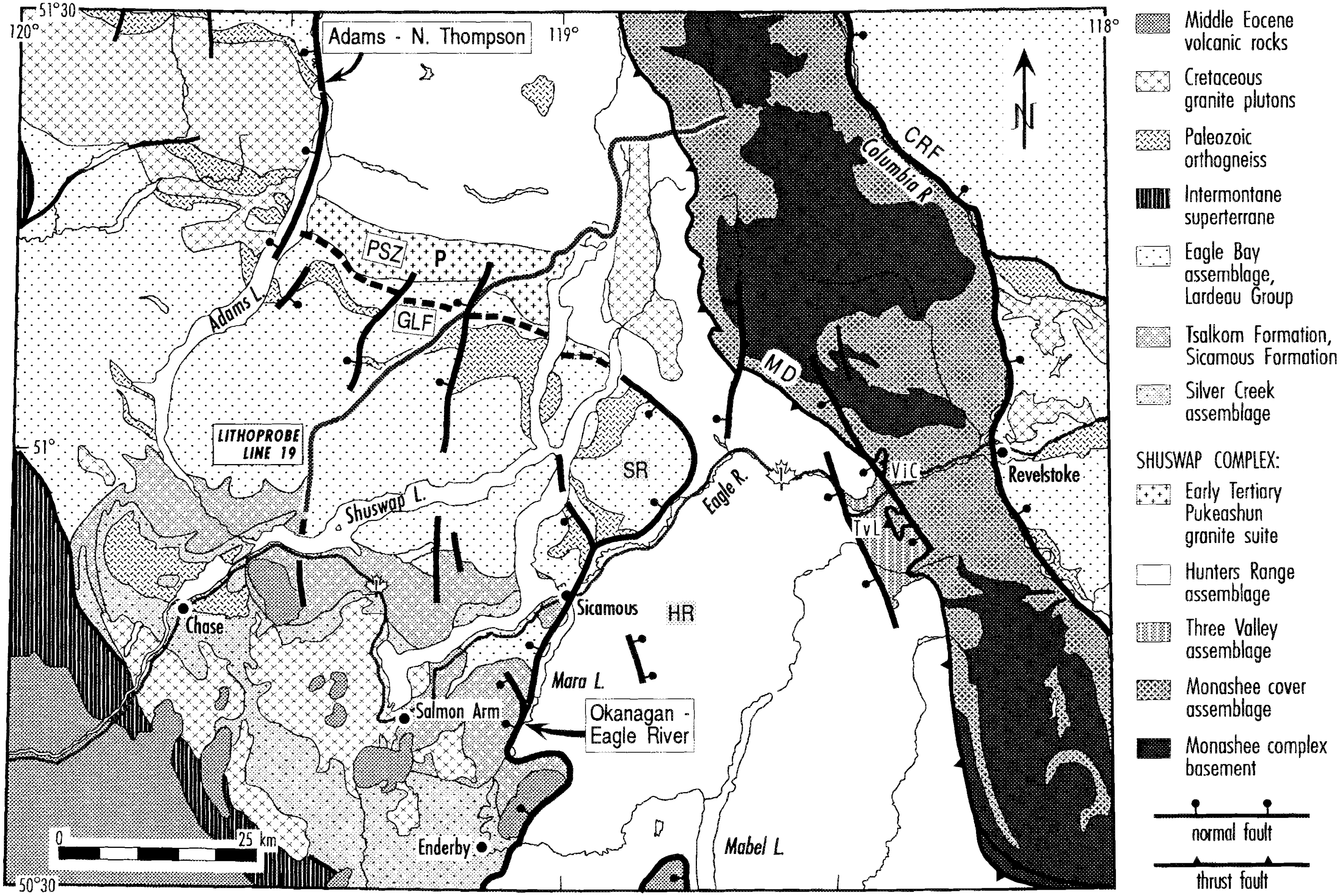


Fig. 4. Geological map of the Shuswap complex and adjacent hanging wall in the Trans-Canada Highway area. Shuswap Lake transfer zone is left step between the en echelon Okanagan – Eagle River and Adams – North Thompson segments of the Okanagan Valley fault system. Pukeashun shear zone (PSZ) lies within the early Tertiary Pukeashun granite. CRF, Columbia River fault; GLF, Grizzly Lake transfer fault (inferred); HR, Hunters Range; MD, Monashee décollement; P, Pukeashun Mountain; SR, Shuswap Range; TvL, Three Valley Lake; ViC, Victor Creek. Maple leaf symbol designates Trans-Canada Highway. Geology compiled from Johnson (1990, 1994), Okulitch (1979), Schiarizza and Preto (1987), Höy and Brown (1981), Journeay and Brown (1986), Bardoux (1993), Bosdachin (1989), Harrap (1990), McNicoll and Brown (1995), and Crowley and Brown (1994).



The Eagle Bay assemblage is intruded by Devonian granodioritic gneiss of the Mount Fowler suite (Okulitch et al. 1975). This is an important relationship because, on the other side (east) of the Shuswap complex at this latitude, the Clachnacudainn gneiss of the northern Selkirk Mountains is the only granitoid suite of this age within the Omineca belt (Wheeler and McFeely 1991; Woodsworth et al. 1991); hence, the Mount Fowler and Clachnacudainn suites are probably comagmatic.

As in the Selkirk Mountains, compositional layering in rocks of the western Omineca belt is deformed by tight synmetamorphic folds and associated penetrative foliation of Middle Jurassic to Early Cretaceous age (Schiarizza and Preto 1987). South-southwesterly overturned folds and associated thrusts dominate the map pattern west of Shuswap Lake (Okulitch 1979; Schiarizza and Preto 1987) and are highly oblique to the cross section shown in Fig. 3. Metamorphic grade ranges from middle greenschist facies in the southwest to staurolite zone in the Shuswap Range north of Sicamous (Fyson 1970; Johnson 1994). The metamorphic peak predated formation of open, steeply inclined folds and crenulation cleavage, but metamorphism outlasted deformation. Mid-Cretaceous granite plutons postdate all major penetrative strain.

Eastern Intermontane belt

Rocks of the eastern Intermontane belt belong to the Quesnellia terrane (Intermontane superterrane). They include Devonian to Permian argillite, volcaniclastic rocks, and limestone of the Harper Ranch Group and overlying Upper Triassic arc-related volcanic and sedimentary units of the Nicola Group (Monger 1985; Monger and McMillan 1989). These are intruded by Late Triassic to Early Jurassic granodiorite and quartz monzonite plutons and are deformed by southwest-verging overturned folds and thrusts of Middle Jurassic age that are similar to structures in the western Omineca belt (Monger 1985, 1989). Metamorphic grade decreases southwestward from upper greenschist to subgreenschist facies (Monger 1989). The northeast-verging thrust boundary along which the Intermontane superterrane was accreted to North America is obscured at this latitude by younger displacement on the Louis Creek fault, interpreted as a Jurassic southwest-verging thrust (Monger et al. 1985) that may have had an Eocene strike-slip history as well (Schiarizza and Preto 1987).

Summary

Low- to medium-grade metamorphic rocks in the hanging walls of the Okanagan Valley and Columbia River normal fault systems are similar in terms of stratigraphy and structural, metamorphic, and plutonic history. Within the Shuswap complex, rocks preserve evidence of high strain at high metamorphic grade. This is most profound on the west side of the complex, in the thick panel of rocks that forms the footwall of the Okanagan Valley fault system and lies above the Monashee basement complex. Displacement on the Columbia River fault has resulted in omission of these rocks across the eastern margin of the Shuswap complex.

Subsurface structure

The subsurface crustal structure is constrained by correlation of surface structural features with seismic reflection data from the Lithoprobe southern Canadian Cordillera transect. Lithoprobe results are detailed in several publications; the reader is referred to papers by Cook et al. (1992) and Brown et al. (1992) for those data important to the interpretation of early Tertiary extensional tectonics of the Omineca belt, which are briefly summarized below. The crustal section shown in Fig. 3 is 60–75 km north of the main Lithoprobe transect (lines 7–11; see Fig. 2 for locations); it crosses the southwest end of Lithoprobe line 19 and crosses the Akolkolex River near the northeast end of an independent seismic transect of Cook (1986).

In Lithoprobe profiles 7–10, the Moho corresponds to a narrow zone of subhorizontal reflections that changes only about 1.5 s, or 4–5 km in depth, over the 200 km transect (Cook 1995). The depth of the Moho in Fig. 3*a* is extrapolated from these data and, east of the Columbia River, from seismic refraction data (Chandra and Cumming 1972; Cumming et al. 1979). The crust tapers gradually from ~32 km thick in the eastern Intermontane belt to ~40 km thick beneath the Selkirk Mountains, then thickens more abruptly to ~50 km beneath the Rocky Mountain Trench at the eastern edge of the Omineca belt.

The Columbia River fault dips 20–30° eastward at the surface and is inferred to have been steeper above the present erosion surface (Read and Brown 1981). Seismic reflectors correlated with the fault dip ~35° and become listric into the middle or lower crust (Cook 1986).

Transposition fabrics associated with the Monashee décollement dip ~25° southwest at the surface on the southwest flank of the Monashee complex. This planar fabric projects to a zone of strong reflections in Lithoprobe data. These reflections lie near the surface at the eastern edge of Lithoprobe profile 7 and outline a crustal-scale thrust ramp to the west, rooting in the lower crust beneath the Intermontane belt. Brown et al. (1992) have argued on the basis of Lithoprobe profiles and the Mesozoic to latest Paleocene timing of motion that the décollement correlates with the sole thrust of the Rocky Mountain foreland belt to the east.

The Okanagan – Eagle River fault dips ~15° westward at Sicamous. In the Eagle River valley east of Sicamous, the detachment is subhorizontal in the plane of section and is warped by corrugations that plunge gently northward (Johnson 1994). The Okanagan – Eagle River fault projects toward a zone of subhorizontal to gently west-dipping reflections in Lithoprobe profile 10 that is traceable into the middle crust at ~15 km depth. There is no evidence whatsoever that this low-angle normal fault penetrates into the lower crust anywhere to the west, and therefore it is presumed to feed into a subhorizontal zone in the middle crust to the west.

Lithoprobe line 19 follows the trace of a high-angle fault for 10 km near the southwest end of Shuswap Lake (Okulitch 1979), where it intersects the cross section (Fig. 3*a*); therefore the profile cannot be used to tightly constrain the depths of structures. However, in accord with profiles 8–10 (Brown et al. 1992), profile 19 does suggest that the Monashee décollement and associated transposed fabric flatten to subhorizontal in the upper middle crust before steepening again to the west. Furthermore, profiles 9 and 10 show that the Okanagan – Eagle River fault does not cut the Monashee décollement, and there is no evidence from profile 19 to the contrary. The subsurface geometry of these major structures depicted in Fig. 3*a* is consistent with all of the reflection data and leads to a realistic palinspastic restoration.

Preextension palinspastic restoration

Figure 3*b* shows the crustal section through the Omineca belt with the Tertiary normal faults restored. An outline of the constraints and assumptions used in the restoration is followed by a discussion of tectonic implications.

Relative timing of extension and contraction

The restoration assumes that displacement on the normal faults postdates final thrust motion on the Monashee décollement and related structures. This assumption is consistent with current knowledge of the timing of the major structures. For example, the Monashee décollement at the southern end of Thor–Odin culmination (Fig. 2) is known to have been active at 59 Ma and to have become inactive by 58 Ma (Carr 1992); ductile shearing related to extension on the Columbia River fault may have been underway as early as 60 Ma, but normal-sense displacement was predominantly Early Eocene (Parrish et al. 1988); some ductile shearing occurred at, and possibly before, ~56 Ma on the Okanagan Valley fault system (Johnson 1994), but much of the displacement is Middle Eocene (Parrish et al. 1988); evidence for a mid-Cretaceous episode of ductile extension north of the Monashee complex has been presented by Scammell (1993), but this earlier period has not been correlated with any known faults. Therefore, thrusting and ductile extensional shearing may have occurred synchronously during a transition from predominantly contractional to predominantly extensional tectonics, but extension accommodated by known major normal fault systems began at about the same time as thrusting stopped.

Metamorphic and thermochronological constraints on preextension crustal depths and exhumation history

Footwall rocks

Table 1 summarizes the constraints on pressure and temperature of the Hunters Range and Three Valley assemblages and of other formerly mid-crustal rocks to the north and south. Rocks of the Hunters Range assemblage were hot enough for partial melting to occur (>640°C in the second sillimanite field; Thompson and Tracy 1979) at least as late as ~70 Ma and were cooled below ~500°C in the Late Paleocene to Early Eocene. The conclusions of thermobarometric studies well to the north and south of the Trans-Canada Highway section (Scammell 1993; Bardoux 1993) imply that metamorphism reached similar peak conditions regionally and suggest that the rocks in this structural zone were exhumed diachronously, reaching upper-crustal levels earlier in the north. The rocks that are currently exposed at the latitude of the Trans-Canada Highway (e.g., Hunters Range assemblage) therefore reached postpeak pressures of ~450 MPa (±150 Ma to account for the 5 km thickness of the structural panel where exposed) sometime between the mid-Cretaceous and the Eocene. Correspondingly, a burial depth of 15–16 km is inferred for the Late Paleocene.

Journeay (1986) documented metamorphic and structural evidence for a two-stage thrusting history for the Monashee décollement at the north end of Frenchman Cap culmination. The first stage occurred at pressures of 640–710 MPa. The second stage involved syntectonic growth of low-pressure (200–340 MPa) metamorphic assemblages that indicate a depth of no more than 12 km. This low-pressure episode appears to have occurred in latest Cretaceous to Paleocene time, and preservation of an inverted low-pressure metamorphic gradient in the footwall of the décollement is attributed to exhumation rates of the order of 2 mm/a (Journeay 1986). At the Trans-Canada Highway, the mineral assemblage that defines fabrics related to the final stage of crustal shortening includes sillimanite + K-feldspar ± muscovite (Bosdachin 1989; Harrap 1990), implying temperatures above ~600°C within the décollement zone and pressures greater than 200 MPa (Spear and Cheney 1989). No firm evidence for the low-pressure metamorphism has been documented either here or farther south in the Thor–Odin culmination, and given the evidence for diachronous exhumation outlined above, the assumption is made here that the Monashee décollement at the highway was at ~400 MPa pressure (~14 km depth) during the Late Paleocene.

Nicholls et al. (1991) concluded that mineral assemblages in amphibolites and paragneisses of the Three Valley assemblage at Three Valley Gap equilibrated at ~700°C and ~800 MPa. These conditions must have been reached well before the Late Paleocene, because the Three Valley assemblage lies in the hanging wall of the Monashee décollement. The restored thickness of cover on footwall rocks shown in Fig. 3*b* is constrained by the data outlined above and by geometric controls outlined below.

Hanging-wall rocks

Rocks in the hanging walls of the Columbia River and Okanagan Valley fault systems were metamorphosed in the Mesozoic (Parrish et al. 1988 and references therein). Paleocene depths of these rocks have been estimated as closely as possible given the largely Mesozoic thermochronological and geobarometric data set summarized in Table 2. An important geological constraint is the similarity between the Eagle Bay assemblage of the Shuswap Range and the Lardeau Group of the northwestern Selkirk Mountains in terms of stratigraphy, metamorphic grade, structural style, and their unique association with widespread Devono-Mississippian orthogneisses. This suggests that these two assemblages were contiguous prior to extension, which has been assumed in the restoration shown in Fig. 3*b*. The K–Ar and $^{40}Ar/^{39}Ar$ data from the Shuswap Range indicate that the Eagle Bay assemblage either was still hotter than the closure temperature for Ar in biotite (280–300°C; Harrison et al. 1985) or was reheated in the Eocene. A minimum Late Paleocene depth of 8.5 km is derived from a temperature of 300°C and a reasonable geothermal gradient for the upper crust of 35°C/km. For the Selkirk Mountains, two independent interpolations based on data in Table 2 each lead to an estimated depth of 6.5–7.5 km: time-averaged exhumation rate to the present (0.14 mm/a) from ~12 km depth in the mid-Cretaceous, and time-averaged cooling rate (~4°C/Ma) from Late Cretaceous $^{40}Ar/^{39}Ar$ cooling ages and an assumed geothermal gradient of 35°C/km. Although these interpolations can only be considered first-order approximations, they are mutually consistent and lead to lateral continuity of Eagle Bay and Lardeau rocks in the restored section. Finally, data from west of Shuswap Lake and the

Table 1. Summary of thermobarometric and thermochronological data for former mid-crustal rocks.

Location	Data	Source	Interpretation
Monashee Mountains north of Frenchman Cap	Peak conditions at 100 Ma: ~720°C, ~730 MPa; retrograde conditions at 94 Ma: ~610°C, ~460 MPa; timing supported by U–Pb monazite and titanite data	Scammell (1993)	Crustal thinning by ductile extension or rapid erosion between 100 and 94 Ma
Okanagan Valley ~45 km south of Vernon	Peak conditions: ~700°C, ~600 MPa; retrograde conditions: ~550°C, ~450 MPa; timing not well constrained	Bardoux (1993)	Metamorphic peak during late stages of Late Cretaceous – Paleocene thrusting, retrograde metamorphism during Eocene tectonic exhumation
Central Hunters Range	U–Pb zircon lower-intercept age of migmatite leucosome, ~70 Ma	Johnson (1994)	Partial melting at T > 640°C at least as late as ~70 Ma
Hunters Range and Three Valley assemblages	Hornblende $^{40}Ar/^{39}Ar$ dates, 60–50 Ma	Johnson (1994)	Cooling below ~500°C in Late Paleocene to Early Eocene
Three Valley Gap	Metamorphic equilibration conditions: ~700°C, ~800 MPa	Nicholls et al. (1991)	Late Cretaceous metamorphic peak (see text)

Table 2. Summary of thermochronological and geobarometric data for hanging-wall rocks.

Location	Data	Source	Interpretation
Northwestern Selkirk Mountains	Al in hornblende from 104 ± 1 Ma granite: 360 MPa	Crowley et al. (1996); Crowley and Brown (1994)	12–12.5 km emplacement depth in mid-Cretaceous
	Biotite $^{40}Ar/^{39}Ar$: ~65 Ma	Colpron (1996)	Cooling below 280–300°C in Late Cretaceous
Eagle Bay assemblage, Shuswap Range	Hornblende $^{40}Ar/^{39}Ar$ and K–Ar: ~74 and ~90 Ma	Johnson (1994); Okulitch (1979)[a]	Cooling below ~500°C in Late Cretaceous
	Biotite and muscovite K–Ar: 52–46 Ma	Okulitch (1979)[a]	Cooling below 280–300°C or resetting in Middle Eocene
Little Shuswap orthogneiss, near Chase	Biotite and muscovite K–Ar: 142–122 Ma	Okulitch (1979);[a] Stevens et al. (1982)	Cooling below 280–300°C in Early Cretaceous
Hanging-wall rocks west of Okanagan Valley	Apatite fission track: latest Cretaceous to Late Eocene	Medford (1975)	Probably cooling below ~100°C
Intermontane belt	K–Ar and Rb–Sr dates, close to crystallization ages of Triassic and Early Jurassic plutons	Monger (1989 and references therein)	Country rocks were below ~300°C in Jurassic, have not since been reheated

[a]Geological Survey of Canada internal reports cited in Okulitch (1979).

Okanagan Valley imply that rocks of the western Omineca belt were much cooler than 300°C by the Paleocene.

Geometric constraints on displacement along the Columbia River and Okanagan – Eagle River faults

All faults are modelled in Fig. 3 as discrete detachments, and for lack of documentation to the contrary their hanging walls are restored as coherent blocks with only minor internal strain to resolve local space problems. This method serves to illustrate preextension structure of the Shuswap complex and gives an approximation of the total amount of extension across the Omineca belt. Restoration of the Shuswap Range and the northwestern Selkirk Mountains to about the same depth places geometric constraints on vertical displacement (throw) across the major normal faults and limits the amount of net hanging-wall extension across the Shuswap culmination to a maximum of ~60 km, the distance between the surface traces of the Columbia River and Okanagan – Eagle River faults. It is recognized that a problem encountered in many attempts to restore extensional fault and shear zone systems is that such systems commonly exhibit complex crosscutting relationships resulting from abandonment of splays during progressive displacement and uplift (e.g., Davis and Lister 1988). The Okanagan Valley fault system shows such complexity farther north (Johnson 1994), but the effects in the plane of this section are thought to be minor.

Estimates of displacement across the Columbia River fault range from 1 to 10 km (Lane 1984*a*, 1984*b*; Harrap 1990) to 40 km or more (Parkinson 1992). In Fig. 3*a*, the Monashee décollement in the footwall of the Columbia River fault is extrapolated above the present erosion surface parallel to the foliation in the Monashee complex from a section by Read and Klepacki (1981), and its position in the hanging wall is modified as per Brown et al. (1993) from an interpretation of seismic data presented by Cook (1986). The distance between the hanging-wall and footwall cutoffs of the décollement is 15 km, the minimum displacement estimated by Read and Brown (1981). Upon restoration, this puts cover on the presently exposed parts of the Monashee complex of a thickness (14–15 km) that is consistent with 400 MPa pressure (Fig. 3*b*).

The restored Okanagan – Eagle River fault in Fig. 3*b* dips westward at an average of ~14° before flattening to horizontal in the middle crust and is shown with 32 km of dip slip restored. The rationale behind this geometry is as follows. First, the dip of the fault was drawn so that the paleotopographic surface has, on average, a subhorizontal or very low easterly dip and so that the Monashee décollement has an overall westerly dip; these constraints satisfy criteria for an east-directed tapered thrust wedge. Next, the Shuswap Range was restored to approximately the same crustal level as the northwestern Selkirk Mountains, as discussed earlier. Finally, the Sicamous Formation was restored to well above the Hunters Range assemblage because there is no possibility of correlation between them. The hanging-wall cutoff of the Sicamous Formation is well constrained south of the section, and its projected depth and apparent thickness in the plane of section are minima, based on surface geology; therefore, the displacement shown is a minimum for the given fault trajectory.

Tectonic implications

Initial geometry of the Okanagan – Eagle River fault

Hanging-wall domains of low-angle normal fault systems typically display internal extension and thinning accommodated by slip and rotation of subsidiary block faults (Wernicke and Burchfiel 1982, and many other studies). Consequently, the master detachment is rotated to a shallower dip by isostatic rebound. The Okanagan – Eagle River fault is shown with an average initial dip of ~14° in the preextension restoration; however, because the hanging wall was modelled as a coherent block without any internal extension, the actual trajectory was probably somewhat steeper than this.

Northerly striking faults that cut the Eagle Bay and other hanging-wall assemblages (Okulitch 1979; A.V. Okulitch, personal communication, 1989; Schiarizza and Preto 1987; Johnson 1994) are interpreted as high-angle normal faults that accommodated only minor extension, perhaps collectively 4–5 km (<10% extension across the western Omineca belt). Similarly, in the southern Okanagan Valley, where the hanging wall is better exposed, only minor internal extension has been documented (Fig. 2 of Tempelman-Kluit and Parkinson 1986). In the Intermontane belt, the total extension that can be attributed to mapped faults is only ~5% across the 140 km width of the belt (Monger et al. 1985).

Comparison of the present and restored cross sections shows that uplift and minor arching of the Okanagan – Eagle River fault has occurred as a result of tectonic unloading; former flat mid-crustal parts now dip gently westward and part of the fault that originally dipped gently westward has been back-rotated to a subhorizontal dip (in the plane of section) along the Eagle River valley (Fig. 3). Spencer (1984) has shown that normal faults with initially uniform low dips should develop a similarly warped postextension geometry by isostatic rebound if the hanging wall extends nonuniformly and if this extension decreases in the downdip direction. Rebound should be greatest below the most highly extended part of the hanging wall, and a pronounced antiformal arch will develop if the fault has a steep listric breakaway. By analogy, the Shuswap Range and the now-eroded hanging wall to the east should be the most highly extended parts of the hanging wall of the Okanagan – Eagle River fault, and the nonuniform dip of the faults in the subsurface may similarly result from nonuniform extension.

Figure 5 shows that when a wedge-shaped hanging wall of length x and maximum thickness h above a low-angle fault dipping θ degrees is stretched uniformly by a factor β, the resulting dip of the fault θ' can be calculated from the expression

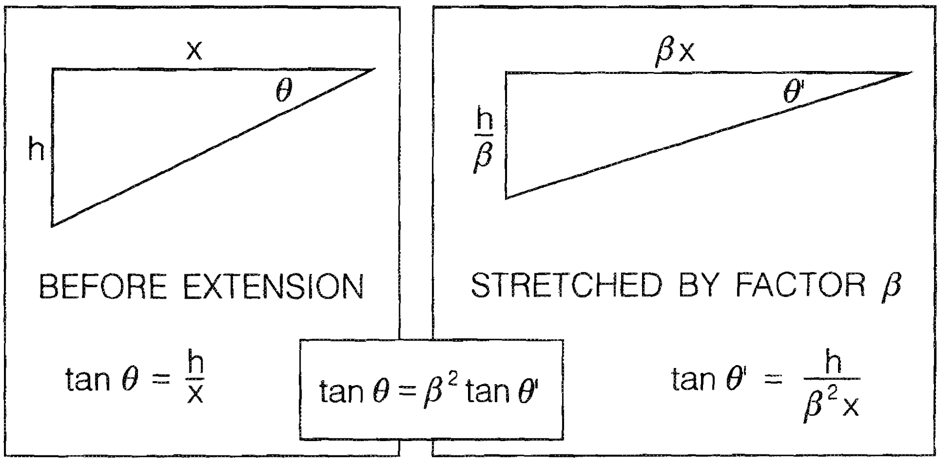
[1] $$\tan\theta = \beta^2 \tan\theta'$$

assuming complete isostatic rebound. From this equation, restoration of 10% ($\beta = 1.1$) internal hanging-wall extension in Fig. 3*b* would only change the average dip of the fault from 14 to 17°. Since the hanging wall was probably extended nonuniformly, with greatest extension east of the present limit of exposure, the fault could have had a steeper breakaway in the upper crust to the east. It is concluded, however, that below ~8 km depth it had an average initial westward dip of less than 20°, a conclusion that concurs with a number of geological, thermochronological, and paleomagnetic studies elsewhere documenting that normal faults can initiate at low angles (Burchfiel et al. 1987; Davis and Lister 1988; Yin and Dunn 1992; Axen 1993; John and Foster 1993; Livaccari et al. 1993).

Relationships between fault dip, hanging-wall extension, and isostatic rebound can have other regional implications. For example, a flat segment of the fault east of the Okanagan Valley farther south is up to 70 km wide (Carr 1991; Cook et al. 1992), reflecting either greater net extension or perhaps a different distribution of hanging-wall strain than at the Trans-Canada Highway. Rebound of the footwall along the Trans-Canada Highway transect could have been accommodated by displacement on steep west-side-down normal faults that cut the footwall, e.g., at Victor Creek and Three Valley Lake (Fig. 4). If so, these faults should be younger from east to west, a prediction that may be testable through $^{40}Ar/^{39}Ar$ dating of micas and feldspars and fission-track dating of zircon and apatite across these faults.

Arching of the Monashee décollement and formation of the Monashee basement culmination are viewed as having been caused in part by pre-Late Paleocene movement of the Monashee complex over a thrust ramp within the basement (Brown et al. 1986; Journeay 1986; Brown and Journeay 1987) and to a lesser degree by isostatic rebound during extensional exhumation. This conclusion is implied by the

Fig. 5. Cross-sectional representation of a wedge-shaped hanging-wall domain, with no internal extension (left) and uniformly stretched internally by a factor β (right), illustrating mathematical relationship between extensional attenuation and fault dip. Initial dips (θ) of 17, 20, 29, and 45° result in a final dip of $\theta' = 14°$ (restored dip of Okanagan – Eagle River fault in Fig. 3*b*) for β values of 1.1, 1.2, 1.5, and 2.0, respectively.



restoration and arises from assumptions made about the present subsurface geometry of the décollement west of its surface trace. Figure 6 shows how the arched décollement can be restored to subhorizontal by removal of 30 km of displacement on a basement thrust that has been drawn to agree with Lithoprobe data (e.g., see Brown et al. 1992).

Magnitude of extension

The total extension across the Shuswap core complex accommodated by the Okanagan Valley and Columbia River fault systems is shown in Fig. 3 as being 44 km, which is 22% of the restored distance from the Rocky Mountain Trench to the North Thompson River. An amount less than this is possible if stratigraphic omission and metamorphic mismatches across the Okanagan – Eagle River fault are partly accommodated by displacement on yet unknown high-angle block faults within the hanging wall. Conversely, since the hanging wall west of the Eagle River has been internally extended a small amount by such faults as discussed in the previous section, this figure could be a slight underestimate. With the present constraints, it is concluded that net extension of 20–25% occurred across the Omineca belt at this latitude, leading to its present width of ~220 km. This magnitude of extension, ~45 km in absolute terms, is greater than that previously estimated by Brown and Journeay (1987) for the same latitude but is considerably less than that estimated by Parrish et al. (1988) for 175 km farther south, where the Omineca belt is thought to have been extended by ~75 km to its present 300 km width.

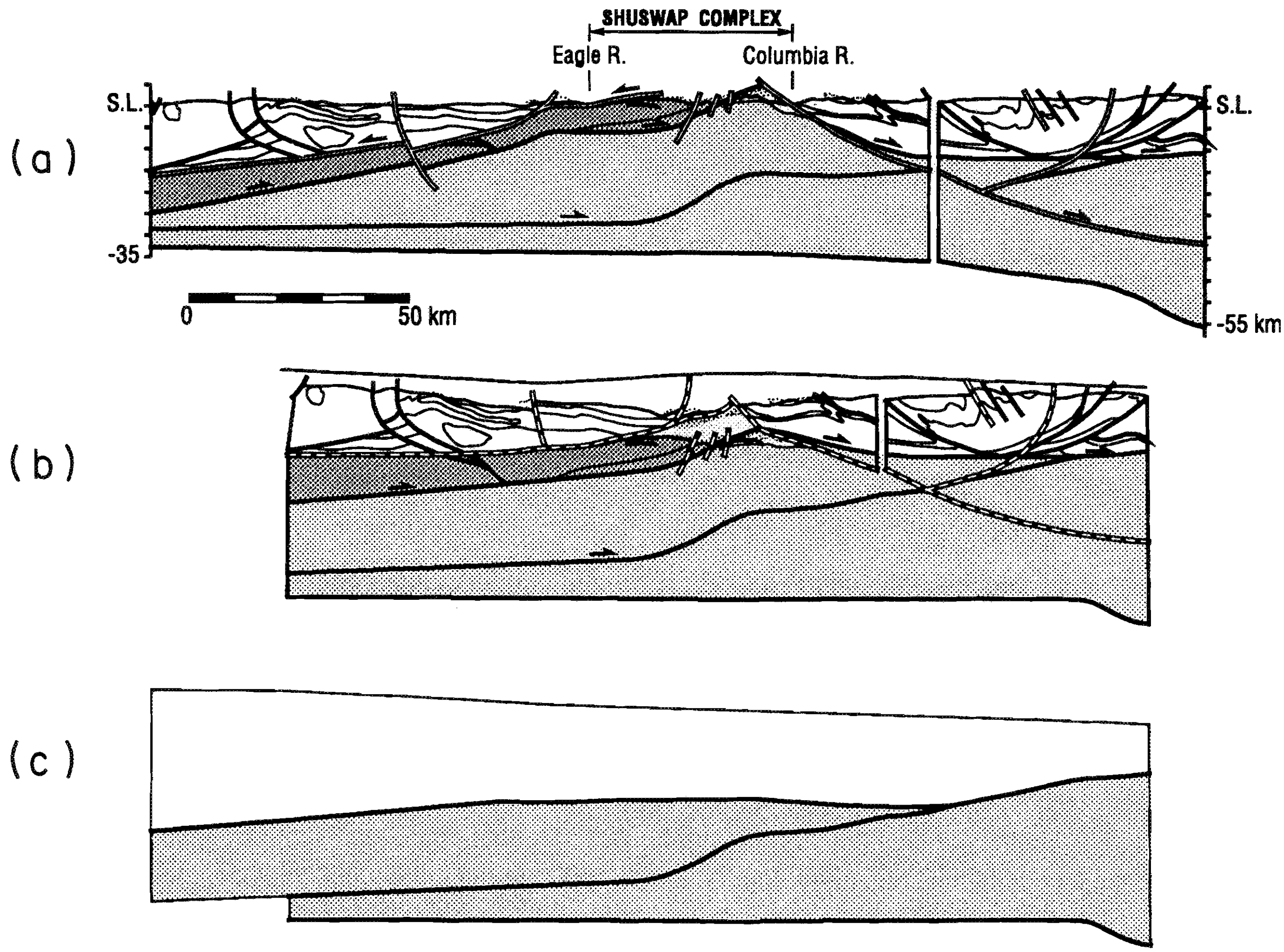
Crustal strain partitioning

The role played by the lower crust during extension is considered in Fig. 7, wherein two different restored configurations are modelled for the footwall domain. In one, the footwall is treated as though it were not stretched in the Eocene (Fig. 7*b*). In the other (Fig. 7*c*), hanging-wall extension and footwall extension are balanced within the limits of the Omineca belt, and it is assumed that no volume has been added to the plane of section (e.g., by Early and Middle Eocene magmatic underplating) or subtracted from it except by erosion; unless it is demonstrated in subsequent work that material has moved into or out of the plane of this section since the Late Paleocene, these assumptions are valid, and this is the favored model (Fig. 3*b*). The alternative shown in Fig. 7*b* is unlikely given that the Okanagan – Eagle River fault apparently does not penetrate the entire crust, because the excess lower crust in the restored section would have to be balanced by shortening of upper crust to the west of the section; the only early Tertiary structures to the west are strike-slip and normal faults in the Intermontane and Coast belts, many of which similarly feed into the middle crust or lower (Jones et al. 1992; Varsek et al. 1993).

In the preferred solution (Fig. 7*c*), extension of the upper crust in the hanging walls of normal faults has been balanced by reciprocal ductile stretching of the lower crust (Price 1992, 1993; Cook et al. 1992; Varsek et al. 1993); hanging-wall extension is greatest between the Okanagan – Eagle River and Columbia River faults as discussed above, whereas the footwall has been most highly attenuated beneath the eastern Intermontane belt. This interpretation is consistent with seismic reflection data, along which dipping reflections in the lower crust beneath the Monashee complex are interpreted as preextensional in origin, whereas the lower crust beneath the western Omineca and eastern Intermontane belts is characterized by strongly layered subhorizontal reflections into which both compressional and extensional structures apparently become listric (Cook et al. 1992). Restored according to this model, the crust in Fig. 3*b* has an approximately uniform thickness of just over 50 km. This agrees well with the restorations of Brown and Journeay (1987) and Cook et al. (1992); Parrish et al. (1988) estimated a 60 km thickness based on restoration of normal faults that penetrate the entire crust, but this geometrical interpretation is now known to be incompatible with seismic reflection data from Lithoprobe.

Importantly, the interpretation outlined above implies that

Fig. 6. Cross section and palinspastic restorations illustrating how antiformal arching of the Monashee complex could have resulted in part from rebound during extensional unroofing and in part by thrusting over a basement ramp. (*a*) Present section. Shuswap complex, exposed in an antiformal culmination between the Okanagan – Eagle River and Columbia River normal faults, consists of basement gneisses (light shading, bounded above by the Monashee décollement) and a "middle crustal" panel of high-grade gneisses (dark shading, bounded at the base by the Monashee décollement and at the top by the Okanagan – Eagle River fault). Vertical and horizontal scales in (*b*) and (*c*) are the same as in (*a*) (sea level not indicated). (*b*) Late Paleocene (~58 Ma). Tertiary normal faults restored; at this stage, the Monashee décollement has been antiformally arched, but the broad antiformal culmination of the Shuswap complex has not yet developed. (*c*) Pre-58 Ma. Restoration of 30 km of displacement on thrust within basement and restoration of décollement to subhorizontal dip.

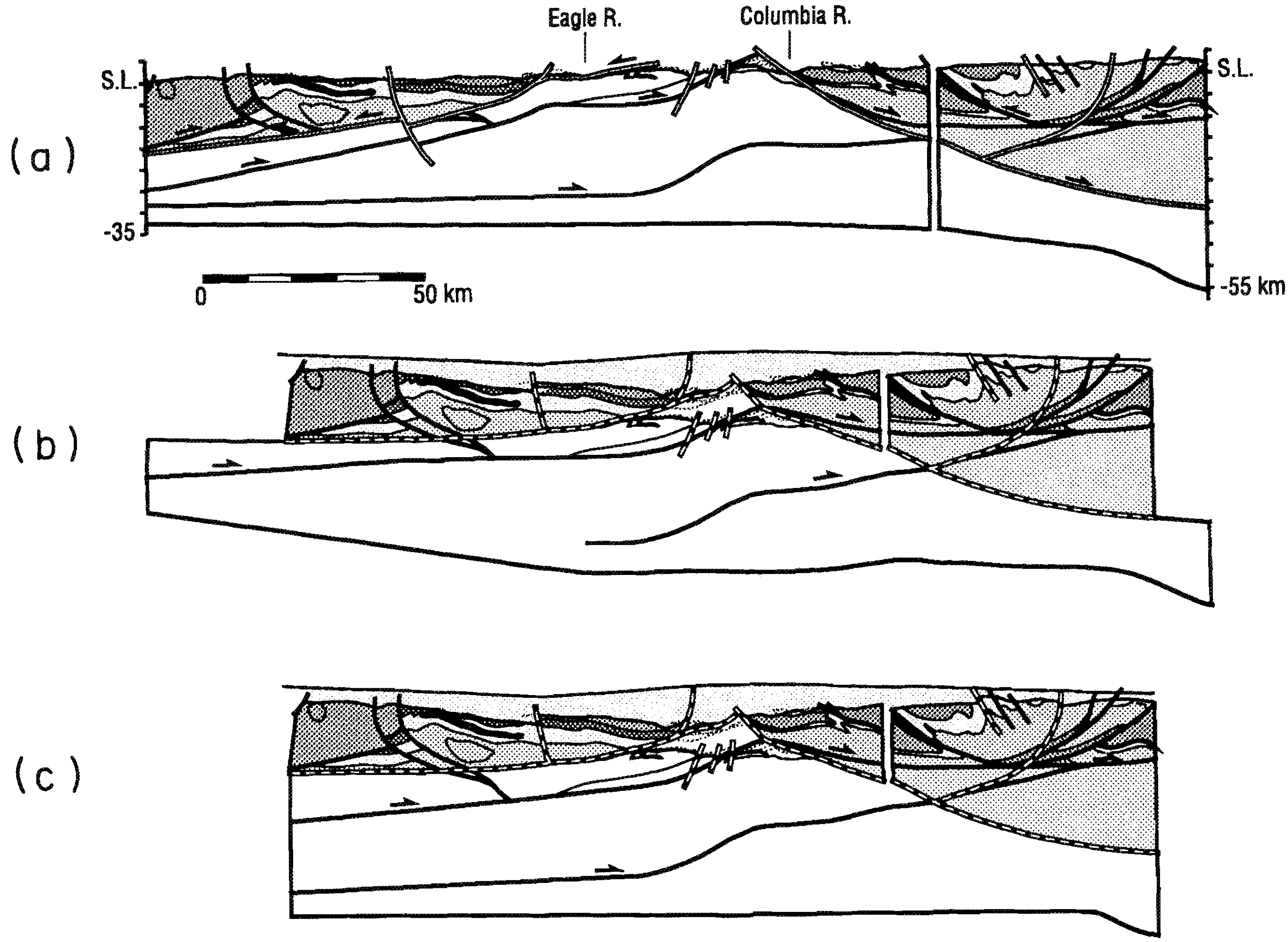


the regionally subhorizontal Moho is a geodynamic equilibrium configuration rather than mere happenstance (Price 1993). A flat Moho may be maintained by lateral flow of weak lower or middle crust in order to relieve lateral pressure gradients that arise where the crust is of variable thickness; the rate of flow is dependent upon viscosity and yield stress and is therefore enhanced by high temperature (Block and Royden 1990; Wernicke 1990; Buck 1991). Heat flow in the Intermontane and Omineca belts is presently very high (>80 mW/m^2) (Lewis et al. 1992) and probably was as high or higher in the early Tertiary when these belts were magmatically active. The model advocated here differs from other models that invoke lower-crustal flow (Gans 1987; Block and Royden 1990; Wernicke 1990) in that the lower crust did not flow toward and reinflate areas of crustal attenuation but merely stretched heterogeneously to complement heterogeneous attenuation of the upper crust.

Conclusions

Metamorphic, stratigraphic, structural, and thermochronological arguments indicate that 30 km of normal-sense displacement on the Okanagan – Eagle River fault near Sicamous, British Columbia, is a geologically reasonable estimate, that the fault initially dipped less than 20° westward in the upper middle crust, and that a steeper breakaway in the upper crust was possible. The present geometry of the fault in the Eagle River area and its inferred geometry in the subsurface are consistent with the profile that would be expected to result from isostatic rebound in response to nonuniform stretching within the hanging-wall domain, with greatest stretching east of Sicamous in rocks that have since

Fig. 7. (*a*) Crustal cross section through the Omineca belt. (*b*, *c*) Palinspastic restorations of Tertiary normal faults illustrating two different geometrical configurations for the footwall domain: (*b*) restoration assuming that footwall was not affected by Tertiary strain; (*c*) restoration assuming that Tertiary extension was accommodated in the footwall by ductile stretching. Vertical and horizontal scales in (*b*) and (*c*) are the same as in (*a*) (sea level not indicated). See Fig. 2 for location, Fig. 3 for geological details, and text for discussion.



been removed by erosion. The nonuniform distribution of hanging-wall strain considered together with Lithoprobe reflection data from the lower crust, geological and geophysical constraints from the Intermontane and Coast belts, and requirements for palinspastic restoration favor a model of crustal strain partitioning whereby stretching of the upper crust is balanced by reciprocal nonuniform ductile stretching of the lower crust.

Restoration of early Tertiary extensional strain and of an estimated amount of cover removed by erosion leads to a Late Paleocene crustal thickness of over 50 km. Net extension across the Omineca belt at latitude 51°N is estimated to have been 20–25% (~45 km) between the North Thompson River and the Rocky Mountain Trench.

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