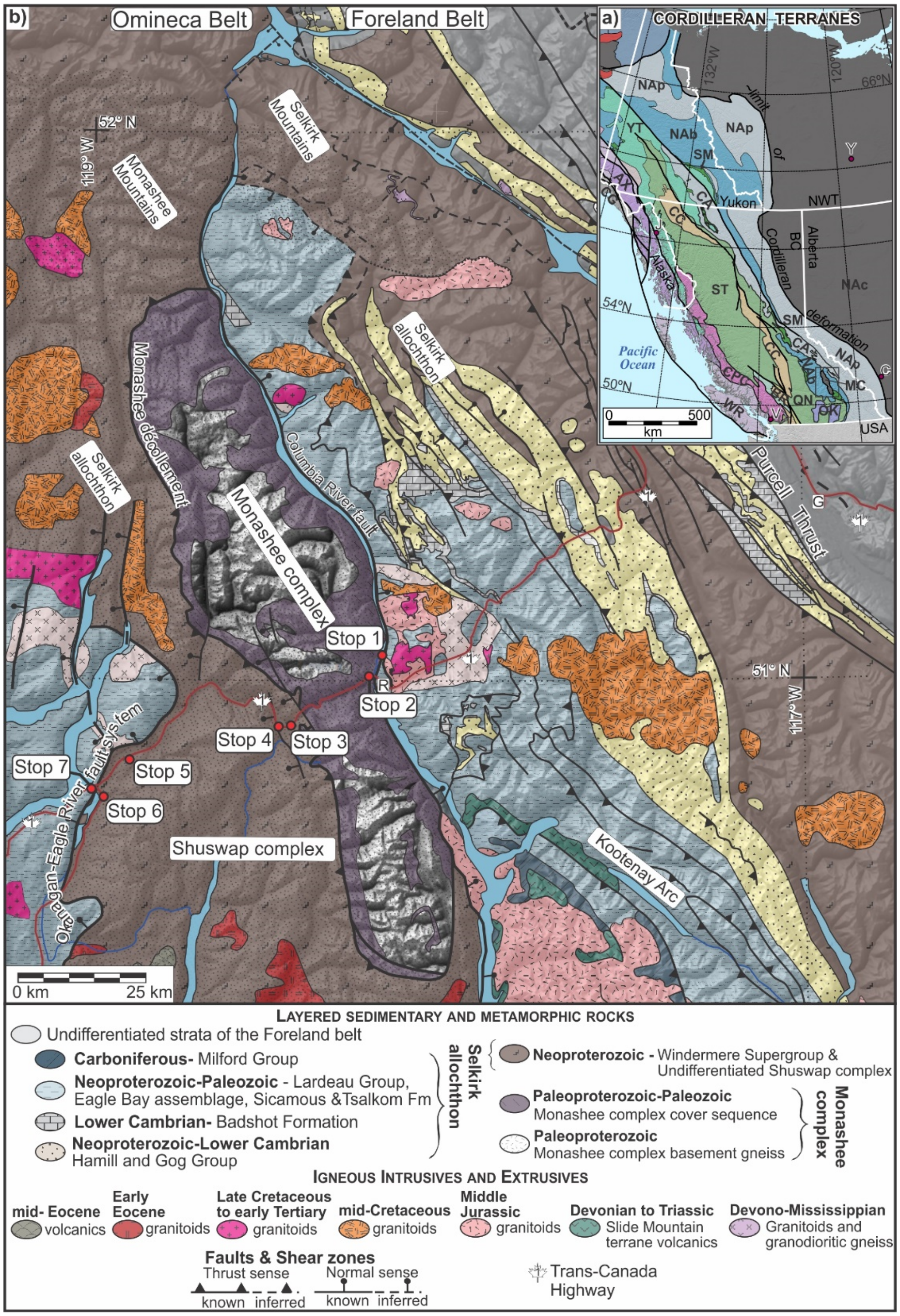
“Orogenic superstructure and infrastructure and its role in the Tectonic Evolution of the Southern Canadian Cordillera”



(a) Cordilleran terrane map after Colpron and Nelson (2011). Terranes: AX = Alexander; BR = Bridge river; CA = Cassiar; CC = Cache Creek; CG = Chugach; CPC = Coast plutonic complex; MC = Monashee complex; NAb = North American basinal; NAc = North American craton & cover; NAp = North American platform; OK = Okanagan; QN = Quesnellia; SM = Slide Mountain; ST = Stikinia; YT = Yukon-Tanana; WR = Wrangellia. (b) Tectonic assemblage map, SE Omineca belt (after Wheeler and McFeely, 1991 and Gibson et al., 2008), showing units of autochthonous Monashee complex (North American basement) and Selkirk allochthon. Stippled pattern in Shuswap and Monashee complexes show Sil-bearing rocks first used to delineate the extent of the Shuswap complex (Sil-bearing rocks in the Selkirk Mts were not included in the original delineation of the Shuswap complex). Towns: C = Calgary; G = Golden; J = Juneau; R = Revelstoke; V = Vancouver; Y = Yellowknife.

Canadian Tectonics Group - Field Trip Guide – 2017

Provided by H.D. Gibson, SFU

Summary of field trip:

The main theme of this CTG field trip will be focused on examining the metamorphic infrastructure of the southern Canadian Cordillera at the latitude of the Trans-Canada Highway. The term 'infrastructure' is applied here in a similar sense to that first suggested by De Sitter & Zwart (1960) and later by Culshaw et al. (2006) when describing mid- to lower-crustal levels in an orogen characterized by high-grade, shallowly dipping, ductily deformed and transposed rocks. Conversely, the overlying 'superstructure' is characterized by more upright, discrete brittle structures and relatively low-metamorphic grade. The field trip will follow a transect west to east across the width of the Shuswap metamorphic complex, focusing on the transition from lesser deformed, lower grade metamorphic rocks of the superstructure to higher grade, partially melted and penetratively deformed rocks of the infrastructure for the southern Canadian Cordillera.

The infrastructure that we will be examining represents the deeply exhumed upper amphibolite facies metasedimentary and plutonic rocks of the Shuswap and Monashee complexes (Figs. 1-3) (Brown and Read, 1983; Okulitch, 1984; Brown and Journeay, 1987; Parrish et al., 1988; Carr, 1991; Parrish, 1995). These rocks have been penetratively deformed by polyphase Mesozoic tectonism (e.g., Gibson et al., 2008; Gervais and Brown, 2011), such that most, if not all, primary structures have been obliterated by intense transposition of these features into the main shallow-dipping composite Cordilleran foliation. The Shuswap complex is located with in the southern Omineca Belt (Fig. 1), which is the metamorphic and plutonic hinterland to the Rocky Mountain Foreland Belt of the Canadian Cordillera that developed during the Mesozoic collision between accreted terranes and North America (Monger et al., 1982). The Shuswap metamorphic complex (including the Monashee complex) is the largest metamorphic core complex in North America (Coney, 1980), where high-grade crystalline rocks exhumed from mid-crustal levels in the Eocene (Parrish et al., 1988; Brown et al., 2012; Fig. 1) are exposed over an area of >40,000 km2. Major periods of tectonism and plutonism in the southern Omineca Belt occurred at 175-160, 100-90 and 75-60 Ma (see Parrish (1995), Brown and Gibson (2006) and Gervais and Brown (2011) for a compilation of age data). The ages of metamorphism and deformation are generally younger with increasing structural depth (Parrish, 1995; Crowley & Parrish, 1999; Gibson et al., 1999, 2008).

At the latitude of this field trip (~51°N) the infrastructure is bound on its eastern and western sides by crustal-scale Eocene extensional fault systems that have served to tectonically denude the infrastructure by dropping the superstructure down to the east and west, respectively (e.g., Parrish et al., 1988; Carr, 1991). The boundary between the infrastructure versus superstructure represented a significant rheological contrast during the Mesozoic evolution of the southern Canadian Cordillera. The following description of the Eocene extension is from Price and Monger (2003):

"The east-west crustal stretching that exhumed the Shuswap metamorphic core complex was oriented obliquely to, and superimposed discordantly on the crustal thickening and the fold and thrust structures that had been produced by the preceding northeast-southwest horizontal compression. It began in the Late Paleocene, at about 58 Ma (Carr, 1992). It may have been linked northwestward to right-lateral displacement on the Tintina-Northern Rocky Mountain Trench fault system, and southwestward to right-lateral displacement on the Yalakom-Ross Lake and Fraser River-Straight Creek fault systems (Price, 1979, 1994; Price and Carmichael, 1986)."

The cause of the Eocene extension has been attributed to a switch from dextral-transpressional convergence along the western margin of the Canadian Cordillera to one of dextral-transtension (Ewing, 1980; Engerbretson et al., 1984; Parrish et al., 1988). Others have also postulated that Eocene delamination of an unstable over-thickened lithospheric root may have also contributed to the extensional collapse of the southern Canadian Cordilleran orogen (e.g., Ranalli et al., 1989; Bardoux and Mareschal, 1994). Interestingly, Boa et al. (2014) attributed the uplift of an Eocene plateau within the Shuswap region to lithospheric delamination. Although Boa et al. (2014) present persuasive arguments to support Eocene lithospheric delamination based on seismic tomography and thermochronologic data, the preponderance of evidence for significant tectonic denudation via crustal extension and the rapid cooling of the Shuswap and Monashee complexes in the Eocene (Tempelman and Kluit, 1986; Bardoux, 1993; Parrish et al., 1988; Johnson and Brown, 1996; Vanderhaeghe et al., 1999; Lorencak et al., 2001; Price and Monger, 2003; Teyssier et al., 2005; Johnson, 2006; Gibson et al., 2008; Rey et al., 2009; Brown et al., 2012), suggests the delamination resulted not in the establishment of an Eocene plateau, rather it led to the extensional collapse of the Cretaceous – early Paleogene plateau.

Time will be spent at each stop examining the geological features (e.g., structural, petrological, geochronological, lithological) that characterize the infrastructure and superstructure. We will discuss their implications for the tectono-metamorphic evolution of this part of the Canadian Cordilleran orogen, and more broadly, the insight that can be gained with regard to understanding orogenic processes operating at different crustal levels, and at different times, within an evolving orogenic system.

Road Log:

On Saturday, October 14^{th}, we will begin the field trip by driving north from Kelowna to Sicamous on HWY 97A. During the drive northward to Sicamous, we will be largely paralleling the NNE-SSW trace of the Eocene Okanagan-Eagle River extensional fault system (OVF; OV in Fig. 1; Tempelman-Kluit and Parkinson, 1986; Parrish et al., 1988, Johnson and Brown, 1996; Johnson, 2006; Brown et al., 2012). More regionally, the OVF is interpreted to represent the southern and central parts of a 450-km-long, en echelon fault system (Johnson and Brown, 1996), which delineates the western margin of the Shuswap metamorphic complex (Leech et al., 1963, p. 26; Wheeler, 1965; Okulitch, 1984). The highway weaves back and forth between the penetratively deformed (often mylonitic), upper amphibolite facies rocks of the footwall domain (a.k.a. lower plate domain) and the low grade, weakly to moderately deformed rocks of the hanging wall (a.k.a. upper plate domain) of the OVF. The estimated amount of west-directed extension accommodated on this fault system varies from south to north, which may either reflect a true variation in the amount of extension along its strike, and/or it reflects the difficulty of accurately assessing the net slip without easily identifiable piercing points. At the latitude of Penticton, Tempelman-Kluit and Parkinson (1986) estimated ~90 km of horizontal displacement. At Vernon, Glombick et al. (2006) estimate only 0-12 km of horizontal extension, whereas farther to the north at the latitude of Sicamous, Johnson and Brown (1996) estimate ~30 km of displacement based on palinspastic restoration of the extension. Another complication to consider is the across-strike distribution of tectonic superstructure (hanging wall) that crosses nearly the entire width of the Shuswap metamorphic complex, such as at the latitude of Vernon, which was a line of evidence used by Glombick et al. (2006) to explain their very modest estimate of horizontal extension. However, Brown et al. (2016) contend that this is explained by east-west trending corrugations of the Okanagan Valley shear zone detachment. Geological

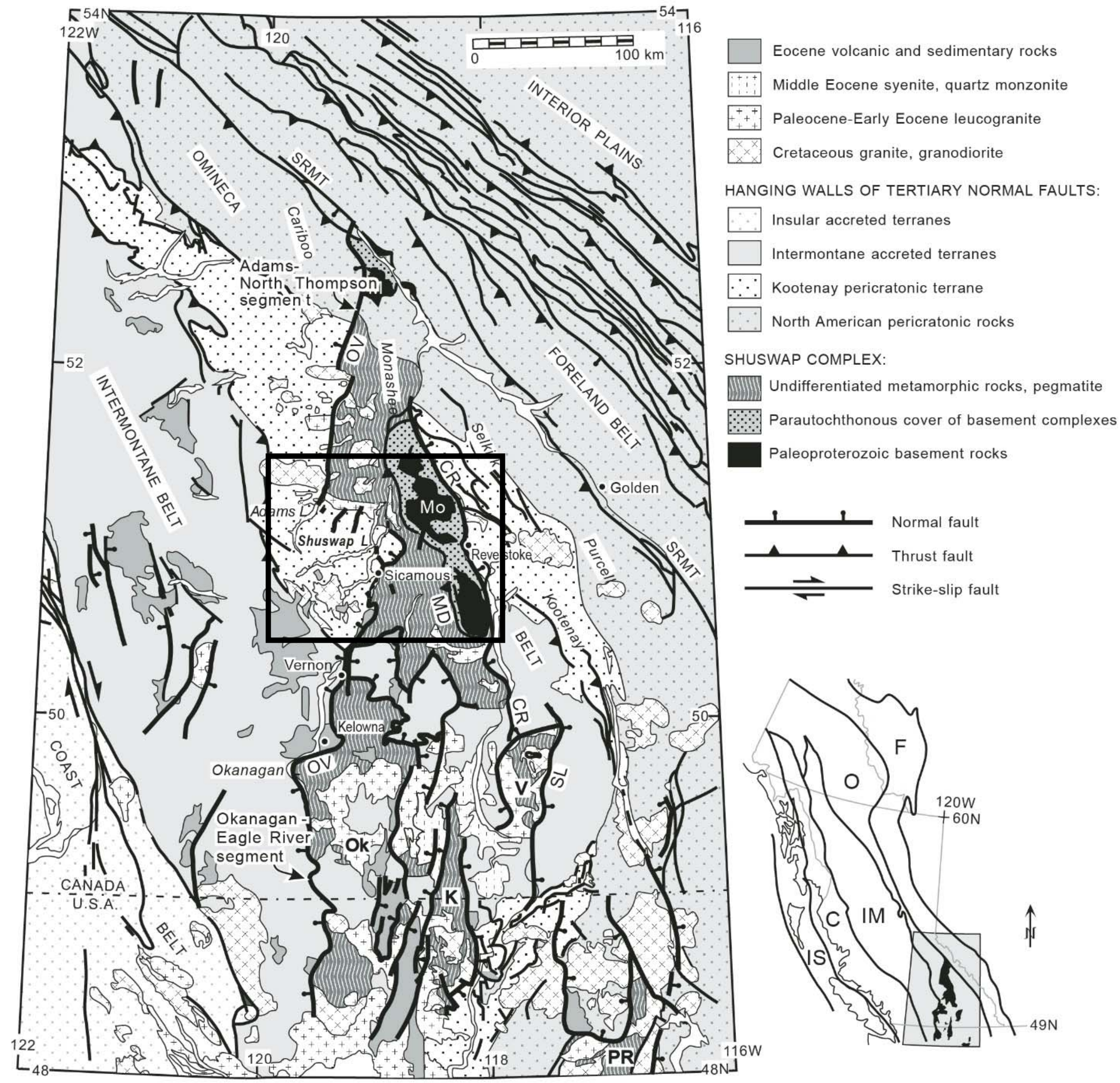


Figure 1. Tectonic assemblage map of the southeastern Canadian Cordillera, modified from Wheeler and McFeely (1991). The Shuswap metamorphic core complex is mostly bounded by Eocene normal faults, including the Okanagan Valley (OV), Columbia River (CR), and Slocan Lake–Champion Lake (SL) fault systems. Okanagan–Eagle River and Adams–North Thompson segments of OV step en echelon across the Shuswap Lake transfer zone northwest of Shuswap Lake. The Southern Rocky Mountain Trench (SRMT) is a morphogeological lineament that marks the boundary between the Omineca and Foreland belts in the region. For simplicity, Jurassic and Paleozoic granitoid plutons in the Omineca and Intermontane belts, and Cretaceous and Neogene volcanic rocks in the Intermontane belt are not shown. K—Kettle–Grand Forks dome, M—Malton gneiss, Mo—Monashee culmination, MD—Monashee décollement, Ok—Okanagan dome, PR—Priest River complex, V—Valhalla dome. Inset map shows the Shuswap complex (black) and morphogeological belts of the Canadian Cordillera (IS—Insular, C—Coast, IM—Intermontane, O—Omineca, F—Foreland). Figure modified from Johnson (2006). The box inset shows location of Figure 2.

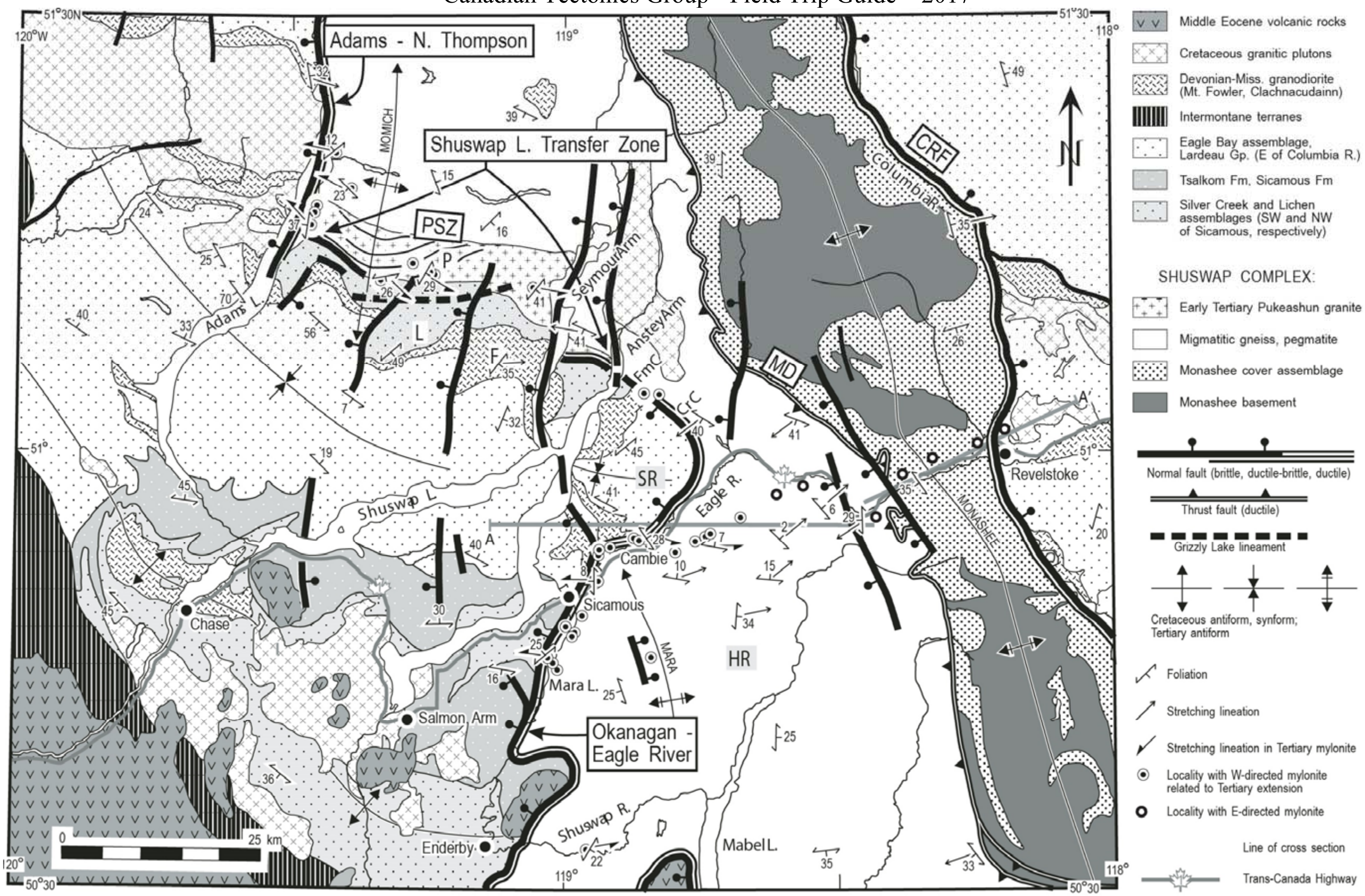


Figure 2. Geological map of the Shuswap Lake area (Modified from Johnson, 2006). The Shuswap Lake transfer zone is the left stepover between the Okanagan–Eagle River and Adams–North Thompson segments of the Okanagan Valley fault system. CrC—Craigellachie Creek, CRF—Columbia River fault, F—Mount Fowler, FmC—Four Mile Creek, HR—Hunters Range, L—Lichen Mountain, MD—Monashee décollement, P—Pukeashun Mountain, PSZ—Pukeashun shear zone (in the Pukeashun granite), SR—Shuswap Range. Sources of data are given in Johnson (2006), Johnson and Brown (1996, their Fig. 4). Additional data are from Wheeler (1965), Journeay (1986), Logan et al. (1996).

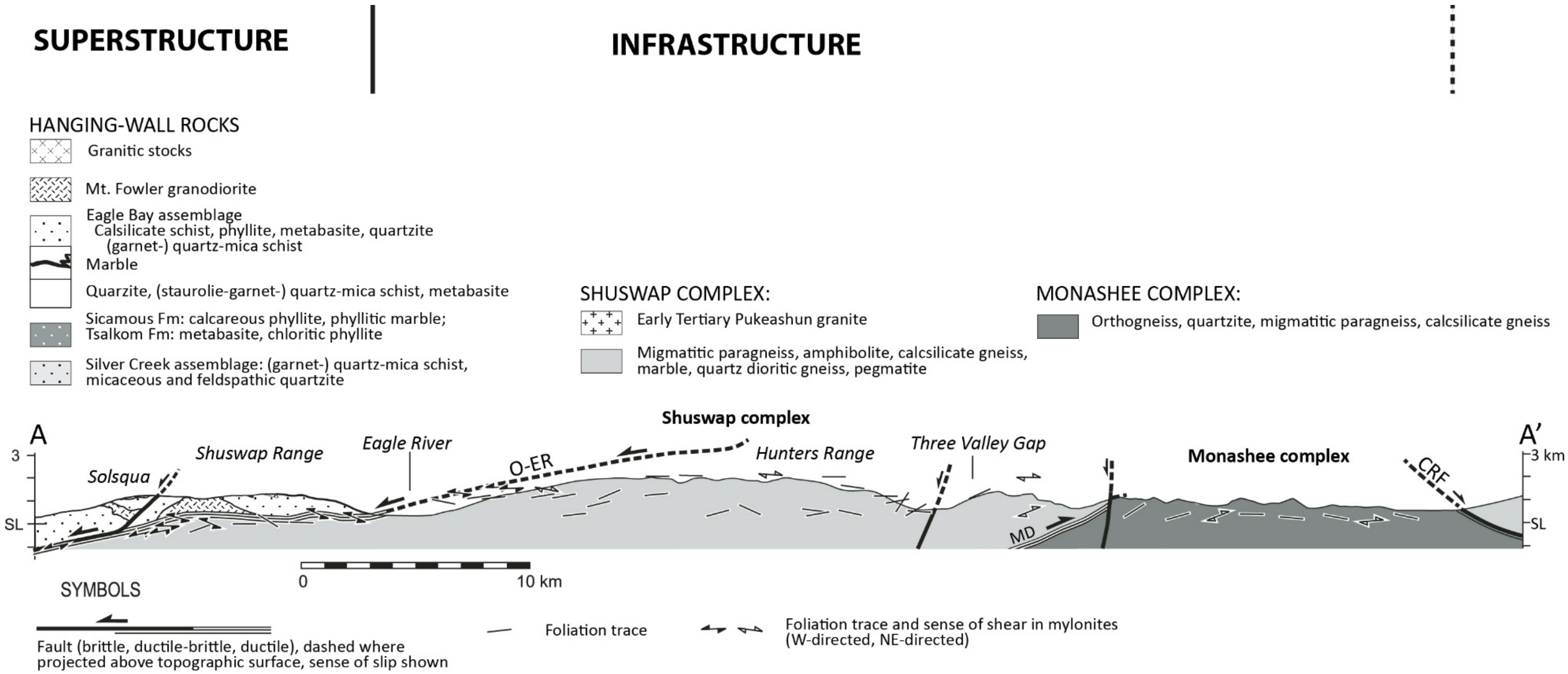


Figure 3. (A–A') Cross section adjacent to the Eagle River and Trans-Canada Highway (modified after Johnson, 2006). The Okanagan–Eagle River fault (O-ER) has juxtaposed low-grade metamorphic rocks of the Eagle Bay assemblage within its hanging wall (Superstructure) with migmatites of the Shuswap complex within its footwall (Infrastructure). W-directed mylonites lie within the upper 1-2 km of the footwall of the shear zone, whereas NE-directed mylonites related to thrusting occur at deeper levels, especially near the Monashee décollement (MD). CRF - Columbia River fault; zSL—sea level.

mapping along the southern Okanagan Valley shear zone has identified 100-m-scale to kilometer-scale corrugations parallel to the extension direction, where synformal troughs hosting upper-plate units are juxtaposed between antiformal ridges of crystalline lower-plate rocks. Analysis of available structural data and published geological maps of the Okanagan Valley shear zone confirms the presence of ≤40-km-wavelength corrugations, which strongly influence the surface trace of the detachment system, forming spatially extensive salients and reentrants.

At Sicamous we will continue eastward to Revelstoke on HWY 1, driving through the upper amphibolite facies rocks (e.g., Sil-Grt-Bt-melt) of the Shuswap and Monashee complexes that provide beautiful exposure of the deeply exhumed infrastructure of the southern Canadian Cordillera. The timing of the peak of metamorphism in this region varies from mid-Cretaceous to early Paleogene (ca. 70 to 50 Ma; Parrish, 1995; Crowley & Parrish, 1999; Gibson et al., 1999; Hinchey et al., 2006; Gervais and Brown, 2011), depending on the structural level you are considering, in that it gets younger with increasing depth. However, the Ar-Ar cooling ages throughout this part of the Shuswap and Monashee complexes are consistently latest Paleocene to Eocene in age, which is in marked contrast to the Jurassic to Early Cretaceous cooling ages in the immediate superstructure (Bardoux, 1993; Johnson and Brown, 1996; Brown and Gibson, 2006 and references therein). The average peak pressures calculated for this part of the Shuswap complex are between 7-11 kbar (e.g., Journeay, 1986; Ghent et al., 1983; Scammell, 1993; Nyman et al., 1995; Spear and Parrish, 1996; Norlander et al., 2002; Gervais and Brown, 2011), which when considering the present Moho is ~35 km depth, this provides an estimate of the average crustal thickness during the peak of Cordilleran crustal thickening in the mid- to Late Cretaceous to early Paleogene time was ~50-70 km (Brown et al., 1986; Bardoux and Mareschal, 1994; Whitney et al., 2004; Gibson et al., 2008), broadly on the same order of thickness presently observed in the Altiplano-Puna plateau in the South American Cordillera and the Tibetan plateau in the Himalaya.

Just north of Revelstoke, at our first stop, we will examine the Columbia River fault zone which bounds the eastern margin of the Monashee complex (basement complex of North American crystalline basement and cover sequence rocks within Shuswap complex). The CRF is an Eocene extensional fault that dips moderately to the east and has up 15 km of east-directed displacement. We will also look at the Revelstoke dam which is built directly on top of the Columbia River fault zone. Back in the early 1970's when this dam was being constructed, the engineers did not recognize the existence of the CRF. Once they were informed of its existence consulting geologists (Richard Brown, Peter Read, John Psutka, Larry Lane), they had to take drastic and very expensive mitigation measures. Farther up the Columbia River, perched over the reservoir to the dam, there are at least two massive (over a billion metres cubed) slides that are on dip slopes inclined directly into the reservoir. These slides have had movement on them since the end of the last glaciation as the glacial deposits are overtopped and offset by the slides. These added to the very expensive mitigation measures that had to be taken to facilitate the building of the Revelstoke Dam and its reservoir within the Columbia River valley. After Stop 1 we will pass back through Revelstoke and head west on HWY 1 making 4 stops between Revelstoke and Sicamous looking at high grade, partially melted and penetratively deformed rocks within the Monashee and Shuswap complexes. Along this part of the transect through the infrastructure we will also look at how shear sense indicators go through a reversal from being tops-to-the-east within the east and central portion of the Shuswap complex to tops-to-the-west in the west flank of the complex proximal to the Okanagan Valley fault system. This reversal in shear sense was one of the reasons some of us (Brown and Gibson, 2006; Gervais and Brown, 2011) have proposed that this part of the Shuswap complex may have undergone "Channel Flow", or at least incipient channel flow.

Descriptions of field trip stop locations

Once reaching the city of Revelstoke, after crossing the Columbia River, we will turn left (north) onto HWY 23 and continue north for ~5 km. We will park on the right on a broad part of the shoulder of the road beside the east abutment of the Revelstoke Dam.

Stop 1 - Hanging wall of the Columbia River fault

[utm: 416556 E; 5655855 N]

At this location adjacent to the eastern abutment of the Revelstoke Dam are garnetiferous amphibolite boudins in sillimanite-bearing pelitic and semi-pelitic metasediments, cut by abundant veins and dikes of pegmatite. This unit is underlain just below the dam crest by highly sheared cover gneisses of the Monashee complex. Interpretation of this east-dipping tectonic boundary representing the expose upper portion of the Monashee decollement (MD) that is arched over the Monashee complex is based on the presumed correlation of the structurally overlying amphibolite-bearing unit with the Semipelite-Amphibolite unit (SPA) of the Windermere Supergroup. Superimposed on this early shear zone is a 400 m thick ductile-brittle zone that was developed during extensional deformation associated with the north striking, moderately east-dipping Eocene Columbia River normal fault (CRF). Differentiating the east-dipping ductile fabrics related to the CRF from those developed along the MD is nearly impossible, where lower metamorphic grade fabrics and brittle overprint related to shear on the CRF can be observed. The brittle deformation related to the CRF include intense fracturing, clay gouge generation, and hydrothermal alteration. Within the CRF fault zone, lamprophyre dykes have been observed that cut all ductile fabrics but are disrupted by brittle shears. The lamprophyres here are not dated, but they occur regionally and provide Eocene cooling ages. The southern continuation of the CRF has been dated as Early Eocene (Parrish et al., 1988), and this age includes the formation of mylonitic fabrics in its footwall. Estimates of displacement on the CRF range from 1 to 30 km. At this latitude, it is estimated to be ~15 km (Johnson and Brown, 1996). Approximately 100 km to the north near Birch Creek, displacement on the CRF is effectively 0, as stratigraphy can be mapped uninterrupted across the valley.

Interesting historical information related to the Revelstoke Dam:

The dam is operated by BC Hydro. Construction of the Revelstoke Dam began in 1978. The powerhouse was completed in 1984 and has an installed capacity of 2480 MW. Four generating units were installed initially, with one additional unit (#5) having come online in 2011. The reservoir behind the dam is named Lake Revelstoke. Construction of the Revelstoke Dam was not without controversy, both environmentally and geologically.

Environmentally, at the time of construction in the 1970's and 80's, people were becoming acutely aware of the significant environmental impact that hydro-electric dams and their reservoirs have on river ecosystems and the surrounding environments. However, hydro-electric power generation was (and still is) considered to be a relatively "clean", renewable resource. Thus, taken on balance, the environmental (and economic - jobs, selling electricity) benefits of the Revelstoke Dam outweighed the local environmental cost, at least according to the promotional videos produced by BC Hydro.

Prior to the completion of the dam, Highway 23 was re-routed to avoid the new water levels along the 128 km reservoir that would extend north to the Mica Dam. As well as construction, logging of the new reservoir was also a major undertaking, as all available merchantable timber was removed. The powerhouse was completed in 1984 and has an installed capacity of 2480 MW. Four generating units were installed initially, with one additional unit (#5) having come online in 2011. The reservoir behind the dam is named Lake Revelstoke. The dam is operated by BC Hydro.

Geologically, the dam had its share of controversy. Richard Brown and Peter Read, and two of Brown's graduate students, Larry Lane (PhD) and John Psutka (MSc), were tasked with mapping the newly deforested Columbia River valley that would soon become the reservoir of the dam. Brown et al. soon realized that the Columbia River Valley represented a tectonic lineament that followed the trace of a rather large, moderately east-dipping Eocene normal fault that they termed the Columbia River fault (CRF). The CRF has both a ductile and brittle component; the site of the Revelstoke dam sits directly on top of the disrupted wall rocks of the CRF. The original plan for the dam was to butress it on either side of the valley using the wall rocks. However, when made aware of this problematic situation and the possible instability of the wall rocks, the dam engineers decided to drill down through the fault to identify the depth of footwall rocks unaffected by the CRF. Then they blasted a large hole to that depth, filled it with cement and used that as a keystone block on which the dam is currently anchored. No doubt that constituted a significant extra cost. Furthermore, in their mapping Brown et al. also identified a huge rockslide (>1 billion cubic metres) composed of Monashee complex cover gneiss precariously perched on a dip slope underlain by biotite schist immediately above the west side of the reservoir ~54 km north up the valley; they termed it the Downie Slide. The Downie Slide shows evidence of post-glacial movement where it is seen to overtop glacial sediments from the last glaciation. Predictably, the dam engineers were quite concerned, as the Vajont dam disaster of 1963 was still fresh in their minds. This involved a massive landslide (~260 million cubic metres; still almost an order of magnitude less than the size of the Downie Slide) into the dam reservoir, which caused 50 million cubic metres of water to overtop the dam in a wave 250 metres high, leading to the complete destruction of several villages and towns, and 1,910 deaths. To mitigate potential failure of Downie Slide, multiple pumping stations have been set up within it to ensure water pressure within the slide remains relatively low.

Drive south back to Revelstoke, and turn west on HWY 1. Continue west for a short distance (~1.4 km), cross the Columbia River and take the first right after the bridge on the side road (Westside Road) for access to Boulder Mountain and Frisby Ridge. Stop 2 is at the first outcrop about 600 m up the road. Pull off on the right.

Stop 2 - Monashee cover gneiss

[utm: 413514 E; 565085 N]

The rocks here consist of Dp-Grt-Bt-Hbl-calcsilicate gneiss with sheared quartz veins that provide a consistent top-to-the-northeast sense of shear. Note that the foliation dips moderately (~35°) to the east, whereas at the stops to the west you will see the foliation dips moderately to the west. This indicates that between Victor Lake (west side of Monashee complex) and here near the east side of the complex, the foliation direction goes through a reversal which is interpreted to be due to doming of the Monashee complex following the formation of the syn-peak (?) metamorphic penetrative foliation which maybe as young as 52-49 Ma (Crowley et al., 2001) for the deepest levels of the complex.

The following is a description of the Monashee Complex provided by Price and Monger (2003): "The Monashee Complex consists of two parts (Figs. 1-4). (1) A "basement assemblage" ("core gneisses") comprises Paleoproterozoic paragneiss, granitoid orthogneiss, and leucogranite. (2) An unconformably overlying "cover assemblage" ("cover gneisses") consists of quartzite, marble, pelitic and semipelitic schist, and amphibolite, and contains deformed 740 Ma syenite, 540 Ma amphibolite, 360 Ma carbonatite, and undeformed Late Paleocene (55– 7 Ma) pegmatite. The "basement assemblage" contains granitic rocks that crystallized at 2077 ± 4 Ma and 1862 ± 1 Ma, and tectonite fabrics that developed before 1848 ± 3 Ma. It has been correlated (Crowley, 1999) with Paleoproterozoic basement rocks under the Western Canada Sedimentary Basin in central Alberta.

The lower part of the "cover assemblage" contains 1.99 Ga detrital zircons and is intruded by 1852 ± 4 Ma pegmatite, 1762 ± 6 Ma leucogranite, and 724 ± 5 Ma syenitic gneiss; the upper part contains detrital zircons dated at ~1.21 Ga (Crowley, 1997). Combining these ages with the probable Paleozoic depositional ages for the middle and upper parts of the "cover assemblage" (Fig. 2-15) constrains the thickness of Mesoproterozoic and/or Neoproterozoic in this succession to <0.2 km, which is considerably less than that of coeval rocks in the hanging wall of the Monashee décollement. This suggests that the deposition above and below the décollement occurred in different parts of the miogeocline (Crowley, 1997). The Monashee décollement separates the Monashee Complex from overlying highly sheared metasedimentary rocks and amphibolites. The Trans-Canada Highway transect of the Monashee Complex is situated in a structural depression between areas of extensive exposure of Paleoproterozoic basement rocks that lie to the north, in the Frenchman Cap culmination, and to the south, in the Thor-Odin culmination, therefore, only the cover assemblage is exposed close to the highway. The Monashee décollement is not exposed along the highway, because it has been down-dropped to the west along a relatively minor west-dipping normal fault (Victor Lake fault) that crosses the highway just west of this locality"

Return to HWY 1 and continue west for ~16.4 km. During most of this part of the drive we will be passing through somewhat monotonous semi-pelites and calc-silicates of the Monashee Complex cover sequence. As mentioned above, you will notice that as we drive westward the moderate-dipping foliations start to shallow and then about half along they begin to dip westward. This is attributed to doming of the Monashee Complex with a ~north-south axis due to lithospheric isostatic rebound related to extensional collapse in the Eocene (Price and Monger, 2003). Just before reaching Three Valley Lake, we will pass Victor Lake on our left (south), which marks the location of a high angle, west-dipping normal fault (Victor Lake fault) that has dropped the Monashee décollement down to the west. Thus, at the latitude of the highway we cannot see the Monashee décollement due to this normal fault. However, the rock types, the metamorphic mineral assemblages, and the tectonic fabrics related to the Monashee décollement can be viewed in the roadcuts on the north side of the highway. The rocks above the Monashee décollement contain sillimanite and K-feldspar; but kyanite has been collected at this locality. Most kinematic indicators record a top-to-the-northeast sense of shear. As we pass Victor Lake, we are now entering into the deepest levels of the Selkirk allochthon which is within the immediate hanging wall of the Monashee décollement.

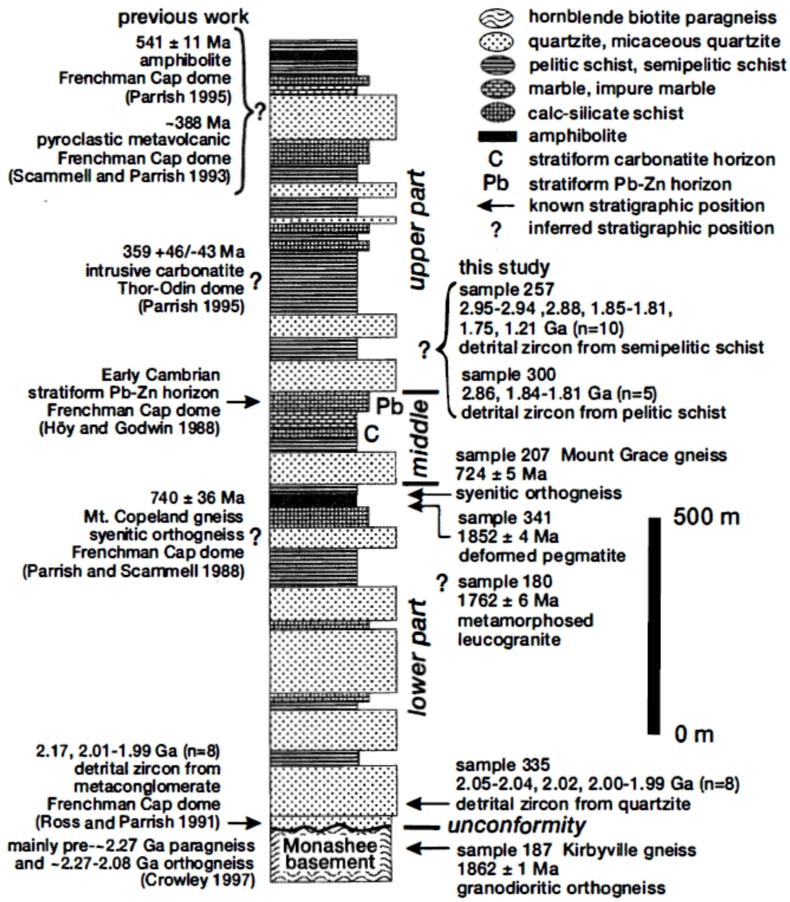


Figure 4. Schematic stratigraphic column from the Ratchford Creek area of northern Frenchman Cap dome, modified after Journeay (1986), showing the position of geochronologic samples from previous work and Crowley (1997). Figure from Crowley (1997).

About 2 km before Three Valley Lake we will pull off the highway on the right (north side) where there is an entrance to a small side road. We will make our way over to the outcrops on the north side of HWY 1 beneath the power lines.

Stop 3 - Migmatitic Sil-Grt-Bt paragneiss of the Three Valley assemblage within the Selkirk Allochthon

[utm: 399814 E; 5644415 N]

Beautiful migmatitic Sil-Grt-Bt paragneiss (lots of coarse sillimanite) of the Three Valley assemblage near the base of the Selkirk allochthon (Johnson, 1994). There are a number of very nice shear sense indicators that give tops-to-the-east sense of shear that include mantled Grt porphyroclasts (Fig. 5), extensional shear bands, sheared veins, C-S and C'-S fabrics. Note that the sense of shear here is congruent with that observed within the Monashee Complex.

Figure 5. Beautiful mantled Grt porphyroclast that gives a tops-to-the northeast sense of shear, situated within a matrix of Sil-Bt + melt.

Return to bus and continue west on HWY 1 for ~1.8 km. Pull into the Three Valley Gap Motel and Restaurant. Park in the motel parking area and walk west along north side of HWY 1 to examine the long roadcut on the south side of the highway.

Stop 4 –Three Valley assemblage and mega-boudins within the Selkirk Allochthon

[utm: 398166 E; 5643270 N]

At this stop we will be examining outcrops of the Three Valley assemblage (Johnson, 1994) The following is a description provided by Price and Monger (2003):
"Boudins up to 13 m long of amphibolite in semi pelitic garnet-sillimanite-biotite-K-feldsparquartz 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 more 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.

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 4°ArrAr age spectra from the amphibolites have patterns suggestive of excess 4°Ar and possible episodic reheating, with probable final closure ages (corresponding to temperatures of about 500°C) of about 55-60 Ma (Johnson, 1993).

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."

We will continue driving west for ~50 km. Of note, as we head west past Three Valley Lake, we cross a brittle, high-angle, west-dipping normal fault. In its hanging wall, and for the rest of the drive to Stops 5 and we will be passing through the Hunters Range assemblage (Johnson and Brown, 1996), which is interpreted to be stratigraphically on top of the Three Valley assemblage, and is thought to be correlative with the Windermere Supergroup to the north within the northern Monashee Mountains. It is also important to note that as we drive west we will be going through a reversal in shear sense from tops-to-the-east to tops-to-the west just before we pass the village of Malakwa. The following is a description of this reversal provided by Price and Monger (2003):

"Two mylonitic fabrics with opposing sense of shear occur in the panel of the high-grade metamorphic rocks between the Monashee décollement and the Okanagan-Eagle River extensional detachment fault (Johnson and Brown, 1996). In the Three Valley assemblage and the lower part of the Hunters Range assemblage, northeast-verging shear is associated with an annealed mylonitic foliation with a lineation that trends 065°; in the upper part of the Hunters Range assemblage, close to the Okanagan-Eagle River fault, mylonitic paragneisses that consistently indicate west-verging shear are associated with a strong stretching lineation defined by sillimanite and quartz-feldspar aggregates that trend 275°."

Approximately 15.5 km west of Malakwa we will pull over on the right (north) side of HWY 1 just before the turn off for a laneway for a local farm and carefully make our way to the south side of the highway to look at a long roadcut for Stop 5.

Stop 5 - mylonitic footwall to OVF (infrastructure)

[utm: 363391m E; 5635701m N]

These high-grade metamorphic rocks of the Hunters Range assemblage are within the footwall domain of the Okanagan-Eagle River extensional detachment fault, and provide abundant tops-to-the-west shear sense indicators related to the OVF.

The following description is from Brown et al. (1993; Stop 1-6):

"The rocks include paragneiss, migmatitic garnet-sillimanite- biotite schist, some biotite-hornblende schist 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 fabrics, asymmetrical extensional shear bands, and feldspar porphyroclast systems. The peak metamorphic mineral assemblage Grt-Sil-Bt-Pl-Kfs-Qtz is synkinematic with the 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 syn-extensional leucogranites to the northwest are Early Eocene or possibly older. Monazites from the pegmatite at this outcrop have given Late Cretaceous U-Pb dates."

Continue ~ west on HWY 1 into Sicamous and turn left (south) on HWY 97A. Drive ~2.5 km and turn left into the Bayview Estates; continue up switch back to the second bench where the roadcuts provide 3-D exposures of beautiful mylonitic footwall rocks of the OVF.

Stop 6 – Distributed shear zone within lower plate of OVF (Infrastructure)

[utm: 361206 E; 5631681 N]

Shallow, west dipping (~16°) mylonitized migmatitic Sil-Bt-Grt bearing paragneiss of the Hunters Range assemblage with dismembered leucosome stringers and pegmatite dikes and veins (Fig. 6) are here situated within the immediate footwall of the Okanagan Valley shear zone (OVF). The lineation defined by the alignment of sillimanite plunges ~13° toward 278°. Beautiful shear sense indicators consisting of winged porphyroclasts (sigma and delta type; fig. 6b), C-S, C'-S and asymmetric boudins within the mylonite give a consistent tops-to-the-west sense of shear. There are a few fine-grained, pyrite-bearing intermediate dikes that strike ~north-south, which may have been feeder dikes to the Eocene Kamloops Groups volcanics.

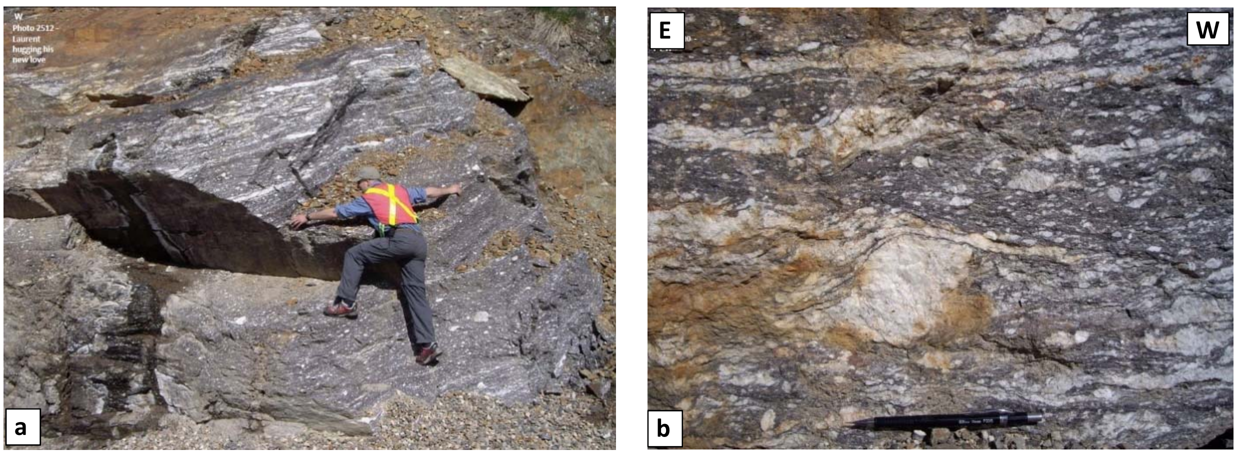


Figure 6. a) Photo shows outcropping of mylonitic Sil-Bt-Grt paragneiss with intensely sheared and dismembered pegmatite at Stop 5 within the distributed shear zone of the Okanagan Valley-Eagle River fault system. Laurent Godin (a notorious rock-hugger) for scale. b) Photo shows a beautiful mantled porphyroclast of dismembered pegmatite that provides one of many tops-to-west shear sense.

Continue west on HWY 1 for ~3.4 km. Drive to west out of Sicamous on Highway 1 and cross the bridge over a narrow arm of Shuswap Lake. Immediately after bridge, turn south (left) across traffic on Highway 1, on to the side road.

Stop 7 - OVF hanging wall (Superstructure)

[utm: Zone 11; 359546 E; 5633373 N]

The last stop of the field trip will be the only one within the hanging wall of the Okanagan Valley-Eagle River fault system (OVF), which is considered to be within the superstructure of this part of the southern Canadian Cordillera. The rocks are of relatively low metamorphic grade and are much less penetratively deformed than the rocks we have examined at the previous stops within the Shuswap and Monashee complex that are a part of the metamorphic infrastructure.

The following description is primarily from Price and Monger (2003; Stop 2-10):
"The rocks at this locality include outcroppings of dark calcareous phyllite with quartz segregations that are mapped as Sicamous Formation, although elsewhere the formation is mainly carbonate. The upper greenschist - lowest amphibolite facies rocks here are in marked contrast with the pegmatite-rich, sillimanite-bearing rocks south and east of Sicamous, which are visible across the Shuswap River from the southern end of the outcrop area. Lithological

correlations with both the Cambro-Ordovician Index Formation of the Lardeau Group and with the Triassic Slocan Formation in the Kootenay Arc have been suggested. The former is currently favoured, not least because the Sicamous has been extensively sampled for conodonts and none have been found. The presence of the limestone masses suggests relatively shallow water, which implies underlying thick crust."

There are also fine-grained, late cross-cutting, near-vertical intermediate dikes that generally strike north-south, and are presumably of the same generation as those observed at Stop 6.

That concludes the field trip. Hopefully, this has provided you with a nice opportunity to examine a portion of some of the most deeply exhumed orogenic infrastructure of the Canadian Cordillera and will spur on some interesting conversations during the rest of the meeting.

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