Metamorphism and Structure of the Southern Kootenay Arc and Purcell Anticlinorium, Southeastern British Columbia (Parts of NTS 082F/02, /03, /06, /07)

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Introduction

This paper provides a summary of preliminary metamorphic, structural and geochronological work within the region between Nelson, Salmo and Creston in southeastern British Columbia. The aim of this study is to elucidate the complex tectonothermal history of the area as a means of putting the mineral deposits in a geological context. The results presented in this report are based on two field seasons.

Regional Geology

The geologically complex region of southeastern BC between Nelson, Salmo, Creston and the Canada–United States border (Figure 1) straddles the tectonic interface between the pericratonic metasedimentary and volcanic rocks of Quesnellia (Unterschutz et al., 2002) to the west, and distal marginal rocks of the ancestral North American margin (Monger et al., 1982) to the east. This tectonic juxtaposition, and subsequent episodes of magmatism, metamorphism and deformation, occurred during Cordilleran orogenesis in a time interval spanning the Jurassic to Eocene.

The primary structural-tectonic domains in the area are the Purcell Anticlinorium, Kootenay Arc and northernmost extension of the Priest River Complex (Figure 1). The Purcell Anticlinorium is a broad, Mesozoic, northerly plunging fold with extensive exposures of rift-related sedimentary rocks of the Proterozoic Windermere and Purcell supergroups (Price, 2000). The Kootenay Arc lies to the west of the Purcell Anticlinorium and is characterized by an increase in metamorphic grade and complexity of deformation, and a decrease in stratigraphic age (Warren, 1997).

The Priest River Complex (PRC) is a metamorphic core complex situated in northern Idaho that extends northward into southern BC. During the Eocene, it was partly exhumed by two normal fault systems, the west-dipping eastern Newport fault and the east-dipping Purcell Trench fault (Doughty and Price, 1999). The PRC consists of Mesoproterozoic Belt-Purcell rocks metamorphosed to middle–upper amphibolite facies, Archean basement gneisses and deformed Cretaceous intrusions. The northernmost expression of the PRC is upper-amphibolite metasedimentary rocks in the footwall of the Purcell Trench fault at the latitude of Creston (Figures 1, 2; Brown et al., 1995). The deformation and metamorphism associated with the PRC appears to gradually die out to the north.

The study area is situated mainly within deformed and metamorphosed Neoproterozoic sedimentary rocks of the Windermere Supergroup (a thick sequence of sandstone and conglomerate, interbedded with pelitic and carbonate layers), which unconformably overlie rocks of the Purcell Supergroup to the east. Unconformably overlying the Windermere Supergroup in the western part of the area are early Paleozoic coarse clastic and carbonate rocks (Figure 2).

Cutting through the study area are two major Eocene normal faults: the Purcell Trench fault (PTF; Daly, 1912; Kirkham and Ellis, 1926; Anderson, 1930; Rehrig et al., 1987; Doughty and Price, 2000) and the Midge Creek fault (MCF; Figure 2; Moynihan and Pattison, in press). These faults juxtapose rocks of contrasting metamorphic grades and mica cooling ages, and are discussed in more detail below.

Intrusions

The above deformed and metamorphosed sedimentary rocks are host to numerous granitoid intrusions that range in age from Middle Jurassic to Eocene and are part of larger intrusive suites extending across southeastern BC (Ghosh, 1995). There are two distinct suites of igneous rocks in the study area: an older, Jurassic 'hornblende-biotite' suite, characterized by hornblende and accessory titanite, and a younger, Cretaceous 'two mica' suite that is characterized by muscovite, biotite and accessory allanite. In addition, there are several small, Eocene syenite stocks. The Mine, Wall and Porcupine Creek are Middle Jurassic stocks (Fig-

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ure 2, Table 1) that intruded the upper Proterozoic rocks of the Windermere Supergroup during regional deformation. Typically, they are medium- to coarse-grained granodiorite with rare megacrysts of potassium feldspar. These intrusions contain primary hornblende and biotite, and are therefore part of the 'hornblende-biotite' suite. Uranium-lead dates on zircon fractions from the Mine and Wall stocks yielded ages of 171 and 167 Ma, respectively (Archibald et

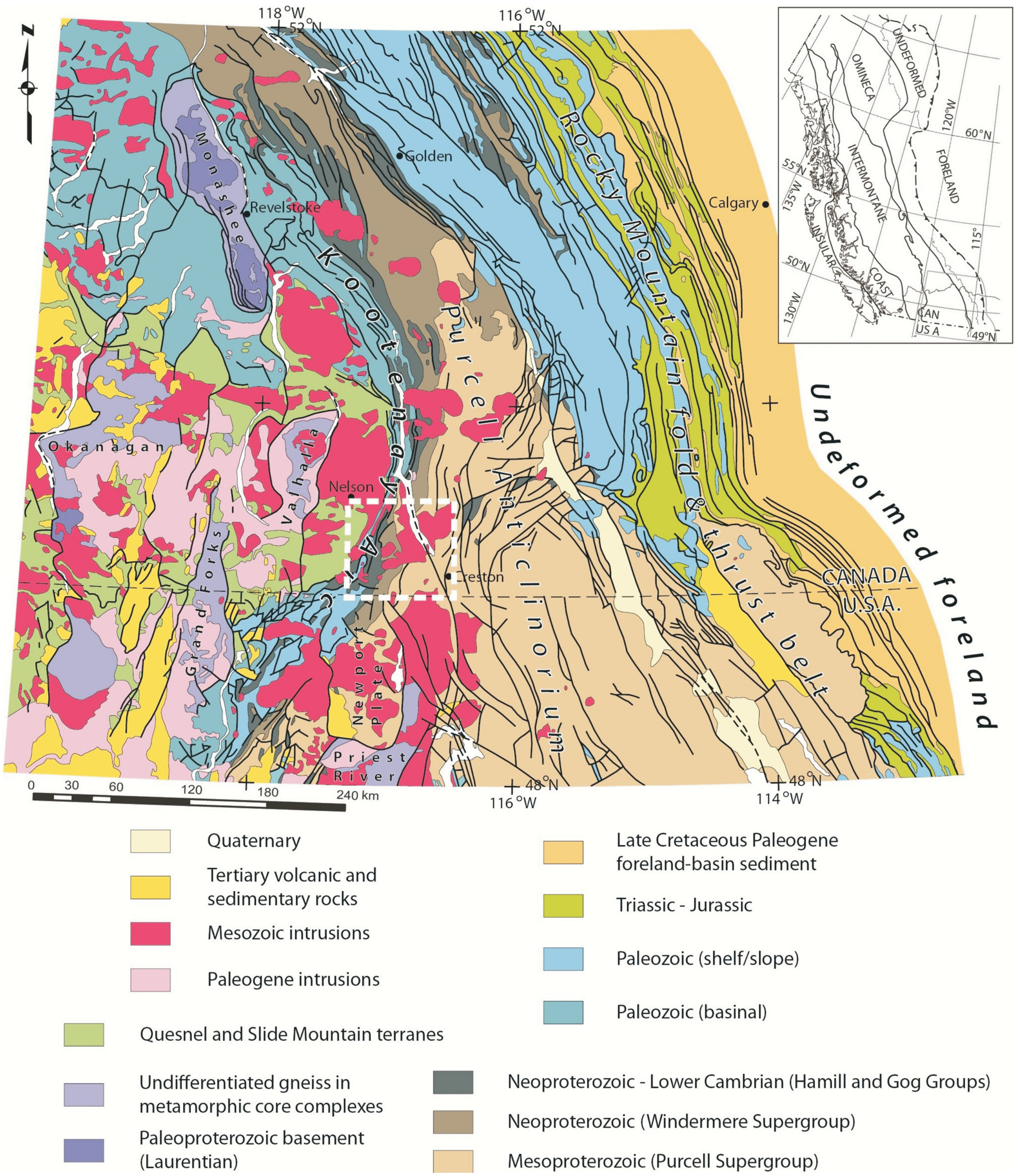

Figure 1. Regional geology of the southeastern Canadian Cordillera. Eocene core complexes are labelled on the map as Okanagan, Priest River, Grand Forks, Monashee and Valhalla. The study area is highlighted by the white dashed square. Map modified from Moynihan and Pattison (in press), originally after Wheeler and McFeely (1991).

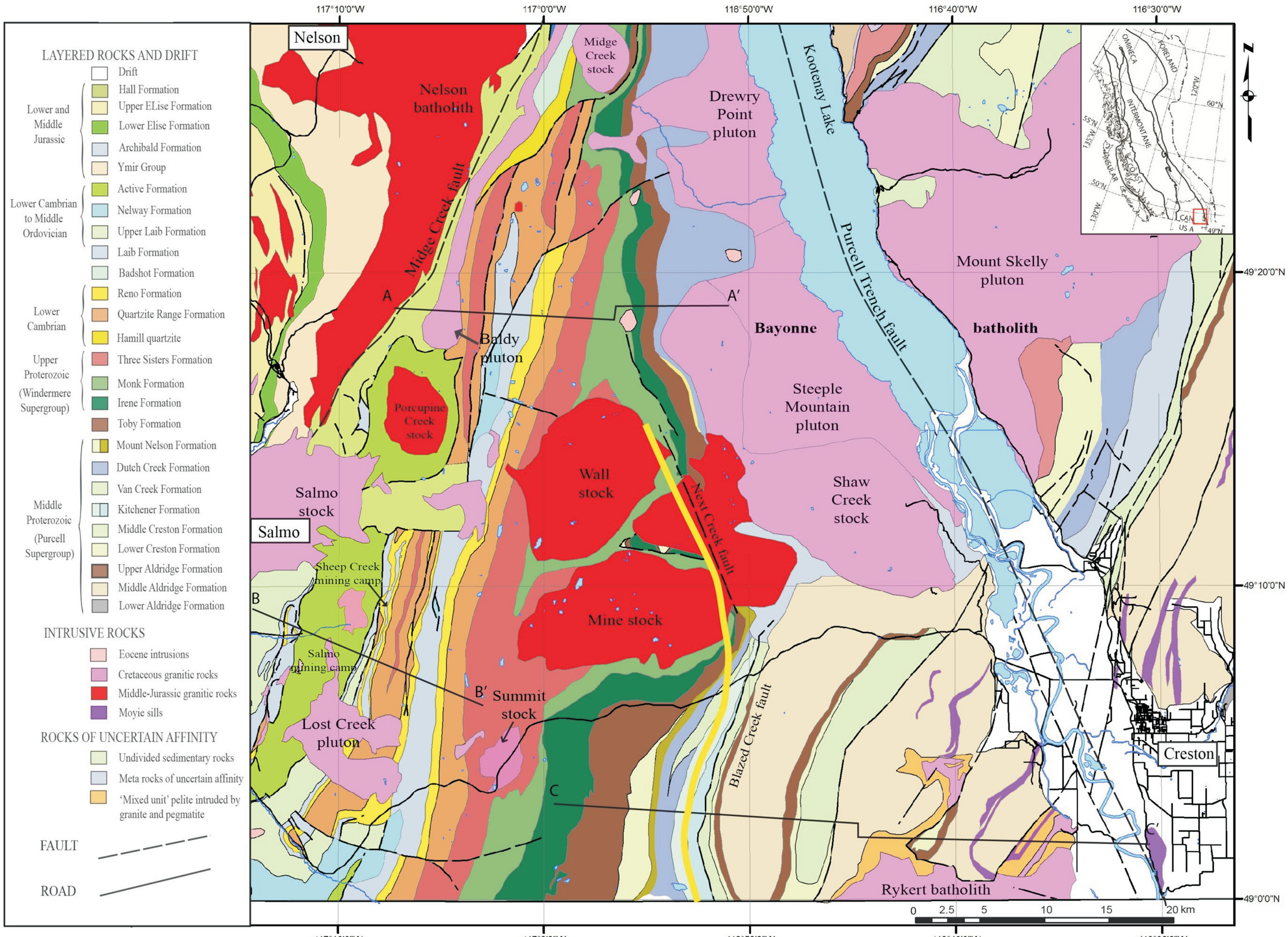

Figure 2. Regional geology of the study area, compiled from Reesor (1996), Höy and Dunne (1998), Glombick et al. (2010) and Paradis et al. (2009). The locations of the cross-sections in Figure 3 are shown. The eastern and western domains are separated by the thick yellow line. The rocks north of the Wall stock are within the northern domain. Inset modified after Wheeler and McFeely (1991).

Table 1. Summary of deformation, ages and dating methods of plutonic rocks in southeastern British Columbia.

Intrusion	Age		Dating method	Deformed	Domain	Reference
	Period	Ma				
Coryell	Eocene	52	K-Ar	No	Northern	Archibald et al., 1983
McGregor	Eocene	50	K-Ar	No	Northern	Archibald et al., 1983
Shaw Creek stock	Cretaceous	76	U-Pb	No	Eastern	Brown et al., 1999
Pegmatite, Highway 3	Cretaceous	83	U-Pb	Yes	Eastern	Brown et al., 1999
Emerald stock	Cretaceous	94	K-Ar	No	Western	Archibald et al., 1983
Rykert batholith	Cretaceous	94	U-Pb	Yes	Eastern	Brown et al., 1999
Steeple Mountain	Cretaceous	95	U-Pb	Partly	Eastern	Brown et al., 1999
Mount Skelly pluton	Cretaceous	99	K-Ar	No	Eastern	Archibald et al., 1983
Lost Creek pluton	Cretaceous	102	K-Ar	No	Western	Archibald et al., 1983
Summit stock	Cretaceous	102	K-Ar	No	Western	Archibald et al., 1983
Midge Creek stock	Cretaceous	111	U-Pb	Partly	Northern	Leclair et al., 1993
Baldy pluton	Cretaceous	117	U-Pb	Yes	Northern	Leclair et al., 1993
Corn Creek gneiss	Cretaceous	135	U-Pb	Yes	Eastern	Brown et al., 1999
West Creston gneiss	Cretaceous	135	U-Pb	Yes	Eastern	Brown et al., 1999
Porcupine Creek stock	Jurassic	157	K-Ar	?	Northern	Leech et al., 1963
Wall stock	Jurassic	167	U-Pb	Yes	Western	Archibald et al., 1983
Mine stock	Jurassic	171	U-Pb	Yes	Western	Archibald et al., 1983

al., 1983; Doughty et al., 1997). The Porcupine Creek stock has a 157 Ma K-Ar hornblende-cooling age. All three intrusions are therefore within the age range of the Nelson Suite (ca. 173–159 Ma; Ghosh, 1995; Table 1).

Cretaceous intrusions with ages of 117–73 Ma (Table 1) range in composition from diorite to granite and are typically leucocratic, medium to coarse grained and equigranular (Archibald et al., 1983). The Bayonne and Rykert batholiths are composite bodies with several phases of differing age and composition. The Bayonne batholith consists of the Mount Skelly pluton, the Shaw Creek stock and the Drewry Point and Steeple Mountain phases that range in age from 99 to 76 Ma. The Rykert batholith consists of the Search Lake, Shorty Peak, Klootch Mt., Ball Creek, Long Canyon and Hunt Creek intrusions, all of which are Cretaceous in age. The intrusive rocks in the study area are locally deformed depending on their spatial location and age (Table 1), as described in the next section. There are also two distinct suites of smaller Eocene intrusive rocks, the McGregor and the Coryell (Little, 1960). These are small, post-kinematic dikes and plugs of syenite and monzonite.

Structures

The structure of the rocks in the southern Kootenay Arc and western limb of the Purcell Anticlinorium is dominated by multiple folds from at least three periods of deformation, spanning the interval from mid-Mesozoic to Eocene (Fyles, 1964, 1967; Glover, 1978; Leclair, 1988; Brown et al., 1995). In general, there is an increase in structural complexity and intensity of deformation going from the southwestern corner of the study area to the east and north, corresponding to progressively deeper structural levels. An exception to this overall pattern is the abrupt change in the degree of deformation and metamorphism across the PTF and MCF. Due to the different episodes of deformation throughout the study area, the structural observations have been split into western, northern and eastern domains, with initially no attempt to correlate between domains. In the following sections, the subscripts $_{\text{'W'}}$, $_{\text{'N'}}$ and $_{\text{'E'}}$ will be used to refer to the western, northern and eastern domains, respectively. Relationships between structures in the different domains are discussed in a separate section.

Structural Observations—Western Domain

The earliest map-scale folds (F_{1W}: Phase 1 structures of MacDonald, 1970) in the western domain are the Laib syncline and Sheep Creek anticline, both of which are isoclines that plunge from north-northeast to south-southwest and are inclined to the west (F_{1W}; Figures 2, 3a, b). A well-developed subvertical cleavage (S_{1W}) is axial planar to the folds and is the dominant penetrative foliation (S_{1W}) in the western domain. Within semipelitic units, the cleavage (S_{1W}) is defined by chlorite, biotite and muscovite. At outcrop scale, F_{1W} folds are typically asymmetrical, upright, Z- and S-shaped isoclinal folds with an axial-planar foliation. These folds are best observed in carbonate layers of the Laib syncline and Sheep Creek anticline, as illustrated in Figure 4a. A shallowly plunging stretching lineation (L_{1W}) that parallels the fold axes is best observed in noncarbonate rocks, especially those rich in quartz and mica. A later crenulation is observed in more pelitic layers and is defined by a crinkling of the S_{1W} foliation. The fold axes of these small crenulations define a lineation (F_{2W}) that is subparallel to the trend and plunge of the F_{1W} fold axes.

Structural Observations—Northern Domain

The northern domain has a dominant, regional, north-northeast-striking structural trend that is the result of multiple periods of deformation. The deformed, metamorphosed sedimentary rocks in this domain are intruded by plutons of the Bayonne and Nelson suites (Figures 2, 3c), which helps

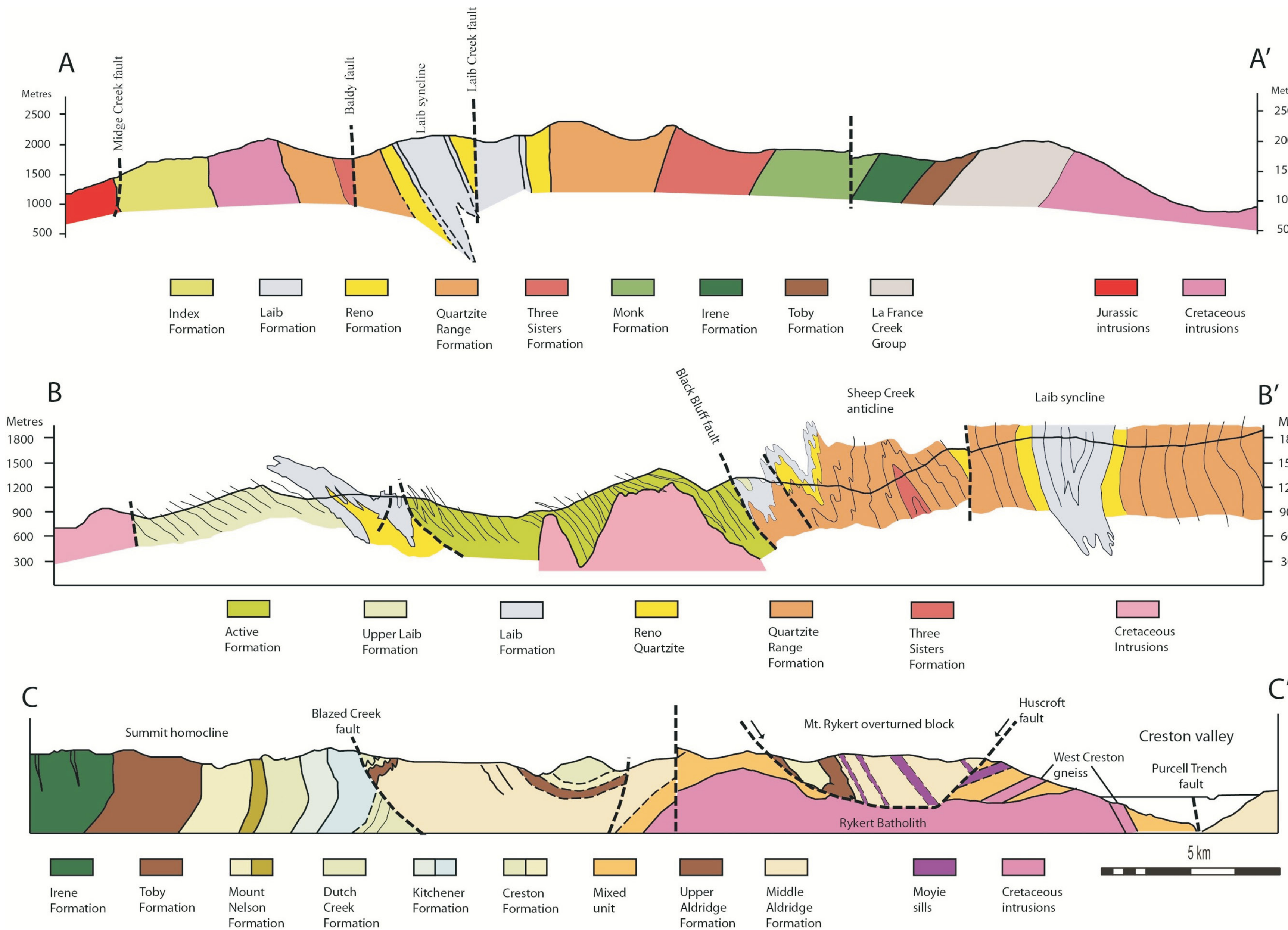

Figure 3. Vertical cross-sections from the study area. The lines of section are shown in Figure 2. Compiled from Leclair (1988 A-A'), Fyles and Hewlett (1959; B-B') and Brown et al. (1999; C-C').

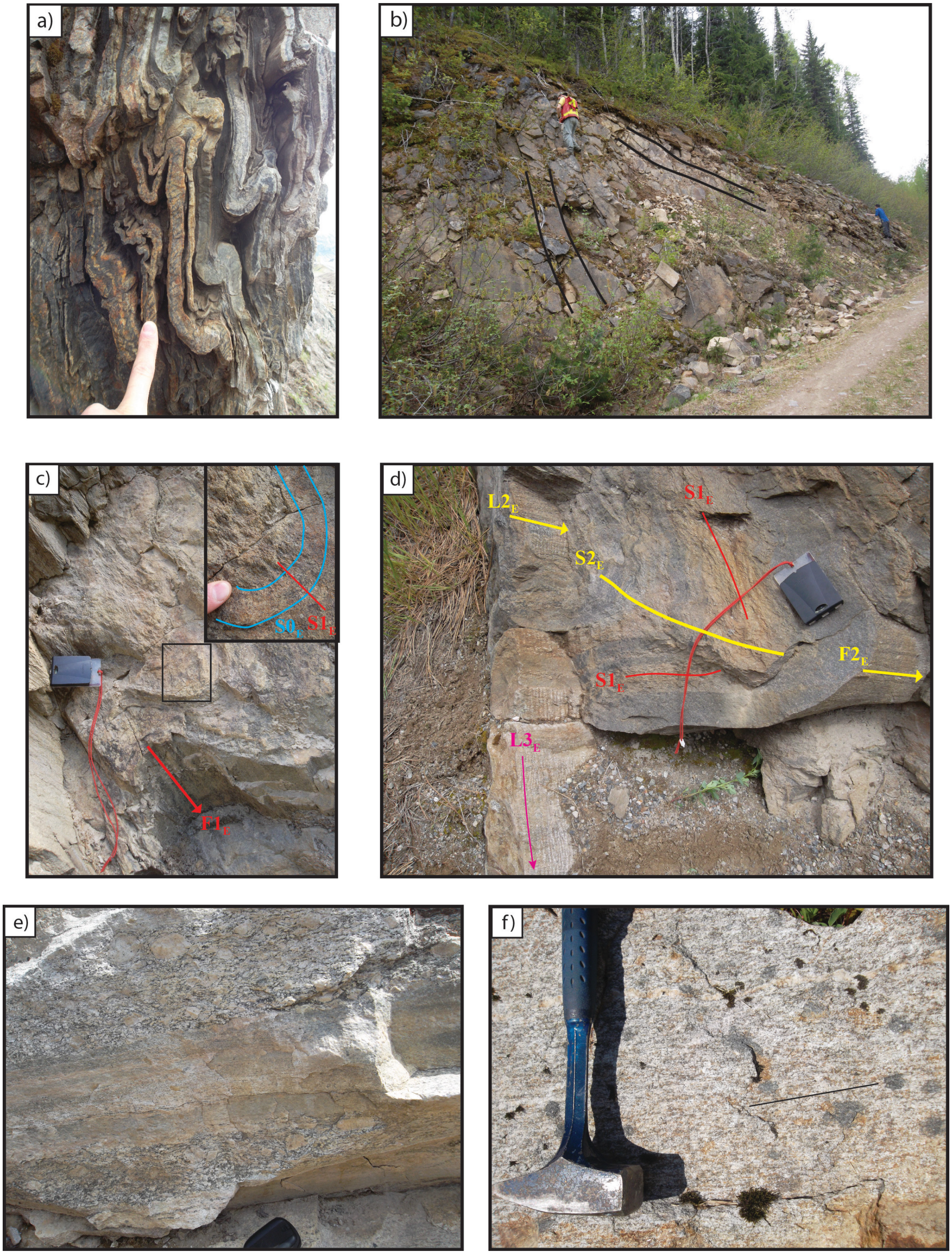

Figure 4. a) S-shaped F_{1W} folds in carbonate rocks of the Laib syncline. **b)** Large, inclined, outcrop-scale F_{2E} fold with a shallow northerly plunge. **c)** F_{1E} folds showing an axial-planar foliation. Inset highlights the axial-planar nature of the foliation. **d)** Gently plunging, recumbent F_{2E} fold with subhorizontal axial plane (S_{2E}). Steeply plunging crenulation lineation (L_{3E}). **e)** Example of the heterogeneous nature of the Rykert batholith with varying degrees of foliation development, mafic content and potassium feldspar megacryst size. **f)** Example of the Corn Creek gneiss with a shallowly plunging stretching lineation highlighted by the thin black line.

separate the timing of the deformation events. The dominant map-scale structures in the area are tight to isoclinal, upright to inclined, north-northeast- or south-southwest-plunging folds with subhorizontal axes (F_{1N}: D_{1N} structures are D2 of Leclair, 1988 and Moynihan and Pattison, 2008). These folds are associated with a regionally penetrative, axial-planar cleavage (S_{1N}) that is generally subparallel to bedding (S_{0N}). The F_{1N} fold axes are parallel to a mineral and stretching lineation (L_{1N}) throughout this domain. This lineation becomes more pronounced with greater proximity to the PTF and MCF, as lower structural levels are exposed. The L_{1N} lineations are defined by rodding of quartz and feldspar in quartzite and in the Baldy pluton. Crenulations of the S_{1N} cleavage are observed in pelitic and semipelitic rocks throughout the northern domain and are locally strong enough to develop a crenulation cleavage (S_{2N}). The crenulation fold axes define a second lineation (L_{2N}) that is subparallel to the F_{1N} fold axes. A second crenulation sporadically crinkles S_{1N} at a high angle to the previous crenulation lineation (L_{2N}), defining a third lineation (L_{3N}) that trends east-northeast and plunges approximately 45°.

Structural Observations—Eastern Domain

The map pattern in the eastern domain is dominated by kilometre-scale, open to tight folds of the Belt-Purcell Supergroup (Figures 2, 3c; Brown et al., 1995). Field observations identified at least three phases of deformation in this domain. The earliest folds (F_{1E}) are upright to recumbent, isoclinal to open folds with an axial-planar schistosity (S_{1E}; Figure 4c). The fold axes commonly have a gentle plunge to the north-northeast or south-southwest (Figure 4). A strong mineral and stretching lineation (L_{1E}) has developed in association with the F_{1E} folds. The lineation is more pronounced in pelitic units, in which micas have aligned parallel to the fold axes.

The F_{1E} folds and S_{1E} schistosity have been refolded by gently plunging, north-northeast- or south-southwest-plunging, upright to recumbent, open to tight folds (Figure 4b, d). These F_{2E} folds are the most prevalent outcrop-scale structures and form the dominant map-scale folds (Figures 2, 3c). The F_{2E} fold hinges are occasionally chevron shaped but are more commonly similar folds, with layering thickened in the hinge zone and thinned in the limbs. The axial planes to the second generation of folding generally dip moderately to the west-northwest and are locally strong enough to develop a second foliation (S_{2E}). A strong crenulation developed in conjunction with F_{2E} folds.

The D_2 structures are more pronounced at deeper structural levels in the footwall of large faults (PTF and MCF), as found by Moynihan and Pattison (2008) in the northern part of Kootenay Lake. This variation in structural intensity is also evident from east to west across the eastern domain. At higher structural levels in the western portion of the eastern domain, F_{2E} folds are less well developed and have smaller wavelengths and amplitudes.

A third episode of deformation (D_{3E}) is observed throughout the eastern domain, manifested as a longer wavelength (centimetre-scale) crenulation and microfolding of micaceous layers. Locally, the crenulation is strong enough to develop a spaced cleavage. The fold axis of these crenulations defines a lineation with a moderate to steep plunge that is easily distinguishable from earlier structures.

Interface between Domains

The large F_{1W} folds of the Laib syncline and Sheep Creek anticline can be traced north from the western domain into the northern domain (Figures 2, 3). The same large structures observed in the west are the dominant structures found in the northern domain. The transition from higher structural levels and lower metamorphic grade in the west to deeper structural levels and higher metamorphic grade in the north appears to be gradual, occurring over several kilometres. The deepest structural levels are exposed in the footwall of the MCF and PTF (Figures 3a, 5), in which the regional metamorphic grade and intensity of deformation are highest.

The interface between the western and eastern domains is less clear. From west to east, there is a change to stratigraphically older rocks, an increase in structural complexity and an increase in metamorphic grade as the PTF is approached. Accompanying this change is a younging trend from west to east in muscovite and biotite $^{40}Ar/^{39}Ar$ cooling ages (Figure 5). The dashed yellow line on Figure 2 is an approximation of where there is a transition in cooling ages, from mid-Cretaceous (<100 Ma) to Middle Jurassic (>150 Ma). The current dataset does not have the spatial resolution to constrain the nature of the interface between the two domains. There does not appear to be any marked change in structural style or metamorphic grade where the change in cooling ages occurs. This will, however, be addressed with future petrological work.

Timing of Deformation

The age of deformation in each domain can be partly constrained by the crosscutting relationships and deformation features contained in igneous bodies of known age. In the western domain, the eastern limb of the Laib syncline is cut by the Middle Jurassic (167 Ma) Wall stock (Figure 2, Table 1), implying that the large map-scale folds (Laib syncline, Sheep Creek anticline) and associated D_{1W} are Jurassic features. Fabrics in the Mine and Wall stocks are parallel to the dominant foliation (S_{1W}) in the surrounding sedimentary rocks, indicating that D_{1W} continued to develop after the emplacement of the stocks. The same conclusions were drawn farther north in the central and northern parts of

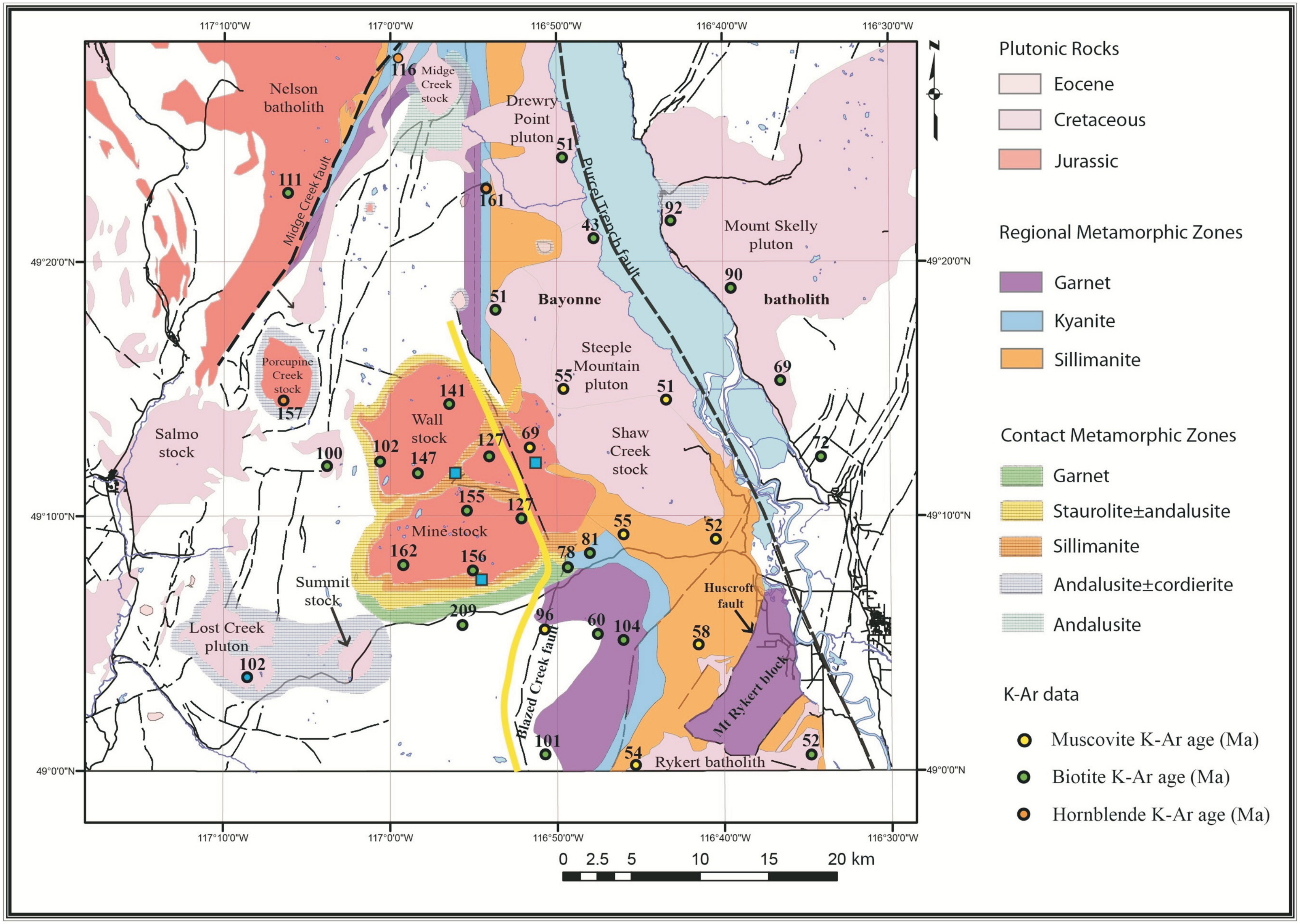

Figure 5. Metamorphic zones and plutonic rocks of the study area, compiled from Glover (1978), Archibald et al. (1983), Leclair (1988), Doughty et al. (1997) and new data. Areas with no shading are of low metamorphic grade. Blue squares are occurrences of kyanite away from the regional kyanite zone. K-Ar data compiled from Archibald et al. (1983), Leclair et al. (1993) and Glombick et al. (2010).

the Kootenay Arc (Warren, 1997). All of the deformation in the western domain has been overprinted by the contact aureole of the post-kinematic Summit stock and Lost Creek pluton (Archibald et al., 1984). Assuming the biotite-cooling age of these intrusions of 102 Ma (Table 1) is close to the emplacement age, it implies that D_{2W} deformation had ceased in the western domain by the mid-Cretaceous.

The Jurassic Sheep Creek anticline and Laib syncline can be traced north into the northern domain. The Cretaceous Baldy pluton (117 +4/-1 Ma, U-Pb titanite; Leclair et al., 1993) is an elongate granodioritic body that is subparallel to the penetrative foliation (S_{1N}) and bedding, and is therefore interpreted to have intruded before or during D_{1N} deformation. The intrusion is foliated and has a strong mineral and stretching lineation (D_{1N}), parallel to those in the metamorphosed sedimentary rocks. This implies that the age of penetrative D_{1N} deformation in the northern domain is Cretaceous, considerably younger than the Jurassic structures in the western domain. A plausible explanation is that the earlier Jurassic structures that extend from the western to the northern domain were tightened in the northern domain during the Cretaceous. The Midge Creek stock (MCS) is a mid-Cretaceous intrusion (111 ±4 Ma, U-Pb allanite; Leclair et al., 1993; Table 1) that crosscuts the regional structures. It is undeformed except at the northern tip (Figure 2), where the dominant foliation parallels the regional trend (Leclair, 1988). This implies that the MCS was intruded during the later stages of the penetrative deformation (D_{1N}), thus constraining the timing of D_{1N}.

The significance of the ages of the Baldy pluton and MCS is uncertain. There is no U-Pb zircon date for either of the intrusions (Leclair et al., 1993). The U-Pb dates for both of these intrusions are from titanite and allanite, and it is possible that either or both of these minerals either formed as metamorphic minerals or were reset during the Cretaceous because the ambient metamorphic temperature was above the closure temperature of these minerals (approximately 600°C). Because the age of these intrusions is critical to determining the age of the metamorphism and deformation in this area, new U-Pb analyses will be conducted.

The D_{1E} structures in the eastern domain appear to be younger than D_{1W} and D_{1N} structures in the western and northern domains. The primary evidence comes from two deformed gneissic bodies, the Corn Creek and West Creston gneisses (both 135 Ma; Table 1), and the deformed Rykert batholith (94 Ma; Brown et al., 1999; Figure 2). All three intrusions contain a penetrative, gently to moderately west-dipping mylonitic foliation and a shallow north-plunging stretching lineation. These are of the same orientation as those in the surrounding country rocks, and are therefore inferred to be younger than these igneous bodies (i.e., post ca. 94 Ma). Several deformed pegmatites occur within the schist of the Aldridge Formation along Highway 3 (Table 1). They lie subparallel to, and are boudinaged within, S_{1W} but locally crosscut the foliation, suggesting emplacement broadly during D_{1E}. One pegmatite yielded an 81.7 ±0.2 Ma U-Pb zircon date, interpreted to be its age of emplacement (Brown et al., 1999). The Shaw Creek stock has an emplacement age of 76 Ma (Figure 2; Brown et al., 1999) and crosscuts D_{1E} and the later D_{2E} structures. These events can therefore be constrained to the interval 94–76 Ma. The timing of D_{3E} is less well constrained and could be as young as Eocene.

In summary, the dominant deformation episodes in the three domains have different ages. The penetrative foliation and dominant folds are Middle Jurassic in the western domain, mid-Cretaceous in the northern domain and Late Cretaceous in the eastern domain. The dominant structures in all three domains have a similar north-northeast orientation, obscuring the relationships between the different periods of deformation and suggesting that earlier structures were overprinted and tightened by later structures in the northern and eastern domains. The nature of the interface between the Late Cretaceous structures in the east and the mid-Cretaceous structures in the north is not presently well understood and will be the focus of future work.

Metamorphism

The regional metamorphic grade in the study area is dominantly greenschist facies, apart from two discrete elongate domains of amphibolite-facies metamorphic rocks (Figure 5). In the northern part of the field area, the amphibolite-facies metamorphism forms a forked isograd pattern. The western fork is parallel to strike and is truncated by the Midge Creek fault. This fork is a continuation of the metamorphic high mapped north of the west arm of Kootenay Lake by Moynihan and Pattison (2008). The eastern fork transects the strike of the lithological units and is approximately parallel to the Purcell Trench fault in the northern part of the study area. This fork continues south into the United States and merges with amphibolite-facies metamorphism in the Priest River Complex. The two forks are separated by a large area of low metamorphic grade (Figure 5).

Contact aureoles have developed in proximity to a number of the intrusions and have distinct textures and mineral assemblages that make them distinguishable from the regional metamorphism. The metamorphic zones presented in this study are based on the distribution of metamorphic index minerals in pelitic rocks (Figure 5) and have been compiled from observations of this and previous studies (Glover, 1978; Archibald et al., 1983; Leclair, 1988; Doughty et al., 1997; Moynihan and Pattison, 2008).

Regional Metamorphism

Three regional amphibolite-facies metamorphic zones have been identified within the map area: garnet, kyanite and sillimanite. These metamorphic zones are typical of Barrovian metamorphism, with the highest metamorphic grade in the footwall of the PTF and MCF, and progressively lower grades with increasing distance from the fault zone. South of the Jurassic Mine and Wall stocks, the regional metamorphic zones are broad (Figure 5) but become progressively narrower to the north (Figure 5). The two belts of amphibolite-facies metamorphism converge in the vicinity of the Midge Creek stock. The map pattern shows that the regional metamorphic zones approximately parallel the PTF and MCF in the northern part of the field area but broaden and are less well defined south of the Mine and Wall stocks.

The MCF juxtaposes greenschist-facies phyllite of the Milford Group against sillimanite-zone schist in the footwall (Moynihan and Pattison, in press). There is also a large contrast in metamorphic grade across the PTF (Figure 5): pelite in the footwall has the mineral assemblage sillimanite±kyanite+garnet+muscovite+biotite+plagioclase+quartz+rutile, whereas pelite in the hangingwall has the assemblage biotite+muscovite+chlorite+albite+quartz (Figure 6). Based on these mineral assemblages, the contrast in peak metamorphic conditions across the fault is >2 kbar and >150°C (Figure 6).

One exception to the large temperature and pressure contrast across the PTF is an area of garnet-zone rocks in the hangingwall of the Huscroft fault (Figures 3c, 5), itself in the footwall of the PTF. These rocks are part of an overturned section of the Aldridge and Creston formations (Brown et al., 1995) and are thought to represent the overturned limb of a regional-scale fold. The upper-greenschist–facies rocks in the hangingwall of the Huscroft fault contrast with the sillimanite-zone rocks beneath the fault, implying a large amount of displacement on the fault. Because the PTF cuts the Huscroft fault, the throw on the PTF must be less than implied by the contrast in peak metamorphic assemblages across the PTF outside the Huscroft block. Further study of this matter is underway.

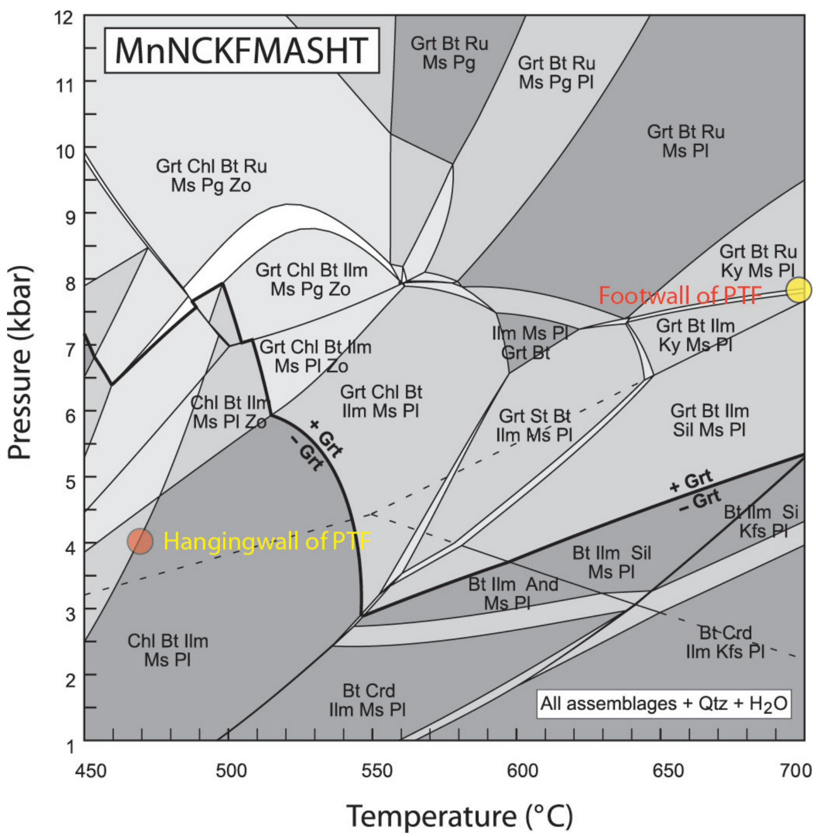

Figure 6. Section of an isochemical phase diagram for an average pelite composition from the Nelson area (modified from Pattison and Tinkham, 2009). The chemical system used to model the phase equilibria was MnNCKFMASHT (MnO-Na_2O-CaO-K_2O-FeO-MgO-Al_2O_3-SiO_2-H_2O-TiO_2, with C and P_2O_5 omitted from the whole-rock analysis, followed by projection from pyrrhotite). The yellow dot represents the stable mineral assemblage in the footwall of the PTF and the red dot represents the stable mineral assemblage in the hangingwall. Mineral abbreviations are from Kretz (1983).

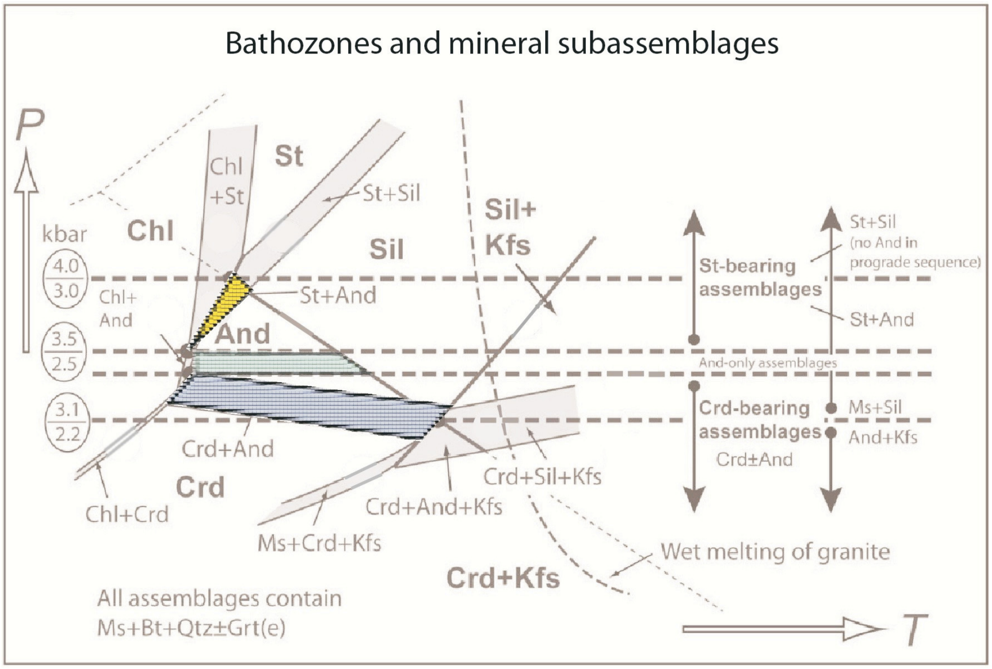

Figure 7. Schematic P-T phase diagram showing the relationship of mineral-assemblage domains to key subassemblages (modified from Pattison and Vogl, 2005). Contact aureoles from the field area are highlighted on the diagram with their corresponding colours. Yellow represents the stable mineral assemblage staurolite±andalusite and pressures of 3.5–4 kbar. Light green represents the stable mineral assemblage andalusite and pressures of 2.5–3.5 kbar. Blue represents the stable mineral assemblage cordierite+andalusite and pressures of 2.2–3.1 kbar. Mineral abbreviations are from Kretz (1983).

Contact Metamorphism

The study area has been intruded by numerous Jurassic and Cretaceous plutons (Figures 2, 5) that have imparted contact aureoles to the surrounding country rock. The contact aureole surrounding the Mine and Wall stocks is developed in regionally low-grade rocks of the Windermere Supergroup. The contact aureole is characterized by assemblages containing garnet, staurolite±andalusite and sillimanite. South of the intrusion, the contact aureole is well developed in pelitic rocks; however, along the western margin of the Mine and Wall stocks, where psammitic rocks predominate, the contact metamorphic zones are not observable. Within the contact aureole, several occurrences of kyanite have been identified that, from microstructural relations, postdate muscovite-rich pseudomorphs after andalusite (Figure 5). It is presently unclear if the kyanite is a result of contact metamorphism or later regional metamorphism; this will be the focus of future petrological work. Based on the abundant staurolite±andalusite assemblages, contact metamorphism associated with the Mine and Wall stocks occurred at 3.5–4 kbar (Figure 7, yellow domain). The Porcupine Creek stock (ca. 157 Ma, K-Ar hornblende age; Table 1) is situated 4 km northwest of the Wall stock and has a lower pressure (~3.0–3.5 kbar) contact aureole with cordierite+andalusite (Figures 5, 7), similar to the southern part of the Nelson batholith aureole (Pattison and Vogl, 2005).

The mid-Cretaceous, post-kinematic Lost Creek pluton (LCP) and Summit stock (SS; Table 1) have imparted the lower pressure contact aureoles on the surrounding low-grade country rocks. The mineral assemblage zonal sequence is cordierite, andalusite±cordierite and sillimanite±K-feldspar (Bjornson, 2012). New mapping (this study) and that of Bjornson (2012) illustrate that these metamorphic zones envelop both intrusions, with a metamorphic ‘high’ in the central domain between the two. Rocks in the contact aureole of the SS and LCP were metamorphosed at 2.2–3.2 kbar (Figure 7; Bjornson, 2012).

In summary, the Jurassic intrusions were emplaced at 3.5–4 kbar, which, for a pressure of 2.7 g/cc, corresponds to an 11–13 km emplacement depth, considerably deeper than the Cretaceous intrusions at 7–11 km. This implies approximately 5 km of aggregate exhumation between emplacement of the Jurassic intrusions and the Cretaceous intrusions.

$^{40}K/^{40}Ar$ and $^{40}Ar/^{39}Ar$ Dating

Archibald et al. (1984) carried out a $^{40}K/^{40}Ar$ and $^{40}Ar/^{39}Ar$ study of the southern Kootenay Arc, including a significant part of this study area (Figure 5). They found early Paleogene cooling ages centred over the band of sillimanite-bearing rocks west of Kootenay Lake (Figures 2, 5). Older cooling ages occur across the PTF to the east and toward lower metamorphic grade to the west. The Eocene to

Cretaceous cooling ages are confined to within approximately 25 km of the PTF (Figure 5), based on the limited dataset of Archibald et al. (1983) and Brown et al. (1995). There appears to be a transition from Cretaceous to Jurassic cooling ages in the vicinity of the Blazed Creek fault, which marks approximately the boundary between the western and eastern structural domains. Mapping by Brown et al. (1995) and this study, however, found no evidence to suggest that there is a large fault in this area. Therefore, further work is planned to address the nature of the interface: fault, gradational or overprinting relationship. Little geochronological data exist for the northern part of the study area, so this area will be the focus of a further $^{40}Ar/^{39}Ar$ study.

Discussion

The observations presented above convey the complex structural, metamorphic and geochronological history of the study area, in which there are spatial variation in the grade of metamorphism, intensity of deformation and $^{40}K/^{40}Ar$ and $^{40}Ar/^{39}Ar$ cooling ages. Eocene extension and exhumation resulted in deeper structural levels, higher metamorphic grade and younger cooling ages being exposed in the footwall of the PTF and MCF. The following discussion is a preliminary synthesis of the geological history of the study area from the Middle Jurassic to the Early Eocene.

The earliest recorded metamorphism and deformation in the study area is restricted to the western domain; however, it likely affected the entire study area but was subsequently overprinted by later events. Regional peak-metamorphic conditions were attained during the Jurassic, broadly coeval with plutonism and deformation (D_{1W}). The well-developed staurolite±andalusite contact mineral assemblage developed around the Jurassic Mine and Wall stocks (Figure 5) implies emplacement depths of 11–13 km. The development of late kyanite implies either that, following the emplacement of these intrusions during the Middle Jurassic, they were deformed and buried to Barrovian metamorphic conditions, or that the kyanite developed in local bulk compositions at pressures and temperatures not significantly different from those of contact metamorphism (e.g., Pattison, 2001). Whatever interpretation is correct, these events must have occurred in the Jurassic because the igneous and metamorphic rocks in the area have Jurassic cooling ages. Following the Middle Jurassic, the western domain remained at higher structural levels while rocks at lower levels were intensely deformed and metamorphosed during the Cretaceous.

North of the west arm of Kootenay Lake, peak metamorphism and the dominant penetrative deformation has been constrained to the interval 143–124 Ma (Moynihan and Pattison, in press). The southern extension of this Early Cretaceous metamorphism and deformation is developed in the northern domain of this study area. In the northern domain, the western flank of the amphibolite-facies metamorphism is cut by the MCF. The lower structural levels exposed in the footwall of the MCF are of much higher metamorphic grade than those in the hangingwall (Leclair et al., 1993: Moynihan and Pattison, in press). A similar trend was observed north of the study area, across the Gallagher fault (Moynihan and Pattison, 2008). Accepting the U-Pb ages for the late-synkinematic Baldy pluton and postkinematic Midge Creek stock as close to the intrusion age would support D_{1N} and peak metamorphism being mid-Cretaceous in age (Leclair et al., 1993; Moynihan and Pattison,in press).

Episodic magmatism continued through the mid-Cretaceous, with different phases of the Bayonne magmatic suite intruding the study area from approximately 100 to 76 Ma. The western domain was intruded by the postkinematic Lost Creek pluton and Summit stock ca. 102 Ma. The well-developed low-pressure cordierite+andalusite contact aureole around the intrusions constrains their emplacement level to 7–11 km depth in the crust. A similar cordierite+andalusite contact aureole can be found around the Mount Skelly pluton on the east side of Kootenay Lake, suggesting a similar emplacement level on the east side of the PTF at ca. 100 Ma.

Rocks in the amphibolite-facies metamorphic belt (Figure 5) in the eastern domain appear to have attained peak metamorphism during the Late Cretaceous, ca. 82 Ma (Brown et al., 1999). South of the Canada–United States border in the PRC, peak metamorphism occurred ca. 75 Ma (Doughty and Price, 1999). The regional metamorphic zones depicted on the west side of the PTF in Figure 5 suggest the presence of a continuous band of amphibolite-facies metamorphism from northern Idaho to the northern end of Kootenay Lake. However, there must be an interface between Early Cretaceous (ca. 145–125 Ma) amphibolite-facies metamorphism in the northern half of Kootenay Lake (Moynihan and Pattison, in press) and in the northern part of the study area, and Late Cretaceous amphibolite-facies metamorphism (ca. 94–76 Ma) extending from south of the border into the southern part of the study area. An 81.7 ±0.2 Ma U-Pb monazite age, interpreted to be a metamorphic age in contrast to the 135 Ma zircon age from the Corn Creek gneiss (Brown et al., 1999), suggests that the Late Cretaceous metamorphism extends at least to the latitude of Creston. Future U-Pb monazite dating is planned to better constrain the interface between the two periods of metamorphism.

The Rykert batholith, the Corn Creek and West Creston gneisses (Table 1) and an 82 Ma pegmatite are deformed by the dominant penetrative foliation and lineation in the eastern domain, implying that D_{1E} is also Late Cretaceous, coeval with peak metamorphism. This area also experienced a strong D_{2E} deformation event, before the emplacement of the Shaw Creek stock at 76 Ma, and a weak D_{3E} event, the timing of which is currently not well constrained. The area was then exhumed to higher structural levels in the early Eocene. This contrasts with what is observed in the west, where (D_{2W}) deformation had completely ceased prior to the emplacement of the LCP and SS, ca. 102 Ma. The nature of the boundary between the different structural, metamorphic and cooling histories of the eastern and western domains is unclear and will be the focus of future work.

During the early Eocene, Cretaceous amphibolite-facies metamorphism and deeper structural levels were exposed in the footwalls of the PTF and MCF. Although there is a significant difference in peak pressure and temperature across the PTF and MCF (Figure 6), caution must be exercised in attributing all of the contrast in peak P-T conditions to low-temperature movement along the PTF in the Eocene. Recent studies have shown that the displacement on large Eocene normal faults may be significantly less than previously thought (Gordon et al., 2008; Simony and Carr, 2011; Cubley and Pattison, in press), due to a two-stage exhumation process in which high-temperature exhumation is followed by low-temperature exhumation on the normal faults.

The Mt. Rykert block of lower grade metamorphic rocks, situated within the footwall of the PTF (Figure 5; Brown et al., 1995), is thought to be analogous to the Newport plate (Figure 1), within the Newport Fault system, south of the Canada–United States border (Doughty and Price, 2000). The lower grade domain of the Mt. Rykert block is probably an extensional klippe, riding on the original low-angle detachment (Figure 3), that was stranded when the steeper PTF developed (T. Doughty, pers. comm., 2012).

Mineral Deposits

A better understanding of the structural, magmatic, metamorphic and fluid events in the area allows for a more complete understanding of the genesis of mineral deposits in the area. The past-producing Pb-Zn and Mo-W deposits of the Salmo camp and the Au-Ag vein deposits of the Sheep Creek camp are situated within the western domain of the study area. The Pb-Zn deposits are carbonate-hosted, stratabound and stratiform lenticular concentrations that have been isoclinally folded (Paradis, 2007). Based on the observations of this study, the authors interpret these structures to be Jurassic D_{1W} structures.

A 50–75 km wide arcuate belt of Cretaceous intrusions, known as the Bayonne magmatic suite, extends from the Canada–United States border to north of Quesnel Lake, crosscutting through the study area. The Bayonne magmatic suite has been associated with Sn, W, W-Mo, U and Ag-Pb-Zn-Au deposits (Logan, 2002). The type of deposit varies depending on the emplacement depth of the intrusion (Lang and Baker, 2001). Relatively undeformed mid-Cretaceous intrusions that were emplaced at relatively shallow, higher structural levels are found throughout the western domain. These are host to the Mo-W mineralization in the Salmo camp, which the authors interpret to have overprinted the older Pb-Zn mineralization. Future work will be conducted to further elucidate on the source of their relationships.

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