Spatially overlapping episodes of deformation, metamorphism, and magmatism in the southern Omineca Belt, southeastern British Columbia

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Abstract: The southeastern Omineca Belt of the Canadian Cordillera preserves a record of overlapping Barrovian and Buchan metamorphism spanning 180–50 Ma. This paper documents the timing, character, and spatial relationships that define separate domains of Middle Jurassic, Early Cretaceous, and Late Cretaceous deformation and metamorphism, and the nature of the geological interfaces that exist between them. A domain of Early Jurassic deformation (D1) and regional greenschist-facies metamorphism (M1) is cross-cut by Middle Jurassic (174–161 Ma) intrusions. Associated contact aureoles are divided into lower pressure (cordierite-dominated; ~2.5–3.3 kbar; 1 kbar = 100 MPa) and higher pressure (staurolite-bearing; 3.5–4.2 kbar) subtypes; contact metamorphic kyanite occurs rarely in some staurolite-bearing aureoles. Jurassic structures are progressively overprinted northwards by Early Cretaceous deformation and metamorphism (D2M2), manifested in a tightening of Jurassic structures, development of more pervasive ductile fabrics, and Barrovian metamorphism. The D2M2 domain is the southerly continuation of the 600 km long Selkirk–Monashee–Cariboo metamorphic belt. Mid-Cretaceous intrusions (118–90 Ma) were emplaced throughout the D2M2 domain, the earliest of which contain D2 fabrics, but cut M2 isograds. The D2M2 domain makes a continuous, southeasterly transition into a domain of Late Cretaceous regional Barrovian metamorphism and deformation (D3M3; 94–76 Ma). The interface between these two domains is obscured by the coaxial nature of the deformation and the apparent continuity of the metamorphic zones, resulting in a complex and cryptic interface. Similarities between the D3M3 domain and the Selkirk Crest of Idaho and Washington suggest that this domain is the northerly continuation of the northward-plunging Priest River Complex.

Résumé : Les roches du sud-est de la ceinture Omenica de la Cordillère canadienne témoignent du chevauchement de métamorphismes barroviens et de type Buchan s’étalant de 180 à 50 Ma. L’article documente les contraintes temporelles, les relations spatiales qui définissent différents domaines de déformation et de métamorphisme, respectivement d’âges jurassique moyen, crétaçé précoce et tardif, et la nature des interfaces géologiques entre ces domaines. Un domaine de déformation (D1) et de métamorphisme régional au faciès des schistes verts (M1) au Jurassique précoce est recoupé par des intrusions d’âge jurassique moyen (174–161 Ma). Les auréoles de contact associées sont divisées en des sous-types de basses pressions (ou dominée la cordiérite; ~2,5–3,3 kbar; 1 kbar = 100 MPa) et de plus haute pression (à staurotide; 3,5–4,2 kbar); de la kyanite issue du métamorphisme de contact est présente en de rares occasions dans certaines auréoles à staurotide. Une déformation et un métamorphisme d’âge crétaçé précoce (D2M2), qui se manifestent par un resserrement des structures jurassiques, le développement de fabriques ductiles plus généralisées et un métamorphisme barrovien, se surimposent graduellement vers le nord aux structures jurassiques. Le domaine D2M2 est le prolongement vers le sud de la ceinture métamorphique de Selkirk–Monashee–Cariboo, longue de 600 km. Des intrusions d’âge crétaçé moyen (118–90 Ma), dont les plus précoces ont des fabricles D2, mais sont recoupées par les isograds de M2, sont présentes à la grandeur du domaine D2M2. Le domaine D2M2 définit un passage continu vers le sud-est à un domaine de métamorphisme régional barrovien et de déformation régionale d’âge crétaçé tardif (D3M3; 94–76 Ma). L’interface entre ces deux domaines est masquée par le caractère coaxial de la déformation et la continuité apparente des zones métamorphiques, qui se traduisent par une interface complexe et cryptique. Les similitudes entre le domaine D3M3 et la crête Selkirk des États d’Idaho et de Washington donnent à penser que ce domaine constitue le prolongement vers le nord du complexe de Priest River, qui plonge vers le nord. [Traduit par la Rédaction]
tonous, pericratonic metasedimentary and volcanic rocks of Quesnellia terrane to the west (Unterschutz et al. 2002; Fig. 2). The tectonic accretion of Quesnellia to the western margin of the North American craton in the Lower Jurassic (ca. 180–170 Ma) marked the onset of Cordilleran orogenesis in this region (Murphy et al. 1995). Several pulses of magmatism, deformation, and metamorphism in a broadly contractional tectonic regime followed in the next 130 Ma (Evenchick et al. 2007, and references therein). Contractional orogenesis ceased in the Eocene (ca. 55 Ma) when there was a transition to extensional tectonics, the latter characterized by the development of major Eocene normal faults and exhumation of metamorphic core complexes (Monger et al. 1982; Parrish et al. 1988; Johnson and Brown 1996; Vanderhaeghe et al. 1999; Cubley et al. 2013). The geological complexity of the Omineca Belt derives from the superposition of these events.

The area of the Omineca Belt under consideration in this study is a ~5400 km² domain between the towns of Nelson, Salmo, and Creston (Figs. 1–3). It occurs at the southern end of the Selkirk–Monashee–Cariboo metamorphic complex of Simony and Carr (2011), a broadly northwest–southeast-trending, 600 km long and 2–100 km wide belt of Early Cretaceous metamorphism and deformation embedded within a more extensive Late Cretaceous orogenic domain (Simony and Carr 2011, and references therein). Previous reconnaissance studies of the area addressed aspects of the bedrock geology, structural geology, geochronology, and cooling history (Fyles 1964, 1967; Crosby 1968; Reesor 1973; Glover...
The aforementioned studies revealed evidence of overlapping domains of deformation, magmatism, and metamorphism of broadly Early Jurassic, Early Cretaceous, and Late Cretaceous age with complex and cryptic overprinting relationships.

The study area contains many of the geological complexities found elsewhere in the Canadian Cordillera: isograd synthforms and antiforms; polyphase metamorphism with seemingly continuous isograds; juxtaposed thermal domains of different age; and coaxial deformation (Digel et al. 1998; Crowley et al. 2000; Reid et al. 2003; Gibson et al. 2008). In this study, we decipher in greater detail than before the distribution and nature of these metamorphic, deformation, and magmatic episodes, and the implications these hold for the tectonic evolution of this part of the Cordillera.

**Geological setting**

Figures 2 and 3 show lithological and metamorphic maps of the study area. The eastern part of the study area is occupied by the Purcell Anticlinorium, a broad, northerly plunging Mesozoic fold structure cored by strata of the Mesoproterozoic Belt–Purcell Supergroup (Fig. 1). The Belt–Purcell Supergroup (1470–1400 Ma) is a ~20 km thick succession consisting of predominantly marine...
Fig. 3. Geology of the study area. Cross-section lines are labeled on the map and shown in Fig. 4. Intrusive rock abbreviations: BP, Baldy pluton; CCG, Corn Creek gneiss; LCP, Lost Creek pluton; MCS, Midge Creek stock; PCS, Porcupine Creek stock; SALS, Salmo stock; SS, Summit stock. MCF, Midge Creek fault. Other abbreviations are the same as in Fig. 2. [Colour online.]
turbidites and broadly coeval mafic dykes and sills (Aldridge Formation and Moyie sills), overlain by a succession of shallower-water clastic and carbonate strata (Price 2000; Figs. 2A, 3). Lower and Middle Creston Fm; Kitchener Fm; Van Creek Fm; Dutch Creek Fm; and Mount Nelson Fm. The Belt–Purcell Supergroup is interpreted to have been deposited in an intracratonic rift system (Chandler 2000; Price and Sears 2000).

The Belt–Purcell strata are overlain unconformably by rocks of the Neoproterozoic Windermere Supergroup (780–540 Ma), another package of broadly rift-related strata that occur on the east and west flanks of the Purcell Anticlinorium (Fig. 1; Price 2000). The Windermere Supergroup comprises, from bottom to top, a thick basal conglomerate (Toby Conglomerate), mafic volcanics (Irene Formation), fine-grained clastic clastic strata (Monk Formation), and a sequence of interbedded carbonate and clastic rocks (Three Sisters Formation; Figs. 2A, 3). The Belt–Purcell and Windermere strata of the Purcell Anticlinorium are of generally low metamorphic grade (up to biotite zone; Fig. 2B).

The western part of the study area is occupied by the Kootenay Arc, a curvilinear, concave-to-the-west, structural belt of polydeformed and metamorphosed rocks, that borders the west flank of the Purcell Anticlinorium (Warren 1997; Moynihan and Pattison 2013; Figs. 1, 2A). The stratigraphy in the Kootenay Arc is younger than that of the Purcell Anticlinorium. It is divided into two distinct tectonostratigraphic packages separated by a major tectonic boundary, the Tillicum Creek and Waneta fault (Fyles and Hewlett 1959; Einarson 1994; Fig. 2). The first package, extending from the eastern flank of the Kootenay Arc where it adjoins the Purcell Anticlinorium westwards to the Waneta fault, comprises early Paleozoic clastics and carbonates that unconformably overlie the strata of the Windermere Supergroup (Fyles and Hewlett 1959; Einarson 1994). These formations include the Quartzite Range, Reno, Laib, Nelway, and Active formations (Fig. 3). These early Paleozoic strata are interpreted to have formed on the rifted margin of the ancestral North American craton (Devlin and Bond 1988).

The second stratigraphic package, located west of the Waneta fault, comprises Paleozoic through Jurassic volcanic and sedimentary rocks of Quesnellia (Figs. 2A, 3). The dominant rocks of Quesnellia, in the study area, are Lower and Middle Jurassic rocks of the Rossland Group. These rocks are composed of turbidite sandstone, siltstone, and argillite of the Archibald Formation that are overlain by a sequence of undifferentiated mafic to intermediate volcanic and subvolcanic intrusions of the Elise Formation (Höy and Dunne 1997). The Hall Formation is the youngest unit of the Rossland Group and is composed of siltstone, argillite, and abundant volcanics (Höy and Dunne 1997). The Rossland Group overlies Triassic fine-grained argillites and minor carbonates of the Triassic Ymir Group (Fyles and Hewlett 1959), which in turn overlie older Paleozoic strata with affinities to the ancestral North American margin. The Triassic and Jurassic rocks of Quesnellia are interpreted to have developed in a back-arc or island-arc setting before being accreted to the ancestral North American margin in the Early Jurassic (Klepaczki 1985; Unterschutz et al. 2002; Figs. 2A, 3), with the Waneta fault marking the accretion boundary (Figs. 2A, 3). In addition to the stratigraphic changes, there is an increase in structural complexity, magmatism, and metamorphic grade going from the Purcell Anticlinorium into the Kootenay Arc (Warren 1997; Moynihan and Pattison 2013; Figs. 2, 3).

The southern part of the study area is occupied by the northern extent of the Priest River Complex (Doughty et al. 1998; Brown et al. 1999; Figs. 1, 2). The Priest River Complex is one of several gneiss complexes, sometimes termed metamorphic core complexes, which comprise the Shuswap domain of the Omineca Belt in British Columbia, Idaho, and eastern Washington (Monger et al. 1982; Fig. 1). The Priest River Complex is a north–south-trending domain comprising Archean basement gneisses, Mesoproterozoic Belt–Purcell rocks metamorphosed to middle–upper amphibolite-facies conditions, and deformed Cretaceous intrusions (Rhodes and Hyndman 1988; Doughty et al. 1998; Doughty and Price 1999). It is largely situated in Idaho, but extends northwards into southeastern British Columbia (Fig. 1). The northerly portion of the Priest River Complex, termed the Selkirk Crest, comprises a large Cretaceous igneous complex (Selkirk Igeous Complex; Doughty et al. 1998) and regionally deformed, amphibolite-facies metasedimentary rocks in the footwall of the east-side-down Purcell Trench normal fault (Figs. 1, 2B).

**Intrusive rocks**

Three intrusive suites occur in the study area, ranging in age from Middle Jurassic to Eocene (Figs. 1, 2A, 3). Intrusive rocks of the Nelson suite were emplaced between ca. 174 and 161 Ma (Ghosh 1995a; Evenchick et al. 2007) and are widely distributed in southeastern British Columbia (Fig. 1). In the study area, members of this suite include the Nelson batholith, Bonnington pluton, Trail pluton, and Mine and Wall stocks (Figs. 2A, 3). These are I-type granitoids that range in composition from tonalite to granite (Fig. 1; Little 1960; Ghosh and Lambert 1995), and are interpreted to have formed in a magmatic arc, above an east-dipping subduction zone (Ghosh 1995b).

The Bayonne magmatic suite is a series of mid-Cretaceous (~120–94 Ma) intrusions that extends southwards from central British Columbia to northern Idaho (Logan 2001; Fig. 1). These are S-type, primarily peraluminous, two-mica granites with less significant subalkaline granodiorites, aplices, and pegmatites (Logan 2001). Members of this suite include the Baldy pluton, Midge Creek stock, Salmo stock, Wallack Creek stock, Summit stock, Lost Creek pluton, and Rykert batholith (Figs. 2A, 3). Several other intrusive bodies of the Bayonne suite have been grouped together into one intrusive body historically known as the “Bayonne batholith” (Fig. 2); these include the Mount Skelly pluton, Shaw Creek stock, Heather Creek pluton, Dreway Point pluton, and Steepie Mountain pluton (Leclair 1988). Geochronology by Davis (1995), Brown et al. (1999), and Webster et al. (2017) have shown that individual phases of the Bayonne batholith range in age from 112 Ma (Mount Skelly pluton) to 76 Ma (Shaw Creek). This range in age suggests that the Bayonne batholith represents a domain where intrusions of different age and possibly origin have been emplaced close to each other, rather than representing a single genetically and temporally linked body.

In the southern part of the study area is the 94 Ma Rykert batholith (Figs. 2A, 3), also part of the Bayonne suite (Archibald et al. 1984; Gaschnig et al. 2012; Figs. 1, 2A, 3). South of the US–Canada border, it is known as the Kaniksu batholith (Archibald et al. 1984), which is part of the larger Selkirk Igeous Complex.

The youngest intrusive rocks in the study area are the McGregor and Coryell plutonic suites of Eocene age (Little 1960). These comprise small dikes and plugs of syenite and monzonite, thought to be related to large plutons (batholiths) further west.

**Structure**

The area has been affected by at least four episodes of penetrative deformation, spanning the interval from the Early Jurassic to Eocene. Some parts of the area have been affected by only the earliest phase of deformation, whereas other parts have been affected by several phases of deformation. In areas that have experienced more than one phase of deformation, interpretation of different fabrics is complicated by the approximately coaxial nature of the folds. In general, there is an increase in structural complexity and intensity of deformation, and decrease in age of the deformation, going from the southwest to the east and north. These changes correspond to the exposure of progressively deeper structural levels, as revealed by increasing degrees of ductile deformation and by an increase in metamorphic grade. Exceptions to this overall pattern are abrupt changes in the degree of deformation and metamorphism across Eocene normal faults, in par-
the Purcell Trench, Midge Creek, and Gallagher faults (Figs. 2, 3). Rocks in the footwall of these faults display more intense ductile deformation and higher metamorphic grade than in the hanging wall.

**Early-Middle Jurassic deformation**

The earliest recognizable phase of deformation in the area (D₁) occurs in the southwestern part of the study area, approximately south of the Baldy pluton, and west of the Blazed Creek fault (Figs. 2A, 3). This area lies within the southeastern portion of the Kootenay Arc (Fig. 1), and is underlain primarily by Paleozoic clastic and carbonate strata (Figs. 2A, 3). Two major D₁ folds (F₁) are recognized: the Laib syncline and the Sheep Creek anticline (Figs. 2A, 3). Both folds are regional-scale isoclines that plunge gently north-northeast to south-southwest, and are inclined slightly to the west (see cross section C–C’ in Fig. 4). Figure 5a shows a panoramic view of the Laib syncline. A well-developed, subvertical axial-planar cleavage (S₁) is accompanied by a shallowly plunging stretching lineation (L₁) that parallels the fold axes and is best observed in semipelitic layers. The western lobe of the Wall stock transects the eastern limb of the Laib syncline, whereas a weakly developed fabric in the Mine and Wall stocks is parallel to S₁ in the deformed sedimentary strata. These observations suggest that these intrusives were emplaced during the latter stages of D₁ deformation (Fig. 5). The ages of the Mine and Wall stocks are 171 and 167 Ma, respectively, constraining the age of D₁ deformation to the Early Jurassic between this age and ~180 Ma, the age of the youngest strata of Quesnellia affected by accretion-related folding (Evanchick et al. 2007). Similar conclusions were drawn farther north in the central and northern parts of the Kootenay Arc (Warren 1997).

**Early Cretaceous deformation**

North of the domain of Early Jurassic D₁ deformation, approximately north of the southern margin of the Baldy pluton (Fig. 3), is a domain affected by a second phase of deformation (D₂; Pyles 1964; Höy 1980; Leclair 1988; Moynihan and Pattison 2013). A northward increase in D₂ strain is manifested in a tightening of F₁ approximately coaxial with F₁. A mineral and stretching lineation that the stock was emplaced during the latter stages of D₂. A lowly plunging stretching lineation (L₁) that parallels the fold axes and is best observed in semipelitic layers. The western lobe of the Wall stock transects the eastern limb of the Laib syncline, whereas a weakly developed fabric in the Mine and Wall stocks is parallel to S₁ in the deformed sedimentary strata. These observations suggest that these intrusives were emplaced during the latter stages of D₁ deformation (Fig. 5). The ages of the Mine and Wall stocks are 171 and 167 Ma, respectively, constraining the age of D₁ deformation to the Early Jurassic between this age and ~180 Ma, the age of the youngest strata of Quesnellia affected by accretion-related folding (Evanchick et al. 2007). Similar conclusions were drawn farther north in the central and northern parts of the Kootenay Arc (Warren 1997).

A third episode of deformation (D₃) is recorded in a domain east of the two domains discussed earlier, broadly bound by the Blazed Creek – Next Creek faults and PTF (Figs. 2A, 3). The domain is characterized by kilometre-scale, open to tight folds of the Belt–Purcell Supergroup (see cross section B–B’ in Fig. 4). F₃ folds are upright to recumbent, isoclinal to open folds with an axial-planar schistosity (S₃; Figs. 5c, 5d) that is the penetrative fabric in this region. The fold axes commonly have a gentle plunge to the north-northeast or south-southwest and are accompanied by a strong mineral and stretching lineation (L₃). The lineation is more pronounced in pelitic units where it is defined by elongate porphyrloblasts of kyanite and sillimanite (Fig. 5e). S₃ has been folded by gently, north-northeast or south-southwest-plunging, upright to recumbent, open to tight folds (F₄; Fig. 5f). The F₄ fold hinges are occasionally chevron shaped but are more commonly similar folds, with layering thickened in the hinge zone and thinned on the limbs. Axes of L₄ crenulations parallel F₄ fold hinges. The axial planes to the F₄ folds and crenulations generally dip moderately to the west-northwest and are locally strong enough to develop a foliation (S₄).

The Corn Creek and West Creston gneisses (both ca. 135 Ma; Brown et al. 1999) and the deformed Rykert batholith (ca. 94 Ma; Brown et al. 1999; Fig. 2) occur within the domain affected by both D₃ and D₄ structures. These intrusive bodies contain a penetrative, gently to moderately west-northwest-dipping mylonitic foliation and a shallow north-northeast-plunging stretching lineation. These are of the same character and orientation as D₃ and D₄ fabrics in the surrounding country rocks, and are therefore inferred to be younger than these igneous bodies (i.e., post 94 Ma). Several deformed pegmatites occur within the schists of the Aldridge Formation along Highway 3 (Fig. 5c), orientated subparallel to the S₄ foliation. The pegmatites are folded and boudinaged within, but also locally cross-cut, the S₄ foliation, suggesting emplacement broadly during D₅. D₄ crenulations of schistose rocks in the interboudin necks indicate that D₄ postdates the emplacement and deformation of the pegmatite. 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 (76 Ma; Parrish and Monger 1992; Fig. 2) cross-cuts D₃ and D₄ structures but is weakly deformed, suggesting emplacement during the late stages of D₄, bracketing the timing of D₃ and D₄ deformation to between 94 and 76 Ma. A late crenulation lineation (L₅) is sporadically developed throughout the region affected by D₃ and D₄. The crenulation lineations commonly have a gentle plunge to the west-northwest or east-southeast.

**Eocene deformation**

During the Eocene, several large normal fault structures developed in the study area: the PTF, Midge Creek fault, Blazed Creek fault, Next Creek fault, and Huscroft fault.

**Purcell Trench fault**

The PTF is an east-side-down normal fault that extends from Coeur d’Alene, Idaho, north, to the west arm of Kootenay Lake in southeast British Columbia (Daly 1912; Kirkham and Ellis 1926; Anderson 1930; Miller and Engels 1975; Rhodes and Hyndman 1984; Rehrig et al. 1987; Doughty and Price 2000). The PTF is not visible at surface, but is assumed to occupy the topographic
Fig. 4. Vertical lithological cross sections and accompanying metamorphic sections showing the orientation of isograds: (a, b) A–A’; (c, d) B–B’; (e) C–C’. The lines of section are shown in Fig. 3. Lithological cross sections are modified from Leclair (1988; A–A’), Brown et al. (1999; B–B’), and Fyles and Hewlett (1959; C–C’). No vertical exaggeration. [Colour online.]
Fig. 5. (a) Panoramic view to the north of the Laib syncline from the Summit of Wolf S3. The syncline is a large Early Jurassic isoclinal fold structure that plunges shallowly to the north-northeast and a steeply east-dipping axial plane. (b) Lineated, granodiorite from the Baldy pluton. (c) Tight isoclinal folding of pegmatite dyke, hosted in the Aldridge Fm. Location is on Highway 3, in the footwall of the Purcell Trench fault. The penetrative foliation (S₃) is axial planar to the fold hinges. (d) Isoclinal F₃ folds in schists of the Aldridge Formation. Fold axes plunge shallowly to the north-northeast. In the darker pelitic layers, kyanite porphyroblasts define a strong north-northeast-trending mineral lineation. (e) Kyanite (Ky) porphyroblasts define a north-northeast stretching lineation (L₃) in polydeformed Middle Aldridge Fm rock to the west of the Rykert batholith. (f) Gently plunging, recumbent (F₄) fold with subhorizontal axial plane (S₄). Location is on Highway 3, in the footwall of the Purcell Trench fault. Compass with red lanyard for scale. (g) Primary sedimentary features including graded bedding and flame structures in the Rykert block. These structures are situated on the east limb of an overturned regional-scale fold. [Colour online.]
Fig. 6. (a–d) Metamorphic mineral assemblage maps for the four areas highlighted in Fig. 2B. And, andalusite; Bt, biotite; Chl, chlorite; Cld, chloritoid; Crd, cordierite; Ctd, chloritoid; Grt, garnet; Kfs, K-feldspar; Ky, kyanite; Sil, sillimanite; St, staurolite; WCG, West Creston gneiss. [Colour online.]
Fig. 6 (concluded).
and Creston Fm rocks, on the overturned limb of a regional-scale structure known as the Huscroft fault (Figs. 3, 4). Leclair (1988) documented a 25 km right lateral separation of the Neoproterozoic Toby Formation along the fault at the latitude of southern Kootenay Lake (Figs. 2A, 3). Combined with marked lateral changes in stratigraphic thicknesses of Neoproterozoic units across the fault, he interpreted that the present PTF developed at the site of a Neoproterozoic, syndepositional, east-side-down, normal fault (Leclair 1988).

At the latitude of Creston, the fault separates sillimanite zone rocks in the footwall (west) from biotite zone rocks in the hanging wall (east). The contrast in metamorphic grade is accompanied by a 25 million years abrupt change in $^{40}$Ar/$^{39}$Ar cooling ages across the fault (45–70 Ma; Archibald et al. 1984; Webster 2016). To the north, adjacent to the west arm of Kootenay Lake, regional sillimanite zone rocks extend across the Purcell trench, and there is no contrast in $^{40}$Ar/$^{39}$Ar cooling ages (ca. 50 Ma; Webster 2016).

**Huscroft fault**

In the footwall of the PTF, west of Creston, is a folded fault structure known as the Huscroft fault (Figs. 3, 4c, 5g). In the hanging wall of the Huscroft fault is a sequence of overturned Aldridge and Creston Fm rocks, on the overturned limb of a regional-scale fold (Figs. 3, 4c, 5g). The structural style and low metamorphic grade (up to garnet zone) are similar to those observed in the hanging wall (east) of the PTF (Figs. 4c, 4d). These contrast markedly with the rocks in the footwall of the Huscroft fault that are polydeformed and typically contain the metamorphic mineral assemblage: sillimanite ± kyanite ± staurolite ± garnet + muscovite + biotite + quartz.

Where the fault zone crops out in the Rykert batholith it consists of a gently subhorizontal north-dipping mylonitic foliation that transitions northwards out of the batholith into a zone of extensive brecciation and chloritization. The Huscroft fault is cut by the PTF; therefore, a significant component of the large amount of contrast in metamorphic grade across the PTF, north of the Rykert block, appears to have been accommodated by the Huscroft fault. The ductile–brittle nature of the Huscroft fault and normal sense of motion is analogous to that observed south of the border along the Newport fault system.

**Blazed Creek and Next Creek faults**

The Blazed Creek fault is a contentious structure interpreted to extend from the Canada-US border northwards to the southern edge of the Mine stock (Figs. 2A, 3). Rice (1941) initially mapped the Blazed Creek fault as a steeply dipping, west-side-down normal fault. More recent studies (Brown et al. 1995), combined with mapping from this work, failed to identify any field-based evidence for the structure. Detailed mapping in the region is hampered by limited outcrop and a lack of good marker units. The proposed location of the Blazed Creek fault links with the Eastern Newport fault, south of the US border.

To the immediate north of the Blazed Creek fault is another late fault, the north-northwest-trending Next Creek fault (Figs. 2A, 3, 4a). The Next Creek fault appears to be either a continuation of the speculated Blazed Creek fault, or a related structure that initiated at the northern tip of the Blazed Creek Fault. Several silicified, brecciated zones, each 10–20 m wide, were observed along the trace of the Next Creek fault within the Mine stock. The dip of the Next Creek fault is unclear; however, the decreasing metamorphic grade to the west suggests it is also a steeply dipping, west-side-down fault (Fig. 4a).

**Midge Creek fault**

The Midge Creek fault is a steeply west-dipping fault that was first interpreted by Leclair (1988) as an east-directed thrust fault that was progressively steepened and locally overturned at the highest structural levels. Vogl (1992) interpreted some later west-side-down normal motion along the fault that postdated emplacement of the southerly tail of the Nelson batholith. Moynihan and Pattison (2013) interpreted the Midge Creek fault as a strand of a larger Eocene fault zone that encompasses the Midge Creek, Gallagher, Lakeshore, and Josephine faults. A significant change in $^{40}$Ar/$^{39}$Ar cooling ages, grade and age of metamorphism, and structural style across the fault zone indicate this as an important metamorphic and geochronological boundary (Vogl 1992; Moynihan and Pattison 2013; Webster 2016; Webster et al. 2017).

**Regional metamorphism**

Regional metamorphic zones are presented in Figs. 2B and 6a–6d, and are based on the distribution of metamorphic index minerals in pelitic and semipelitic rocks. They have been compiled from observations of this study and those of previous studies (Glover 1978; Archibald et al. 1983; Leclair 1988; Doughty et al. 1997; Moynihan and Pattison 2013). The regional metamorphic grade in the study area is predominantly of chlorite or biotite zone (green-schist facies), apart from two discrete, elongate domains of Barrovian (amphibolite-facies) rocks that merge into one another (Fig. 2B). The first is a ~100 km long, north–north-east-trending belt that extends northwards from west of the Baldy pluton, in the footwall of the Midge Creek fault, to the northern end of Kootenay Lake (Fig. 2B). The structural and metamorphic evolution of this domain was described by Moynihan and Pattison (2013). The second domain, which is the primary focus of this study, is a south-southeast-trending belt in the footwall of the PTF. It extends for over 60 km along the west side of southern Kootenay Lake, broadening from a width of ~10 km north of the Midge Creek stock to ~25 km at the latitude of Creston, before continuing south into the US (Fig. 2B). These two metamorphic belts are part of an elongate, >600 km long, 2–100 km wide metamorphic domain that has been traced from Idaho to the Cariboo Mountains, at approximately 53°30'N (Symons and Carr 2011, and references therein).

In the northern part of the study area, the amphibolite-facies belt forms a forked isograd pattern, south of which is a domain of low metamorphic grade (Fig. 6a). The forked isograd pattern reflects a synformal structure of isograd surfaces between two elongate metamorphic highs, interpreted to represent the flanks of metamorphic antiforms (cross section A–A' in Fig. 4b; fig. 11 in Moynihan and Pattison 2013). The western antiformal domain is intruded by the Midge Creek fault, and the eastern antiformal domain is truncated on its eastern flank by the PTF. North of the west arm of Kootenay Lake, the elongate domal culmination in
metamorphic grade seen in Fig. 2B represents an antiformal structure of the isograd surfaces that is fault-bounded to the west side by the Midge Creek – Gallagher fault system (see fig. 11 of Moynihan and Pattison 2013).

Low-grade (chlorite–biotite–chloritoid) zone

The lowest metamorphic grade is represented by semipelitic and pelitic rocks containing combinations of chlorite, biotite, and chloritoid, broadly corresponding to the greenschist facies. Rocks of this grade occur primarily in the southwest of the area and in the eastern part of the area, east of (in the hanging wall of) the PTF (Fig. 6c). These rocks range from pale green crenulated phyllites to fine-grained schists, characterized by the assemblage: muscovite + chlorite + plagioclase + quartz ± biotite ± chloritoid ± tourmaline (Fig. 7a). Chlorite occurs within the foliated matrix and less commonly as post-kinematically porphyroblasts that overgrow the foliation. Chloritoid is primarily observed north of the Mine and Wall stocks in aluminous rocks of the Windermere Supergroup and Cambrian clastic strata (Figs. 2, 3, 6a–6d). In one isolated locality, east of the southern tip of the Baldy pluton, garnet was observed in the low-grade zone (Fig. 6b) in an assemblage of garnet + biotite + muscovite + chlorite + chloritoid + quartz (Fig. 7c), most likely reflecting an unusual (probably Mn-rich) bulk composition.

Garnet zone

The garnet zone occurs adjacent to the low-grade zone outlining the isograd synform (Fig. 2B). It is subdivided into an eastern zone that is broadly parallel to Kootenay Lake and occurs in the footwall of the Blazed and Next Creek faults, and a western zone that occurs to the east, in the footwall of the Midge Creek fault. Garnet zone rocks also occur in the Rykert block in the hanging wall of the Huscroft detachment fault, adjacent to the town of Creston (Fig. 6c).

Metafolitic rocks from the garnet zone are typically fine-grained crenulated schists that contain the assemblage: garnet + biotite + muscovite + plagioclase + quartz ± chlorite ± chloritoid (Fig. 7b).

Microstructural investigations provide insight concerning the timing of metamorphic mineral growth with respect to deformation fabrics. Garnet porphyroblasts from the garnet zone east of the Midge Creek stock, in the footwall of the PTF (Fig. 6a), contain straight inclusion trails that are oblique to the enveloping S,(Figs. 7b; sample 250). Similar observations are made in garnet-bearing rocks north of the Wall stock (Fig. 6b), in which garnets contain straight inclusions trails (S2) that are at a high angle to the enclosing micaceous fabric, S4 (Fig. 7c). Therefore, the metamorphism (M4) in these areas occurred prior to, and was outlasted by, D3 deformation.

Staurolite zone

A poorly defined staurolite zone occurs upgrade of the garnet zone, paralleling the garnet zone map pattern (Fig. 2B). The staurolite zone assemblage, staurolite + garnet + biotite + muscovite + plagioclase + quartz, is sporadically developed throughout this zone (Figs. 6a–6d). The staurolite occurs as either large poikiloblasts (~3 mm; Fig. 7d), or as small blocky crystals (0.5 mm).

In a sample, south of the westward protruding arm of the Drewry Point intrusion (Fig. 6a; sample 126), within the domain of D2 deformation, poikiloblastic staurolite has enveloped garnet porphyroblasts (Fig. 7d), implying staurolite growth postdating garnet. Farther south, within the domain of Late Cretaceous D3 deformation, in the footwall of the Next Creek fault, a sample from the staurolite zone (Fig. 6b; sample 926) contains garnet porphyroblasts that are wrapped by the dominant micaceous fabric (S3). The staurolite porphyroblasts are either wrapped by the same fabric, or grow across it, suggesting that M3 metamorphism is broadly coeval with D3 deformation in this region.

Kyanite zone

In the footwall of the PTF a narrow, ~1 km wide kyanite zone occurs directly upgrade of the staurolite zone (Fig. 2B) and is confined to rocks of the Belt–Purcell Supergroup. The rocks are coarse-grained schists containing the assemblage kyanite + biotite + muscovite + quartz ± staurolite ± garnet (Fig. 7e). Kyanite typically forms elongate porphyroblasts (1 mm to 10 cm).

Northeast of the Midge Creek stock (Fig. 6a; sample 283), 10 cm long kyanite porphyroblasts are oriented within the plane of the dominant foliation, S3, and define a well-developed mineral lineation (L5), that is parallel to F2. Kyanite zone rocks from the footwall of the Midge Creek fault display sigmoidal inclusion trails in garnet porphyroblasts that are continuous with the matrix foliation (S2; Fig. 7f). The observations described earlier suggest that M2 metamorphism and D2 deformation were broadly contemporaneous, but that D3 outlasted M2.

At the latitude of Creston, kyanite is locally observed randomly oriented within the plane of foliation (S2; Fig. 7f), yet more commonly defines a shallowly plunging mineral lineation within the plane of S3 (Figs. 5d, 5e), and parallel to F3 fold axis. These fabrics suggest that D3 deformation was probably coeval with M3 metamorphism.

Sillimanite zone

At the latitude of Creston, the sillimanite zone is a broad region ~15 km wide. It narrows northward towards the west arm of Kootenay Lake (Fig. 2B), merging with the band of sillimanite zone rocks of the north-northeast-trending belt of metamorphism. Throughout this zone, coarse-grained schists are characterized by the assemblage sillimanite ± kyanite ± staurolite ± garnet + biotite + muscovite + plagioclase + quartz ± rutile (Figs. 7g, 7h). Sillimanite typically forms aggregates of fine-grained fibrolite, although in places is coarse grained and prismatic. Where present, staurolite typically appears as wormy embayed relics that suggest they are unstable in the assemblage (Fig. 7g). Kyanite coexists with sillimanite; however, it is rarely directly pseudomorphed by sillimanite. Sillimanite is typically surrounded by intergrowths of quartz and coarse-grained muscovite. If garnet is present, it commonly includes inclusions of sillimanite (Fig. 7g), suggesting coeval growth of both minerals or late garnet growth.

North of the Drewry Point intrusion, sillimanite is aligned in the plane of foliation (S3) and forms a mineral lineation (L5), which again parallels the F3 fold axis. South of the Shaw Creek stock, sillimanite is typically parallel to S3 (Figs. 7g, 7h), however, in places forms radiating mats with no preferred orientation. Locally garnet rams have overgrown a sillimanite fabric (L5; Fig. 7g). The combined interpretation of these textural relationships suggests that in the northern sillimanite zone D2 outlasted M3, but south of the Shaw Creek stock M3 and D3 are broadly coeval.

Contact metamorphism

Contact aureoles have developed in proximity to a number of the intrusive bodies in the region and have distinct textures and mineral assemblages that make them distinguishable from the regional metamorphism. Contact mineral assemblages found adjacent to igneous intrusive bodies can be broadly broken down into two distinct types: (1) those dominated by cordierite + andalusite, and (2) those dominated by staurolite + andalusite, with both types developing sillimanite closer to the igneous contacts. According to the analysis of Pattison and Tracy (1991) and Pattison and Vogl (2005), the two different suites are indicative of lower pressure and higher pressure conditions, respectively (Fig. 8).

The absolute values of the pressure bands in Fig. 8 (Pattison et al. 2002; Pattison and Vogl 2005; Pattison and DeBuhr 2015) are tightly constrained by the phase equilibria and are calculated for the bulk composition of average worldwide metapelite (Mg/(Mg + Fe) = 0.45), close to the value for the pelite compositions of this study. The resultant pressure ranges are 3.5–4.2 kbar (1 kbar =...
**Middle Jurassic: Mine and Wall stocks (171–167 Ma)**

The Middle Jurassic Mine and Wall stocks (171 and 167 Ma) have locally imparted a well-developed contact aureole in regional low-grade rocks of the Windermere Supergroup (Figs. 2B, 6b). The aureole is especially well developed in pelitic rocks of the aluminous Monk Formation along the southern and northern margin of the intrusions, whereas along the western margin where psammitic rocks predominate, the contact metamorphic zones are not observable. The lowest-grade development of andalusite porphyroblasts along the southern margin of the aureole occurs approximately 1.5 km from the igneous contact. Approximately 300 m upgrade of the contact andalusite isograd, staurolite porphyroblasts become visible in the rocks, followed by sillimanite a further 250 m upgrade of the contact staurolite isograd. Microtextures indicate that staurolite predates andalusite, suggesting that the first development of andalusite farther from the igneous contact than the first development of staurolite is due to bulk compositional factors.

Within the contact aureole, several occurrences of kyanite have been identified. Two samples (Z-74 and A-109; Fig. 6b) contain three alluminosilicate phases: andalusite, kyanite, and sillimanite (Fig. 9a). U–Pb geochronology in conjunction with $^{40}$Ar/$^{39}$Ar thermochronology on the kyanite-bearing samples constrain the age of this metamorphism to Middle–Late Jurassic (Webster 2016; Webster et al. 2017), the same age as the Mine and Wall stocks, and older than the Cretaceous regional kyanite zone metamorphism to the north and east of the Mine and Wall stocks (Figs. 2B, 6a, 6c). The textures of the kyanite-bearing rocks are similar to those of the contact metamorphic kyanite-free, andalusite + staurolite-bearing rocks. Garnet crystals have sigmoidal inclusion trails that are oblique to the matrix fabric and are locally partially enveloped by large andalusite porphyroblasts. Andalusite has grown across the $S_1$ fabric, as revealed by inclusion trails parallel to the matrix foliation (Fig. 9f). Staurolite is sporadically developed throughout the matrix, is commonly small (<1 mm), found as inclusions in andalusite, and is typically replaced by sericite. A second, younger foliation is partially developed in rocks from this area (Fig. 9g). Both the andalusite and staurolite overgrow the younger $S_2$ fabric (Figs. 9f, 9g), suggesting the stock is Early Cretaceous and part of the Bayonne magmatic suite.

**Middle Jurassic: Porcupine Creek stock (162 Ma)**

The Porcupine Creek stock is an undeformed Middle Jurassic intrusion (162 Ma; Webster et al. 2017) within the regional low-grade $D_3$ zone (Figs. 2B, 3, 6b). The host rocks are dark black, graphitic slates of the Active Formation with a well-developed penetrative cleavage ($S_2$). The first development of porphyroblasts occurs about 500 m from the intrusive contact, with both cordierite and andalusite occurring together (Fig. 9e). Samples within the aureole contain cordierite, andalusite, both, or neither, implying bulk compositional control. Both cordierite and andalusite are undeformed, have abundant fine-grained inclusions, and have grown across the foliated graphitic matrix. Where both porphyroblasts are in contact with one another, cordierite grows around the andalusite, suggesting cordierite postdates the growth of andalusite (Fig. 9e).

**Middle Jurassic or Early Cretaceous: Wurrtemberg stock**

The Wurrtemberg stock (Fig. 6a) is a small, granodioritic intrusive body emplaced into the Cambrian Laib and Hamill formations, within the low-grade region between the Nelson batholith and Steeple Mountain pluton (Figs. 2B, 6a). It is unclear whether the small stock is part of the Middle Jurassic Nelson plutonic suite or part of the mid-Cretaceous Bayonne magmatic suite; the intrusion is constrained to be older than 106 Ma from muscovite $^{40}$Ar/$^{39}$Ar dating (Webster 2016). The contact aureole extends up to 1000 m from the intrusive contact and has a well-developed prograde mineral sequence represented by andalusite, staurolite, and sillimanite contact isograds (Fig. 6a).

Garnet crystals have sigmoidal inclusion trails that are oblique to the matrix fabric and are locally partially enveloped by large andalusite porphyroblasts. Andalusite has grown across the $S_1$ fabric, as revealed by inclusion trails parallel to the matrix foliation (Fig. 9f). Staurolite is sporadically developed throughout the matrix, is commonly small (<1 mm), found as inclusions in andalusite, and is typically replaced by sericite. A second, younger foliation is partially developed in rocks from this area (Fig. 9g). Both the andalusite and staurolite overgrow the younger $S_2$ fabric (Figs. 9f, 9g), suggesting the stock is Early Cretaceous and part of the Bayonne magmatic suite.

**Early Cretaceous Midge Creek stock aureole (111 Ma)**

The Midge Creek stock is an Early Cretaceous intrusive body (111 ± 4 Ma; Leclair et al. 1993) situated between the Baldy and Drewwy Point plutons (Figs. 3, 6a). It intrudes penetrative $D_2$ structures and regional metamorphic isograds and is undeformed except at its northern tip where the dominant foliation parallels the regional $S_2$ trend (Leclair 1988). The stock has a well-developed aureole on its northern and eastern margins where it has intruded into the pelitic Monk Formation. The contact aureole extends up to 1 km from the intrusive contact, based on the outermost occurrence of staurolite porphyroblasts, and is characterized by staurolite, andalusite, and sillimanite isograds (Fig. 6a).

The parts of the aureole developed in host rocks of the regional kyanite zone show overprinting relationships. Staurolite occurs in two distinct forms: (1) deformed trains of staurolite intergrown with kyanite within the matrix foliation ($S_3$); locally overgrown by andalusite (Fig. 10a); and (2) staurolite porphyroblasts that are larger and less deformed, are orientated oblique to the fabric, and contain inclusion trails that are continuous with the matrix fabric (Fig. 10b). Large (3–7 mm) andalusite porphyroblasts have over-
grown the penetrative fabric, and have matrix-parallel inclusion trails (Figs. 9h, 10a). Garnet has sigmoidal to straight, inclusion-rich cores that in some grains are overgrown by inclusion-poor rims. We interpret that the staurolite + kyanite + garnet aligned within the S₂ foliation grew during M₂ metamorphism prior to contact metamorphism, and that andalusite, coarse-grained staurolite porphyroblasts oblique to the foliation, and possibly the garnet rims developed during contact metamorphism (Figs. 9h, 10a, 10b).

Southern of the Midge Creek stock, between the Drewry Point pluton and Wurrtemburg stock, is a large domain of andalusite-bearing assemblages identified by Leclair (1988). The complete mineral assemblages were not documented. These samples occur in a domain with no mapped intrusions, most likely indicating the presence of an intrusion of unknown age that is close to the surface, but not exposed.

**Late Cretaceous: Shaw Creek stock (76 Ma)**

The Shaw Creek stock is a Late Cretaceous (76 Ma; Parrish and Monger 1992) intrusion located between the Jurassic Mine stock and the mid-Cretaceous Steeple Mountain plutons (Figs. 3, 6a, 6c). The Shaw Creek stock is a massive biotite granite that is locally foliated around its margins. A contact aureole around this intrusive body has not been identified, possibly owing to the semipelitic protolith and high metamorphic grade (sillimanite zone) of the Belt–Purcell Supergroup in which it is emplaced.

In one sample near the northern tip of the intrusion, an andalusite-bearing assemblage was identified (Fig. 6h). Andalusite porphyroblasts (2–6 mm) are abundant and filled with inclusions of biotite, staurolite ilmenite, and aligned in the S₂ foliation (Fig. 10c). Staurolite crystals are small (~0.1–0.25 mm), blocky, and only found as inclusions within larger andalusite porphyroblasts (Fig. 10c). Kyanite is aligned within the foliation and has fine-grained quartz inclusions that are typically oblique to the foliation. Garnet porphyroblasts have sigmoidal to straight inclinations that are typically oblique to the S₂ fabric that wraps them (Fig. 10c). Fibrolitic sillimanite occurs in radiating mats associated with biotite and quartz; rarely, sillimanite has directly replaced andalusite. These textural observations indicate that an early kyanite + garnet regional metamorphic assemblage was overprinted by an andalusite + sillimanite contact metamorphic assemblage.

**Early Cretaceous Summit stock and Lost Creek pluton aureole (112 Ma)**

The post-kinematic Summit stock (112 Ma; Webster et al. 2017) and Lost Creek pluton are two-mica granites that were emplaced into the Upper Proterozoic Monk Formation and Cambrian Laib, Reno, and Quartzite Range formations. The contact aureole overprints regional chlorite zone assemblages and has a well-developed prograde mineral sequence represented by cordierite + andalusite and sillimanite + K-feldspar isograds. The first development of porphyroblasts is represented by cordierite-bearing spotted slates, in which cordierite overgrows the well-developed regional S₁ slaty cleavage. Andalusite occurs as millimetre-size, elongate porphyroblasts (Fig. 10d).

Within the cordierite + andalusite zone, the occurrence in close proximity of mineral assemblages containing cordierite, andalusite, and cordierite + andalusite suggests variations in bulk composition. At some of these zones, K-feldspar locally occurs in pelitic hornfels containing cordierite, andalusite, and sillimanite. Some of the rocks are migmatitic (Fig. 10e). Sillimanite in this zone typically forms as fibrous mats intergrown with muscovite and quartz, and rarely as a direct replacement of andalusite, with the andalusite commonly showing evidence of resorption.

The contact metamorphic isograds envelop both the Summit stock and Lost Creek plutons, forming a single contact aureole with some of the highest-grade assemblages occurring between the two intrusions (Fig. 6d). It is likely that the two intrusions are connected at depth. The outcrop pattern of the Lost Creek pluton suggests it is a flat-lying, sheet-like intrusion that extends eastwards to the Summit stock.

**Other Cretaceous intrusions**

Other intrusive bodies within the study area have poorly defined contact aureoles, most likely owing to a combination of sample sparseness and bulk compositional control. Andalusite + cordierite-bearing assemblages were identified adjacent to the Early Cretaceous Mount Skelly pluton (109 Ma; Webster et al. 2017) and the Drewry Point intrusion (Fig. 6a).

**Phase equilibria modeling**

The bulk compositions of 23 metapelite samples from the regional and contact metamorphic zones were determined by X-ray fluorescence (XRF) at Acme labs. When plotted on an AFM diagram (Fig. 11), the samples show a narrow Mg/(Mg + Fe) range, whereas the A’ varies significantly. The variation in A’ correlates with stratigraphic unit: rocks of the Windermere Supergroup and Early Paleozoic strata are more aluminous than those of the Belt–Purcell Supergroup. The average Windermere composition plots above the garnet–chlorite tie line, whereas that of the Belt–Purcell plots below (Fig. 11). Rocks of the Monk Formation of the Windermere Supergroup are especially aluminous.

Phase equilibria analysis was combined with the constraints provided by the isograd sequences to estimate the P–T conditions of the regional and contact mineral assemblages. Phase diagrams were constructed using the phase equilibria modeling software Theriax/Domino (de Capitani and Brown 1987; de Capitani and Petrakakis 2010) in conjunction with the thermodynamic database “ds5.5” of Holland and Powell (1998, 2003 update). Activity models used are as follows: plagioclase (Holland and Powell 2003; ternary feldspar, Cbar field); muscovite (Coggon and Holland 2002); chlorite (Tinkham et al. 2001); biotite, ilmenite, and garnet (White et al. 2005); melt (White et al. 2007); all other phases including water (Holland and Powell 1998).

To provide a comparative frame work for the variation in P–T conditions in the region, two representative phase diagrams were
calculated in the chemical system MnNCKFMAST (MnO–Na2O–CaO–K2O–FeO–MgO–Al2O3–SiO2–H2O–TiO2) for the two average whole rock compositions discussed earlier: a high Al pelite representative of the Windermere Supergroup and Early Paleozoic strata, and a low Al pelite representative of the Belt–Purcell Supergroup (Figs. 12A, 12B). Fe3+ was not incorporated in the chemical system because ilmenite is the stable Fe–Ti oxide and magnetite is not present, suggesting relatively low and not strongly varying Fe3+.

P–T estimates for regionally metamorphosed rocks

Peak P–T conditions are estimated by comparison of modeled and observed mineral assemblages for 23 samples, of which rep-
P-T estimates for contact metamorphic rocks

The contact metamorphic aureoles can broadly be divided into those containing cordierite ± andalusite-bearing assemblages or staurolite ± andalusite-bearing assemblages in rocks containing muscovite, biotite, and quartz (Fig. 2B). Although differing bulk composition, in particular Mg/(Mg + Fe), can account for development of these assemblages at the same conditions (Pattison and Vogl 2005), the relatively small observed range of Mg/(Mg + Fe) in the rocks (Fig. 11), and the fact that individual aureoles do not contain mixtures of these assemblages, suggests that the primary control on their development is pressure.

Figure 8 shows the qualitative relations between these assemblages, illustrating how cordierite + andalusite-bearing assemblages occur at lower pressure than staurolite + andalusite-bearing assemblages, and how cordierite-bearing assemblages without andalusite occur at still lower pressures. A narrow pressure interval occurs between the staurolite + andalusite-bearing and cordierite + andalusite-bearing assemblages in which andalusite-bearing assemblages develop without either cordierite or staurolite (Pattison and Tracy 1991; Pattison and Vogl 2005). Within cordierite + andalusite-bearing aureoles, a further pressure discriminant comes from which Al2SiO5 polymorph develops with K-feldspar at the muscovite + quartz breakdown: andalusite (lower pressure) or sillimanite (higher pressure).

The pressure ranges of Fig. 8 are shown as pressure bands in Fig. 12. These ranges may be displaced by a combined ±0.3 kbar for the most common range of whole rock Mg/(Mg + Fe), 0.4–0.5, and the presence or absence of graphite (Pattison et al. 2002; Pattison and DeBuhr 2006). The pressure bands provide more restrictive pressure limits than indicated by the calculated stability range of the assemblages in some of the phase diagrams in Fig. 12, in particular cordierite + andalusite assemblages that are predicted to be stable as low as 1.5 kbar. Phase diagrams in Fig. 12 were calculated using the thermodynamic database of Holland and Powell (1998, 2003 update), which predicts cordierite-bearing phase equilibria that are at odds with natural constraints (Pattison et al. 2002; Pattison and DeBuhr 2015). We therefore favour the pressure estimates represented by the pressure bands of Pattison and Vogl (2005).

The Jurassic Mine and Wall stocks are largely hosted within the Al-rich Monk Formation of the Windermere Supergroup and have staurolite + andalusite + biotite-bearing assemblages developed in their contact aureoles, implying a pressure range of 3.5–4.2 kbar (13–15 km depth). An unusual feature of these aureoles is the occurrence of kyanite in three localities within the aureole (Figs. 6b, 9a). As described earlier, textural criteria demonstrate that kyanite developed prior to staurolite and biotite, all of which formed before andalusite and sillimanite.

Modeling in the MnNCKFMASHT system with both average bulk compositions or more Al-rich compositions of the Monk formation (Figs. 12A, 12B) fails to predict a stability field for kyanite at low grade; whereas samples from the Monk formation (EW11BC03; Fig. 6b), when modeled in the simpler KFMASH system (Fig. 12E), predict a kyanite stability field downgrade of the latter. These have the effect of reducing the amount of Al available to form AFM minerals like kyanite and staurolite, thereby reducing...
ing their stability compared with KFMASH (compare Figs. 12B and 12E). The prediction of a stability field for kyanite in KFMASH at relatively low grade, consistent with the observations, raises the possibility that plagioclase did not fully participate in the reactive bulk composition under these relatively low-grade conditions.

The staurolite + andalusite + biotite assemblages in the aureoles of the Midge Creek, Wurrtemberg, and Shaw Creek stocks (Figs. 6a–6d) suggest a pressure range of 3.5–4.2 kbar, comparable to that of the Jurassic Mine and Wall stocks (Fig. 12B), but perhaps a little lower in pressure owing to the absence of kyanite. Lower pressure cordierite-bearing mineral assemblages found adjacent to numerous intrusions developed in the pressure range 2.5–3.3 kbar, equivalent to a depth range of 9–12 km (Fig. 12C).

**Discussion**

From the observations, the thermotectonic evolution of the study area can be inferred. This evolution reflects the development of the Canadian Cordillera from a small accretionary orogen in the Early to Middle Jurassic to a large, 800–900 km wide, bivergent orogen in the Late Cretaceous (Archibald et al. 1983; Webster 2016). The domain where D1 and M1 are developed is continuous with the elongate antiformal Barrovian culmination centred over northern Kootenay Lake (Fig. 2B), described by Moynihan and Pattison (2013). The age of metamorphism of this more northerly Barrovian domain was constrained using monazite U–Pb geochronology to the period 144–134 Ma (Moynihan 2012), overlapping with ages documented elsewhere within this belt (Digel et al. 1998; Reid et al. 2003). As found in the northern part of the study area, this M1 metamorphism was outlasted by D2 deformation.

Assuming the age of regional M2 metamorphism is about the same as farther north, the kyanite zone regional assemblages in the study area were formed at ~25 km depth in the period 144–134 Ma, and were then exhumed approximately 10 km before the emplacement of the Midge Creek stock at 111 Ma.

Regionally deformed Barrovian metamorphic rocks in the footwall of the PTF are cross-cut by the westward protruding arm of the Drewry Point pluton (Fig. 2). The intrusion is undated, but based on the mineralogy and texture (Leclair 1988), the pluton is considered to be part of the Cretaceous Bayonne magmatic suite (ca. 120–90 Ma), thereby constraining the deformation and metamorphism in this area to Early Cretaceous.

In addition to the domains of D1 deformation and M1 metamorphism in the northern area, a domain of mid-Cretaceous (100–90 Ma) biotite and muscovite cooling ages (Archibald et al. 1983; Webster 2016) exists in the south of the area in garnet zone rocks in the footwall of the Blazed Creek fault (Figs. 6a–6d, 14). This suggests that the regional metamorphism of these rocks occurred during the Early Cretaceous. Structural and geochronological evidence suggests that the rocks of higher metamorphic grade to the east of the garnet zone developed in the Late Cretaceous, suggesting a cryptic overprinting relationship in a metamorphic zonal sequence that appears to be continuous (Fig. 6c). This point is discussed in more detail in the following text.

**Late Cretaceous (94–70 Ma)**

Continued crustal thickening in the southern Omineca Belt during the Cretaceous (Evenchick et al. 2007, and references therein) culminated in large regions of high-grade metamorphic rocks and metamorphic core complexes (Fig. 1). These exhibit a downward-younging trend in the timing of deformation and metamorphism from the overlying supracrustal sequences (Simony and Carr 2011, and references therein). A similar trend is observed in the study area as progressively deeper structural levels are exposed from west to east (Fig. 13). Jurassic through Early Cretaceous metamorphism and deformation in the southern part of

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**Early Cretaceous (145–111 Ma)**

The Early Cretaceous, ~500 km long, Barrovian metamorphic complex that occupies much of the eastern internal zone of the southeastern Canadian Cordillera in the Purcell, Selkirk, and Carrie mountains of southeastern British Columbia (Simony and Carr 2011) can be traced southwards into the study area (Moynihan 2012; Moynihan and Pattison 2013, this study).

The domain where D2 and M2 are developed is continuous with the elongate antiformal Barrovian culmination centred over northern Kootenay Lake (Fig. 2B), described by Moynihan and Pattison (2013). The age of metamorphism of this more northerly Barrovian domain was constrained using monazite U–Pb geochronology to the period 144–134 Ma (Moynihan 2012), overlapping with ages documented elsewhere within this belt (Digel et al. 1998; Reid et al. 2003). As found in the northern part of the study area, this M2 metamorphism was outlasted by D2 deformation.

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**Fig. 12.** (A, B) Thermodynamically calculated equilibrium-assemblage diagrams for the two average bulk compositions (see text) in the MnNCKFMASH (MnO-Na2O-CaO-K2O-FeO-MgO-Al2O3-SiO2-H2O-TiO2) system. A thick purple line marks the garnet-in reaction. The grey bands are representative of pressure ranges for cordierite ± andalusite and staurolite ± andalusite contact metamorphism. The interpreted metamorphic field gradient is illustrated with a dashed grey line. (C) P–T summary diagram showing the stability fields for peak metamorphic assemblages. The stability fields are taken from individual equilibrium-assemblage diagrams that are modeled in MnNCKFMASH. The samples span a range of metamorphic zones; an estimated field gradient is shown. Several contact metamorphic assemblages, also modeled in MnNCKFMASH, are superimposed on the diagram and help constrain contact metamorphic pressure conditions. (D) P–T diagram showing peak metamorphic assemblages of samples from the northern and southern parts of the study area, all within the regional sillimanite zone. Individual equilibrium-assemblage diagrams were again calculated in MnNCKFMASH. There appears to be no difference in the modeled P–T estimates from the north and south. (E) Equilibrium-assemblage diagram for the average high Al pelite bulk composition, modeled in the reduced chemical system KFMASH. An isobaric metamorphic field gradient is shown for the Jurassic Mine stock. Ep, epidote; Ilm, ilmenite; ma, margarite; Pi, plagioclase; Ru, rutile; Sp, sphene; Prg, paragonite. [Colour online.]
study area merge eastward into a domain between the Purcell Trench and Blazed Creek-Next Creek faults (Figs. 6c, 13) that records a third episode of regional metamorphism (M₃), and a third (D₃) and fourth (D₄) episode of deformation. The cross-cutting relationships and textural and geochronological data present suggest broad contemporaneity of M₂ and D₂ in the interval 94–76 Ma, overlapping with 82 Ma pegmatite deformed within D₃. These ages are comparable to Late Cretaceous (82 Ma) metamorphic monazite ages from the Corn Creek gneiss (Brown et al. 1999), and to metamorphic monazite ages from the Corn Creek gneiss (Stein et al. 2015). These are higher than the peak conditions of the muscovite-bearing, sillimanite zone rocks in the southern part of the study area and in the adjacent Selkirk Crest (Fig. 1) in northern Idaho (6.7 kbar and 650–675 °C). These differences indicate that the study area, and by extension the Selkirk Crest, are less deeply exhumed portions of the Priest River Complex, consistent with the north-plunging domal geometry of the Priest River Complex.

Paleogene (65–50 Ma)

Final exhumation of the region was accommodated, in part, by Eocene ductile–brittle shear zones and faults. These are of a similar character and age as those bounding many of the core complexes of the Omineca Belt of southeastern British Columbia (e.g., Valhalla complex: Carr et al. 1987, Parrish et al. 1988; Grand Forks: Cubby et al. 2013; Priest River Complex: Doughty et al. 1998). In the study area, these faults comprise the Midge Creek–Gallagher fault system, PTF, and the Huscroft fault (Fig. 2).

The Huscroft fault system (Fig. 4d) juxtaposes rocks of markedly different metamorphic grade (biotite zone in hanging wall versus sillimanite zone in footwall), indicating a significant amount of
Fig. 14. Map illustrating different age domains of deformation and regional metamorphism. The age of metamorphism and deformation in the eastern area of the map is of unknown age, but is assumed to be Proterozoic. [Colour online.]
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