The southern tail of the Nelson batholith, southeast British Columbia: emplacement and deformation along a terrane accretion zone

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Abstract

The terrane accretion zone (TAZ) in the Kootenay arc of southeast British Columbia was intruded by Mid-Jurassic plutons, which have been commonly used to constrain the age of terrane accretion and regional deformation. These plutons display a range of geometrical shapes, concordance of contacts, and strain characteristics, suggesting that classification as pre-, syn- or post-tectonic, may be an oversimplification that obscures important spatial and temporal strain patterns. The Middle-/Late-Jurassic Nelson batholith comprises an ~1500 km² largely unfoliated main body and a 25 km-long, southward-narrowing, foliated tail that occurs within the TAZ. The ca. 166 Ma tail was mapped to address emplacement processes and to delineate the timing, kinematics, and spatial distribution of strain within the evolving TAZ.

The tail comprises at least five subvertical, compositionally distinct granitic sheets that are separated by screens of country rock. The western and northeastern granite-host contacts are generally concordant and demonstrably intrusive, but the east margin coincides with a mylonitic shear zone. Granitic rocks of the tail display gently plunging lineations and pervasive steep foliations that increase in intensity toward the eastern mylonite zone. These fabrics record regional dextral transpression that was focused within the TAZ. Deformation culminated with formation of the eastern mylonite zone as strain became concentrated within the Midge Creek fault. Kinematic indicators from the eastern mylonite zone indicate both subhorizontal dextral motion and east-side-up motion, which we interpret as forming after steepening of the fault, subsequent to significant top-to-the-east thrusting. Thus, granite tectonites of the tail record a kinematically evolving TAZ zone.

Field observations suggest that the tail formed by coalescence of magmatic sheets, with magma injection guided by steep bedding planes and faults. Despite the fact that sheets were emplaced at a high angle to the regional shortening direction, space appears to have been created by wedging apart of the bedding planes along most of the length of the tail. We suggest that the tail is largely a primary intrusive feature, resulting from southward flow of magmas away from the main body induced by horizontal
shortening during inhomogenous dextral transpression. Syn-emplacement and subsequent solid-state
dextral shearing also helped shape the final geometry of the tail.

INTRODUCTION

The manner in which strain is partitioned in evolving orogens is an issue that is central to our
understanding of the evolution of mountain belts. Documentation of such strain partitioning requires
extensive dating of fault movements and penetrative strain fabrics, but is hindered by limitations of
commonly applied isotopic techniques. In deformed areas affected by magmatism, however, structural
studies of plutons and their aureoles can provide an important means of bracketing ages for fabrics and
faults. The effective use of plutons as age markers for regional deformation requires detailed
observations/mapping throughout the pluton, its aureole, and into adjacent areas (e.g., Paterson and
Tobisch, 1988). Such observations are also critical for assessing mechanisms of pluton emplacement and
the relationships between magma emplacement and regional structures.

The Kootenay arc in southeast British Columbia is an arcuate structural zone where island arc and
marginal basin terranes have been thrust onto the North American miogeocline and its distal equivalents
(Figs. 1-3). The region is intruded by Mid-Jurassic subduction-generated granitic plutons that have been
widely used to bracket the age of regional deformation within the Kootenay arc (e.g., Little, 1960; Fyles,
1964; Crosby, 1968; Archibald et al., 1983). The Mid-Jurassic plutons are generally regarded as late syn-
to post-kinematic with respect to the dominant folding and foliation-forming deformation in the region
(e.g., Archibald et al., 1983). However, the Mid-Jurassic plutons vary greatly in structural characteristics,
ranging from unfoliated to strongly foliated, and from elongate concordant shapes to discordant “blobby”
shapes. Furthermore, there is no obvious correlation between pluton age and structural characteristics,
with plutons yielding identical U-Pb crystallization ages displaying vastly different structural
characteristics. Adding to the ambiguity is the fact that although deformation in the Kootenay arc is
widely regarded as early to Middle Jurassic, a strongly foliated elongate granitic pluton has yielded a
Cretaceous (ca. 117 Ma) U-Pb age (Leclair et al., 1993).
These relationships raise many questions regarding both the age and origin of the foliations in the Mid-Jurassic plutons and the progressive structural development of the Kootenay arc. When did the foliations form? Are the foliations the result of emplacement-related strains or syn-to post-emplacement tectonic strains? What are the controls on the spatial distribution of strained vs. unstrained and blobby vs. elongate plutons? What is the relationship between deformation and pluton-emplacement mechanisms?

We have addressed these questions through a study of the Nelson batholith, which occurs within the terrane accretion zone in the central and southern Kootenay arc (Fig. 1). The composite batholith consists of a largely unfoliated and discordant northern mass of about 1500 km² main body and a foliated 25 km-long southward-protruding "tail" (Figs. 1-3). It therefore spans the range of structural characteristics observed in the Mid-Jurassic plutons. Our study consisted of mapping the geometries of various granitic phases of the tail, delineating the nature of the contacts with the metasedimentary host rocks, and mapping the character of strain fabrics (fabric orientations, amount and type of strain, and physical conditions during strain accumulation) through field and petrographic observations. In this paper we report the results of this work and discuss the significance with regard to the structural evolution of the terrane accretion zone and the processes of magma emplacement.

REGIONAL GEOLOGIC SETTING

Stratigraphic ties and detrital zircon studies indicate that, prior to Jurassic juxtaposition and pluton emplacement, the terrane assemblages of the Kootenay arc were deposited outboard of, but in proximity to, the North American craton. (Klepacki, 1985; Colpron and Price, 1995, Smith and Gehrels, 1991). Juxtaposition by thrust faulting and folding of the assemblages began by the latest Early Jurassic (Höy and Andrew, 1989; Andrew and Höy, 1991; Murphy et al., 1995). The major assemblage-bounding faults (Waneta, Midge Creek and Seeman Creek-Oxide faults) in the study area are interpreted as east-directed thrust faults that have been progressively steepened and locally overturned at the highest structural levels in the southern part of the area (Figs. 2 & 3; LeClair, 1988; Einarsen, 1994). Well-documented kinematic histories and precise timing constraints are lacking for these faults. We loosely refer to the area near the main assemblage-bounding faults as the terrane accretion zone (TAZ).
Jurassic deformation led to the development of a regional axial-planar foliation and metamorphism that ranges from lower greenschist to upper amphibolite facies. The regional distribution of isograds delineates a north-south-trending metamorphic culmination that reaches sillimanite-grade near Kootenay Lake (e.g., Archibald et al., 1983). The Nelson batholith intruded chlorite- and biotite-grade rocks (Beddoe-Stephens, 1981; Powell and Ghent, 1996; Pattison and Vogl, 2004) that lie on the west flank of this metamorphic culmination. Porphyroblast-matrix relationships in parts of the contact aureole of the batholith have led to the suggestion that emplacement occurred during the last stages of penetrative deformation and regional metamorphism (Fyles, 1967; Crosby, 1968; Archibald, 1983). Throughout most of the Kootenay Arc, penetrative deformation and metamorphism appear to have ceased by the latest Jurassic and the focus of deformation shifted to deeper structural levels, which are now exposed farther east (Archibald et al., 1983, 1984), as well as to the west in the Valhalla complex (e.g., Carr et al., 1987; Schaub et al., 2002).

Widespread Eocene normal faults indicate a change from regional shortening to extension (Parrish et al., 1988). One of the largest of the normal faults, the shallowly dipping Slocan Lake fault with a displacement of 10 - 30 km, bounds the west margin of the main body of the Nelson batholith (Fig. 2) and has produced a strong fabric in the Nelson granitic rocks (Carr et al., 1987). A series of W-dipping faults mapped by Fyles (1967) near the east margin of the main body of the Nelson batholith, referred to collectively as the Ainsworth faults, have been interpreted as thrust faults that were reactivated as normal faults during Eocene extension (Carr et al., 1987).

THE NELSON BATHOLITH - PREVIOUS WORK

The Nelson batholith is composed of numerous granitoid (tonalite to granite) phases that are largely unfoliated, with granite-host contacts that are generally discordant but locally deflect the regional layering into concordance (Cairnes, 1936; Hedley, 1952; Little, 1960; Fyles, 1967; Brown and Logan, 1988). In contrast, McAllister (1951) and Little (1964) described pervasive foliations in the elongate tail that is broadly parallel to regional structures and suggested that the granite of the tail formed by metasomatism (granitization). U-Pb dating indicates that the different phases of the main body were intruded between
The only U-Pb date from the tail (southern tip; Fig. 3) yielded a well-defined chord for three slightly discordant zircon fractions yielding a lower intercept age of 166.0 ± 3 Ma (Ghosh, 1995a), indicating that the tail was emplaced during construction of the main body of the batholith. U-Pb titanite and zircon data from quartz monzonite outcropping near the city of Nelson yield indicate a crystallization age of 61±1 Ma (Sevigny and Parrish, 1993). The extent of this Paleocene intrusion was delineated in figure 2 by our reconnaissance mapping and aeromagnetic data (GSC Map NM-11-M). K-Ar hornblende and biotite ages from the main body range from 130 to 167 Ma (Nguyen et al., 1968; Wanless et al., 1968). Two biotite samples from granitic rocks of the tail yield K-Ar and $^{40}$Ar/$^{39}$Ar plateau ages of ~124 and 110 Ma, respectively (Fig. 3; Archibald et al., 1983; Leclair et al., 1993). Geochemical characteristics, including $(^{87}\text{Sr}/^{86}\text{Sr})_i$ of 0.704-0.708 and $\varepsilon_{\text{Nd}}$ values between –3.0 and –9.1, of the Nelson batholith suggest emplacement in a continental arc setting above an E-dipping subduction zone (e.g., Ghosh, 1995b).

LITHOPROBE seismic reflection (Cook et al., 1988) and potential field data (Jones et al., 1988; Eaton and Cook, 1990) suggest that the main body of the batholith has a flat-bottomed floor at about 4-7 km below sea level with a 2 km upward step in the northwest quadrant (Fig. 2). Using the subsurface geophysical data we have depicted the three-dimensional geometry of the batholith in figure 2 from which we estimate volumes of ca. 10,000-15,000 km$^3$ for the main body and ca. 300-500 km$^3$ for the tail.

Contact aureole mineral assemblages indicate that the entire Nelson batholith was emplaced at pressures of ~2.5-4 kb southward (Fig. 4; Pattison and Vogl, 2005). The distribution of pressures suggest that, following emplacement, the batholith was tilted shallowly westward and that the tail plunges gently southward (Fig. 4; Pattison and Vogl, 2005). Although a similar westward tilt for the main body was interpreted by Ghent et al. (1991) on the basis of aluminum-in-hornblende geobarometry, the pressures of 3.1 to 6.4 kb are locally much higher than those indicated by the andalusite-bearing contact aureole. To explain the anomalously high pressures (and the presence of epidote interpreted as magmatic), Ghent et al. (1991) proposed a model involving upwarping of isobaric surfaces (perhaps by diapiric rise) above a feeder in the southern part of the main body near the city of Nelson. Chemical changes accompanying

~159 and 173 Ma (Duncan and Parrish, 1979; Parrish, 1992; Sevigny and Parrish, 1993; Ghosh, 1995a).
deformation preclude application of the hornblende geobarometer to rocks of the tail region. Most importantly, the contact aureole assemblages indicate that the tail was emplaced at depths similar to much of the main body (Fig. 4), and therefore does not represent a deeper level of exposure than the main body.

**STRUCTURE OF THE TAIL**

**Geometries and compositions of the igneous sheets**

Our mapping reveals that the tail comprises a series of subvertical, subparallel, compositionally distinct granitic sheets (referred to as A-E) that trend N to NNE, subparallel to the external contacts of the tail (Fig. 3). Individual sheets range in composition from granite or granodiorite to quartz monzonite and are readily distinguishable in the field by differences in the amount of megacrysts, quartz, total mafic minerals and hornblende/biotite ratios. The sheets are typically separated by screens of country rock which obscure the relative age relationships. Pegmatite intrudes all sheets.

Sheet A on the west side of the tail, is a weakly to strongly foliated, biotite-hornblende granite to tonalite (depending on the modal amount of K-feldspar megacrysts present in a similar groundmass). This sheet is medium-grained and generally equigranular, with microcline megacrysts occurring locally.

Sheet B comprises well-foliated, hornblende-biotite quartz monzonite to granodiorite. It is medium-grained and porphyritic with orthoclase megacrysts evenly distributed throughout. Sheet B is distinguished from sheet A by the abundance and even distribution of megacrysts and a higher hornblende/biotite ratio.

Sheet C comprises two phases: C1 and C2. The contact between these two phases could not be traced continuously, thus, they have been grouped together in figure 2. Phase C1 is a leucocratic, medium-grained, porphyritic granite. Hornblende is the dominant primary mafic mineral in this phase; biotite occurs in modal amounts of <2%, some of which is a product of hornblende alteration. This phase is strongly lineated and weakly foliated. In rare contact exposures, dykes of C1 are found intruding adjacent phases B and D. Also, in one locality where sheets B and C1 are not separated by a screen, enclaves of B are found in C1. Therefore, C1 is younger than sheets B and D.
Phase C2 is a medium-grained, porphyritic biotite-quartz monzonite. Phenocrysts are generally larger and more abundant in phase C2 than in phase C1. Biotite is the only mafic mineral present. Muscovite also occurs in phase C2, but much of it appears to be secondary. This phase is typically well-foliated, although deformation textures observed in thin-section suggest that this phase is consistently less strained than phase C1 and other adjacent sheets suggesting that phase C2 may be the youngest of the intrusive sheets.

Sheet D, on the east side of the tail, consists of weakly to strongly foliated, medium-grained, porphyritic quartz monzonite to quartz monzodiorite. Microcline megacrysts are abundant and homogeneously distributed. Mildly strained samples from the northeast part of the map area have aligned K-feldspar megacrysts and prismatic hornblende set in a medium-grained, hypidiomorphic granular groundmass. This sheet is coarser-grained and contains more hornblende and less quartz than broadly similar sheet B.

Sheet E occurs within sheet A as two kilometre-scale lenses that may be megaboudins (Fig. 3). These rocks are more mafic than other sheets and consist of a range of rock types, all of which are composed dominantly of hornblende, plagioclase and biotite with accessory quartz and titanite. The foliation in sheet E rocks is defined by sub-/euhedral hornblende and plagioclase. Well-preserved igneous zoning and grain boundaries indicate that these rocks have not recrystallized. Sheet E contacts are commonly characterized by zones of abundant enclaves of hornblende-rich phases occurring within more felsic rocks. Enclaves of sheet E rocks also occur within sheet A and sheet E could be the oldest sheet, now preserved as a disrupted screen isolated in sheet A.

Two lobes of granite/granodiorite have been mapped adjacent to the tail in the area west of Ymir Mtn. (Fig. 3). These lobes, referred to herein as the Apex Creek plutons, are largely unfoliated and contain less biotite than sheet A.

Long narrow screens of metasedimentary host rocks occur throughout the tail (Fig. 3). Screens range in width from a few metres to hundreds of metres. Screens are found at all elevations in the map area, (over 1500 m of relief) suggesting that they are not roof pendants exposed only at the highest levels of
the intrusion. Screens separate the granitic sheets along the length of most of their contacts, but also occur within individual sheets. Bedding orientations within screens are similar to bedding orientations in country rocks outside the tail and the surface traces of the contacts between sheets follow the strike of the bedding. Sills and lenses of granite, pegmatite and aplite are numerous within the screens. Although not mapped in detail, large, irregularly shaped pendants occur in the northeast part of the tail (Figs. 2 & 3). If the three-dimensional geometry depicted in the figure 2 is accepted, the individual sheets constituting the tail may have volumes varying between 25 and 150 km$^3$.

**External contacts and the southern terminus**

Along the steeply west-dipping west margin of the tail, granitic rocks intrude fine-grained siliceous and semi-pelitic rocks of the Ymir Group. These host rocks are tightly folded and display a steeply dipping Chl-/Bt-grade foliation that is generally parallel to bedding. The western contact is intrusive as evidenced by granitic sills interdigitated with metasedimentary rocks and granite apophyses cross-cutting layers. The west margin has a well-developed contact aureole containing porphyroblast assemblages of andalusite, cordierite±andalusite, or staurolite±andalusite (Fig. 4; Pattison and Vogl, 2005) that have overgrown the dominant steep foliation, but are locally pulled apart or wrapped by the same foliation.

Both the eastern contact and the foliations at the eastern margin steepen southward from moderate west dips near the West Arm of Kootenay Lake to vertical south of Seeman Creek (Figs. 2 & 3). North of Seeman Creek, pegmatite and granitic rock are interlayered with Grt-grade metasedimentary rocks of the Slocan and Milford group and are mildly strained, suggesting an intrusive contact. In sharp contrast to the northeast and the west margins, subvertical mylonitic granitic rock with transposed pegmatite veins characterize the east margin south of Seeman Creek (Fig. 3), and cross-cutting apophyses were notably absent. Furthermore, contact aureole porphyroblasts were not observed along the southeast contact, suggesting that either the granitic rocks have been displaced from the contact aureole or that the quartz-rich rocks did not have suitable compositions.

Mapping of scattered isolated outcrops near the southern terminus of the tail between Oscar and Porcupine Creeks reveals variable granite-host rocks contact relationships. At its southern terminus a
The metasedimentary septum separates the tail into two sections (Fig. 3). The NNE-trending west contact of the septum cuts sharply across both the cleavage/bedding in the metasedimentary septum and the foliation in the granite, both of which strike northwest (Fig. 3). In contrast, the granite foliation is parallel to the metasedimentary layering and to the contact at the southwest margin of the tail. Thus, the west fork of the tail tip has a western concordant contact with a margin-parallel foliation and an eastern discordant contact transected by the foliation.

The east contact of the septum is characterized by a complete gradation from pegmatite dykes intruding the host to metasedimentary blocks completely enclosed by pegmatite. Near the southeast margin, granite and pegmatite are highly fractured with extensive alteration of feldspars and mafic minerals.

The ridge between Oscar and Porcupine Creeks contains small, scattered outcrops, making it difficult to address important changes near the southern terminus. Outcrops at the highest elevations are metasedimentary, perhaps suggesting that in this area the roof of the tail is exposed. This is consistent with the contact aureole mineral assemblages (Pattison and Vogl, 2004), which indicate that this is the structurally highest exposed level of the tail.

Along the northern and southern contacts of the Apex Creek plutons the NW-striking regional cleavage and bedding have been rotated toward parallelism with the contacts. As a result, external contacts of these plutons vary from discordant to near concordant.

**STRAIN**

**Macrostructure/mesostructure**

All main granitic sheets (A - D) and pegmatites within the tail show variably developed foliations and lineations. Foliations are generally steep and strike north-northwest to north-northeast (Fig. 3). Lineations defined by quartz ribbons, mafics clots, and elongate mafic enclaves plunge shallowly southward. Fabric orientations within the granite are parallel to fabrics in the enclosing strata and screens within the tail.
Using ductile fault rock terminology of Sibson (1977), deformed granites of the tail comprise ultramylonite, mylonite and protomylonite, as well as foliated granite (defined herein as consisting of <15% grain-size reduced recrystallized matrix), and brittlely deformed rock. Finite strain markers are not widespread, thus, we use the amount of recrystallized matrix as a qualitative measurement of the amount of solid-state finite strain.

The generalized distribution of ductilely stained rocks is shown in figure 5 and can be summarized as follows. Strain gradients are present at the scale of tens to hundreds of metres but are generally absent at the outcrop scale. Exceptions include mm-scale shear bands and discrete ultramylonite zones generally less than one metre thick that are common within sheet C. The highest strains are recorded along the NNE-trending eastern margin of the tail south of Seeman Creek, where a prominent zone of subvertical NNE-striking mylonite/ultramylonite was mapped in granitic rocks (herein referred to as the eastern mylonite zone or EMZ). Farther north, where the eastern tail contact swings north, however, the amount of strain recorded in granitic rocks is much lower than in the EMZ to the south (Fig. 5). In a broad zone immediately west of the EMZ, strain gradients occur on the scale of tens of metres and the rocks vary between protomylonite and mylonite (Fig. 6a & b). This zone coincides with sheet C and the western part of sheet D. The west half of the tail (sheets A and B) consists of protomylonite and foliated granite (Fig. 6c) and strain decreases gradually toward the northwest. In several screens, the foliation in the granite was observed to be axial-planar to folded metasedimentary layering. The Apex Creek plutons contain only local weakly developed foliations that are parallel to the granite-host contacts.

A zone of brittle deformation occurs along the southeast margin of the tail and affects granitic rocks of the tail, country rocks outside the margin, and screens of mylonitic country rock inside the east margin. Granitic mylonites are brittlely overprinted in the northern part of this zone, but brittle deformation affected less strained granitic rocks in the southern part of the zone.

Prior to the emplacement of the tail, metasedimentary were tightly folded and developed an axial-planar foliation. In addition to the foliation and folds, two zones of intense deformation have been observed in country rocks within the tail. Little (1960, 1964) mapped a fault in two large pendants in the
northeast part of the tail as separating the Ymir Group from undivided Paleozoic strata (possibly the northern continuation of the Waneta fault as discussed above; Figs. 2 & 3). The fault zone is marked by a carbonate-pegmatite melange and highly contorted schists and marbles with granite interlayers. The melange consists of pegmatite with carbonate/calc-silicate xenoliths and carbonate with tectonically incorporated pegmatite clasts, indicating some fault movement after magma emplacement.

Highly strained screens are also present near the east margin of the tail. In the northern part of the brittle zone (Fig. 5), screens and wall rock consist of quartzose metasedimentary rocks with folded and fractured mylonitic layering. Also, within the ESZ, a highly strained Milford Group (?) marble band contains tectonically incorporated clasts of sheet D mylonite.

**Microstructures**

Microstructures in the low-strain sheet A rocks in the Ymir Mtn. area display aligned subhedral plagioclase and biotite (Fig. 7a). Plagioclase shows primary zoning and biotite is not kinked or recrystallized. The alignment of these minerals displaying primary igneous features suggests that the foliation formed while in a magmatic state. Polygonal recrystallized quartz ribbons with low aspect ratios indicate a transition to solid-state deformation.

Where more highly strained, near, and north of Ymir Mtn. and upper Kutetl Creek (Fig. 3), granitic rocks are characterized by recrystallized polygonal, strain-free matrix grains of quartz and feldspar tending toward a uniform grain size (Fig. 7b). Biotite displays no recrystallized grains at its margins and it is generally not kinked or crenulated. Strain-free porphyroclasts of hornblende and feldspar also occur in recrystallized protomylonites (7b).

In contrast to the northern region, microstructures south of Seeman Creek are characterized by recrystallized matrix grains of quartz and feldspar with irregular boundaries and grain sizes which are typically at least one order of magnitude smaller than matrix grains in samples from the northern region (Fig. 4). Porphyroclasts are typically strained as indicated by undulose extinction, local discontinuous fractures, and large equant subgrains with irregular boundaries (Type II subgrains of Hanmer, 1982)
decorated with fine recrystallized grains. Biotite typically occurs as cores with fine recrystallized grains at the margins.

Although, microstructures vary with amount of finite strain, the general microstructural patterns of the northern and southern regions cross strain gradients, indicating they are not simply the result of strain magnitude. The central area between microstructural domains displays microstructures with characteristics intermediate between those of the northern and southern domains.

The microstructural differences in ductilely deformed rocks probably reflect a higher rate of thermally activated syn- to post-kinematic recrystallization in the northern areas. Thus, it is suggested that the northern part of the map area underwent deformation at higher temperatures and remained at relatively high temperature longer than the southern part of tail, presumably due to its greater width and closer proximity to the large main body of the batholith. In contrast, the central and southern parts of the tail likely received little heat from the main body of the batholith following emplacement and the narrow tail would cool rather quickly, effectively limiting syn- and post-kinematic grain boundary recrystallization processes and grain growth.

**Kinematics**

We have observed various meso-/microscopic kinematic and shear sense indicators in both subhorizontal outcrop- and thin-sections oriented parallel to the lineation and perpendicular to the foliation (XZ sections) and subvertical sections cut perpendicular to the lineation and foliation (YZ sections). Shear-sense indicators in subhorizontal XZ-sections within the EMZ, discrete mylonite bands, and the lower strain western part of the tail display a consistent dextral shear sense. Shear-sense indicators include rotated porphyroclasts, asymmetric microfolding, C-S fabrics, an asymmetrical extensional shear bands (Fig. 8; Hanmer and Passchier, 1991; Platt and Vissers, 1980), as well as the curvature of pre-existing foliations into discrete shear zones. A dextral shear-sense is also indicated by sigmoidal inclusion trails within garnets, asymmetric pressure shadows around garnet, and asymmetric extensional shear bands in metasedimentary rocks adjacent to the east margin of the tail. Shear-sense indicators in
subvertical YZ sections in granitic rocks from the EMZ, such as asymmetrically folded quartz ribbons, rotated porphyroclasts, "quarter structures" (Hanmer and Passchier, 1991), and oblique grain-shape fabrics in quartz ribbons, indicate an east-side-up motion in the EMZ (Fig. 9).

Boudinaged beds, asymmetric extensional shear bands and pulled apart porphyroblasts in screens and host rocks adjacent to the pluton margins, and pulled-apart hornblende and feldspar porphyroclasts and asymmetric extensional shear bands within the granitic rocks suggest a shortening component across the layering. Folded granitic veins with an axial-planar foliation further suggest shortening across the tail. Overall, the fabrics and kinematic/shear-sense indicators suggest that the fabrics in the tail record dextral transpressive subhorizontal shear and subsequent(?) E-side-up motion that may be localized along the east margin of the tail.

DISCUSSION

Origin of the strain

We interpret both the pervasively developed fabrics and the EMZ as the result of regional, rather than emplacement-generated, deformation. Solid-state fabrics are pervasively distributed across the tail and the magnitude of strain associated with the fabrics does not increase in a simple way toward the pluton margins, as would be expected from emplacement-generated strains. Also, fabric orientations in the tail are parallel to the regionally developed fabrics, and the homogeneous foliation locally cuts obliquely across granite-host contact (see discussion of west fork of the southern terminus), further indicating that most of the solid-state strain did not result simply from emplacement of younger magmas.

In the northern part of Ymir Creek, the EMZ occurs along, or within ~100 metres of the inferred trace of the Midge Creek fault and is adjacent to locally mylonitized carbonate and black phyllite of the Milford Group. Farther north, where the margin is more than a kilometre west of the Midge Creek fault (Fig. 3), granitic rocks along the contact are only mildly strained. The observation that the highest strain zones spatially coincide with the Midge Creek fault, rather than conforming to the pluton margins,
indicates that the fabrics in the EMZ are tectonic in origin. Thus, we infer that there was some syn- to post-emplacement motion on the Midge Creek fault.

**Age of the strain fabrics**

The strain features described above suggest that much of the pervasive strain in the tail occurred during and shortly after emplacement. The Nelson batholith and, in particular, its tail was emplaced into greenschist-facies rocks at relatively shallow depths (see Pattison and Vogl, 2005), where pervasive, penetrative ductile deformation of granitic rocks, such as that observed in the tail, is not expected unless the granitic rocks are at elevated temperatures. Most granites deformed under greenschist facies conditions are characterized by discrete anastomosing shear zones that bound relatively unstrained rock (Choukroune and Gapais, 1983; Vernon et al., 1983, Gapais, 1989), whereas the homogeneously distributed strain (lack of abrupt strain gradients) of the tail is more characteristic high-temperature shear zones. Higher temperatures lead to the operation of plastic deformation mechanisms in feldspars (Tullis and Yund, 1977, 1980) and to a thermal softening that allows most of the volume of the rock to be deformed without the strain being partitioned into strain-softened zones (White et al., 1980). Simple calculations of conductive cooling using the equations of Carslaw and Jaeger (1959) indicate that the centre of a 5 km thick granitic sheet emplaced at 800°C would cool to ambient temperatures of ~400°C in less than 0.5 m.y. Thus, combined with the nature of the deformation features, thermal calculations reinforce the suggestion that deformation occurred during emplacement and initial cooling. In addition, the distribution of high vs. low temperature microstructures was interpreted above to be the result of the temperature distribution during initial cooling of the granitic rocks. This interpretation is strengthened by microstructural evidence for a transition from magmatic to high-temperature solid-state flow.

Thus, it appears that much of the homogeneous fabric development in the tail occurred in the late Middle Jurassic (emplacement age of 166 Ma obtained by Ghosh (1995) for phase A at the southern tip of the tail). It is difficult to say whether the lower temperature mylonites in the east half of the tail (EMZ) developed from strain localization during initial progressive cooling or whether they formed at a significantly later time. Archibald et al. (1983) obtained an $^{40}$Ar/$^{39}$Ar biotite plateau age of ~110 Ma from
the east-central part of the tail (Fig. 3), where deformed and locally recrystallized igneous biotite is present, as is biotite that formed from hornblende breakdown. Thus, the 110 Ma age represents only a minimum age of mylonitization. Given the primary igneous textures preserved in the northwest part of the tail, the K-Ar biotite age of 124 Ma (Archibald et al., 1983) from that area probably represents the time at which primary biotite cooled below ~300°C. Although traditional interpretations have viewed most of the deformation in the region as Early to Middle Jurassic, the ca. 117 Ma date from the strained Baldy pluton immediately east of the tail indicates that Cretaceous deformation also affected the area (LeClair et al., 1995). Our cursory examination of the Baldy pluton indicates that the fabrics are similar in orientation and kinematics to the fabrics in the east half of the tail, leading to the possibility that some of the discrete mylonite zones of the tail formed in the mid-Cretaceous.

Brittle deformation along the southeast margin (Fig. 5) may have been synchronous with deformation in the EMZ, in which case the temperature may have been lowered there due to the rapid cooling at the southern margins. Brittle deformation could also be due to higher fluid pressure from accumulation of magmatic fluids, evidence for which includes the abundance of pegmatite and the common alteration of feldpars in the southeast fork of the southern terminus. Alternatively, the brittle zone may post-date and be unrelated to motion in the ESZ.

**Implications for the structural evolution of the region**

Much of the deformation in the Kootenay Arc has been ascribed to two deformation events. Immediately east and northeast of the tail, the dominant D₂ deformation produced a syn-metamorphic foliation (S₂) that is axial-planar to mesoscopic and map-scale folds (LeClair, 1988). Metamorphism and folding were accompanied by thrusting on the terrane-bounding faults (Leclair, 1988; Einarsen, 1994). As is the case throughout the central and southern parts of the Kootenay arc, gently plunging mineral lineations are parallel to fold axes and the trace of the arc. Thus, the pervasive foliations and gently plunging lineations within the tail are parallel to those in the metasedimentary host rocks, suggesting that they formed as a result of the regional D₂ event. Andalusite and staurolite porphyroblasts in the contact
aureole overgrow the dominant D₂ foliation, but are locally pulled apart and wrapped by the D₂ foliation, suggesting emplacement during the latter stages of D₂. The intensity of the strain fabrics in the east half of the tail indicates accumulation of a significant amount of post-emplacement strain, thus, the fabrics are recording more than just the final increment of regional D₂ shortening.

Available age constraints and thermobaromteric data (Fig. 4) indicate that the variation in structural characteristics of Mid-Jurassic plutons does not correlate with either emplacement age or level of emplacement. We suggest that the geometries and strain characteristics of the Mid-Jurassic plutons are the result of spatial variations in late-D₂ strain rates and in the magnitude of late-/post-D₂ strain. Plutons intruded into Quesnellian/Slide-Mountain terrane (e.g., Apex Creek plutons, main body of the Nelson batholith, Bonnington plutons) west of the TAZ are largely discordant, unfoliated, and have blobby shapes. Plutons east of the TAZ plutons are generally unfoliated and have blobby shapes, although some (Mine and Wall Creek stocks) have evidence that some late- D₂ strain accumulated in their aureoles (e.g., Archibald et al., 1983). The only elongate plutons with significant solid-state fabric development (Nelson tail and Procter pluton) are found within the TAZ. These relationships suggest that late- to post- D₂ strain was inhomogeneously distributed, with significantly more strain having accumulated within the TAZ.

Differences in the structural characteristics of the Mid-Jurassic plutons are also probably related to higher strain rates within the TAZ compared with surrounding areas during the late stages of D₂. Higher strain rates may be partly responsible for elongate pluton shapes inasmuch as higher rates of horizontal shortening near the terrane-bounding faults could have driven relatively rapid horizontal flow of magma to produce sheet-like bodies before freezing could occur. Furthermore, during pluton emplacement, higher strain rates within the TAZ are required to produce significant accumulation of high-temperature solid-state strain as recorded by much of the homogeneous fabrics in the tail. At lower strain rates cooling to ambient temperatures would produce a significant strengthening of the granitic rocks and would prevent large amounts of high-temperature strain accumulation. Thus, the first-order characteristics of the Mid-Jurassic plutons are attributable to the competing effects of strain rate versus cooling and crystallization rates (e.g., Paterson and Tobisch, 1992).
The kinematic significance of the subhorizontal mineral and stretching lineations in the Kootenay arc has received little attention, apart from Ellis (1986) who suggested they result from dextral oblique convergence. Broadly consistent with the view of oblique convergence, our observations suggest that the homogeneous strain fabrics formed from shortening with a component of subhorizontal dextral shear (transpression). The dextral shear component may be difficult to recognize in the folded metamorphic rocks, but may be better recorded in the strained granitic rocks.

The location and orientation of the EMZ indicates syn- to post-emplacement motion on the Midge Creek fault. However, both the subhorizontal dextral and E-side-up movement in the EMZ differ from the interpretation of the Midge Creek fault as an E-directed thrust fault (Leclair, 1988). A significant amount of thrust displacement, however, probably predated emplacement of the tail, suggesting that only the later motions on the fault, which we suggest were different from the main stage of movement, are recorded by the EMZ.

The anomalous late-stage motions on the Midge Creek fault may be explained by changes in the manner in which oblique convergence was accommodated. This study and Leclair (1988) show that both the major faults and S₂ fabrics dip westward near the northeast margin of the tail, but are progressively overturned and have steep east dips in the region of the EMZ. Leclair’s mapping showed that the east dips are part of a fan structure, which he suggested formed by post-metamorphic eastward wedging of the Quesnellia-Slide Mountain terranes into, and beneath, the thickened metasedimentary package of North American rocks (Fig. 10). Leclair (1988) noted an E-dipping S₃ crenulation cleavage and W-vergent folds on the west side of the fan. The tail may have been intruded while the Midge Creek fault dipped moderately to steeply westward, but subsequent steepening and overturning of the fault and S₂ fabrics may have made the fault unfavorable for further thrusting. We suggest that once the Midge Creek fault steepened, the dextral strike-slip component of the oblique convergence was partitioned into the fault zone, with continued eastward thrusting occurring on deeper faults that propagated eastward (Fig. 10). Furthermore, as shortening continued, the structural fan east of the tail formed, leading to uplift of the fan relative to rocks of the tail (Fig. 10). This uplift may explain the evidence for E-side-up motion along the
EMZ that coincides with the Midge Creek fault. This model is testable through kinematic analysis of the W-dipping portion of the Midge Creek fault (to the north) since in this model the E-side-up motion would be limited to the vertical and overturned sections of the fault. Evidence for E-side-up motion on the W-dipping portions would suggest, instead, that the fault had a period of normal motion prior to overturning.

**Emplacement of the tail**

The separation of compositionally distinct granite sheets by narrow, subvertical screens, and the parallelism between granite contacts and bedding planes or faults (Fig. 3) indicate that emplacement of the granitic sheets of the tail was controlled by structural anisotropies and occurred largely by magmatic wedging. Since screens also occur within individual compositional sheets, it is likely that each igneous phase comprises multiple sheets of similar composition. Thus, the tail is an example of pluton emplacement by the amalgamation of a number of relatively small (25-150km³) sheet-like bodies, perhaps by magmatic wedging along preexisting anisotropies.

The strain fabrics in the tail suggest emplacement during ~SW-NE shortening with a component of dextral shearing (noting that the NNE-trending tail was probably rotated clockwise during later development of curvature of the Kootenay arc). Thus, the sheets are oriented at a high angle to \( \sigma_1 \) rather than \( \sigma_3 \) and therefore must have been emplaced by wedging with magma pressures sufficient to overcome regional compressive stresses. Many recent interpretations of granitic bodies emplaced into transcurrent shear zones, have called upon local dilational structures as a means of providing space for the intruding magma (e.g., Hutton, 1982, 1988; Guineberteau et al., 1987; McCaffrey, 1992; Tikoff and Teyssier, 1992; Castro and Fernandez, 1998). Evidence for such transient dilational sites allowing passive emplacement of magmas, however, is not present in the tail region. We view the Midge Creek and Waneta faults and regional cleavages as exploited planes of weakness rather than active space creators. Space was likely made by ductile flow and folding of host rock in the screens and aureole as evidenced by boudinage, pulled apart contact aureole porphyroblasts, and synmagmatic folds. Subhorizontal strike-parallel stretching lineations in the tail, aureole, and surrounding region suggest that the maximum extension
direction was horizontal. Assuming minimal extension normal to the lineations (i.e., vertical) and minimal volume change in the host rocks, this creates a space problem of material transfer in the aureole. One explanation is that as the sheets wedged southward, as proposed below, host rock material flowed northward toward the main body, which may have been the magma source region for the magmatic sheets of the tail.

The relationship between the tail and main body, and the overall shape of the Nelson batholith may be explained by one of several processes. Numerous examples of asymmetric tailed plutons have been described in other magmatic belts around the world (Holder, 1979; Jegouzo, 1980; Brun and Pons, 1981; Davies, 1982; Vernon and Paterson, 1993; Rosenberg, 1995; Archanjo et al., 1999; Molyneux and Hutton, 2000; Rosenberg et al., 2004). In some cases, such as the Bergell pluton (Alps), the tail has been interpreted as a deeper level feeder dyke with the overall drop-shape resulting from exposure of an oblique crustal section (e.g., Rosenberg et al., 1995; Rosenberg, 2004), and thus is a primary ascent/emplacement feature. The tilt geometry and very small tilts along ca. 50 km of the tail and east margin of the main body documented by contact aureole mineral assemblages (Fig. 4: Pattison and Vogl, 2004) suggest that this is not the case for the Nelson batholith.

The tailed plutons cited above were all emplaced into regions of non-coaxial strain or transcurrent shearing, with the asymmetrical shape consistent with the sense of shear. This suggests a genetic relationship between regional deformation and tail formation. Some pluton tails have been regarded as secondary features, resulting from syn- or post-emplacement shearing of a more equant body (e.g., Molyneux and Hutton, 2004). However, in most cases, the processes of tail formation are not explicitly discussed. The proximity of Nelson batholith to a zone of dextral shear suggests that the tailed geometry is also the product of interaction between the magmas and transcurrent shear zone. However, the nature of the relationships between magma emplacement, transcurrent shearing, and final pluton geometry is not clear and warrants further discussion.

The character, kinematics, and distribution of the strain fabrics in the tail of the Nelson batholith indicates that solid-state dextral shearing has contributed to the final shape. However, the fabrics in the
western part of tail record limited strain, suggesting that solid-state shearing was not likely the dominant tail-forming process. Dextral shearing while in a magmatic state may have also contributed to the tail, but unreasonably high strain rates would be required to produce the full length of the tail without freezing.

We suggest that, in addition to minor magmatic and solid-state shearing, magma may have flowed past the host rocks horizontally southward from the main body. Southeast- and southward magma flow was guided by steep anisotropy of cleavage and bedding planes and by the faults. Such flow is supported by the presence of steep magmatic foliations parallel to the fabrics in screens and wall rock and by the presence, in the least deformed parts of the tail (westernmost sheets), of subhorizontal lineations such as elongate enclaves formed in a magmatic state. The driving force of the southward flow may have been the active transpression, which we suggest was concentrated adjacent to the Midge Creek fault. Horizontal shortening of magmas emplaced into the zone of transpression at the southeast margin of the main body would induce southward horizontal flow at a high angle to the maximum shortening direction. Thus, in our model, the tail is largely a primary feature resulting from interaction between the magmas and regional stresses. The asymmetry of the tail is then the result of dextral shearing and the curved anisotropy of the host rocks near the shear zone.

The physical experiments of Roman-Berdiel et al. (1997) may be somewhat relevant to the Nelson batholith and other tailed plutons. Their experiments produced asymmetric tailed plutons when the model magma was injected adjacent to the strike-slip fault and spread into the fault producing the “sheared tails”. The experiments are similar to the model for the main body of the Nelson batholith proposed by Ghent et al. (1991), who inferred that the magmas ascended near the city of Nelson before spreading laterally to the north and east, where we suggest they encountered the zone of dextral shear. Although not discussed explicitly by Roman-Berdiel et al. (1997), it appears that the “sheared tails” of the experimentally produced asymmetric plutons resulted from a combination of strain-induced flow past the host rocks and shearing along the strike-slip fault, similar to combination of processes that we propose. Although the experiments adequately reproduce the first-order characteristics of asymmetric tailed
plutons, they cannot sufficiently account for the effect of the large viscosity increases during progressive cooling and crystallization of the magma.

In summary, we suggest that the geometry and fabric characteristics of the Nelson batholith and tail are the result of a combination of processes (both primary and secondary) related to magma emplacement adjacent to a zone of inhomogeneous dextral shear. In our model, the tail geometry was largely the product of southward magmatic flow induced by horizontal shortening. This flow was guided by steep anisotropies (cleavage/bedding/faults) and occurred by magmatic wedging. Simultaneous dextral shearing of the magmas along the Midge Creek fault zone probably also contributed to smearing out of the tail. The final stages of magma emplacement were dominated by fracturing across layering and stoping at the southward-advancing tip as evidenced by the sharp discordant contacts and stoped blocks at the southern terminus. Subsequent to freezing, solid-state shearing was superimposed on the tail, shaping its final geometry and distribution of strain fabrics.

An outstanding question is whether the same process was repeated with the emplacement of each sheet over a time interval of several million years or whether the sheets were emplacement during one event. This is an important question considering recent suggestions that plutons in general may be emplaced over time intervals that are much greater than expected crystallization times (Glazner et al., 2004).

REFERENCES


FIGURE CAPTIONS

**Figure 1.** Generalized geological map of southeastern British Columbia showing the spatial distribution of terranes and pluton suites. Abbreviations: N=Nelson; R=Revelstoke; BB=Bayonne batholith; BP=Bonnington pluton; FCB=Fry Creek batholith; TP = Trail pluton; CRF=Columbia River fault; PF=Purcell; PTF=Purcell Trench fault; SLF=Slocan Lake fault; VSZ=Valkyr shear zone. Modified from Colpron et al. (1996).

**Figure 2.** Block diagram of the Nelson batholith and surrounding area. Lines at northern margin of the Nelson batholith represent structural trends in the Slocan Group that have been deflected by the batholith (from Cairnes, 1934). AF=Ainsworth faults; MCF=Midge Creek fault; SLF=Slocan Lake fault; WF=Waneta fault; SL=Slocan Lake; Based on maps of Little (1960), Fyles (1967), Klepacki (1985), LeClair (1988), Einarsen (1994), and geophysics from Cook et al. (1988) and Jones et al. (1988).

**Figure 3.** Map of the tail and surrounding area showing the distribution of the five main granitic phases that make up the tail. Thin dashed lines within the Nelson tail are boundaries between different granitoid phases. See figure 1 for location.

**Figure 4.** Map summarizing contact metamorphic mineral assemblages and interpreted tilt pattern. Pressures of emplacement range from approximately 2.5-3.0 to ≤ 4.0 kb using the alumino-silicate triple point of Pattison (1992). Dashed and solid lines separate areas with different intermediate-grade mineral assemblages and are interpreted to approximate the traces of isobaric surfaces. Regional metamorphic zones from Archibald et al. (1983) are also shown. Modified from Pattison and Vogl (2005). And = andalusite; Crd = cordierite; Bt = biotite; Kfs = K-feldspar; Ky = Kyanite; Sil = sillimanite; St = staurolite

**Figure 5.** Map showing the strain distribution (tectonite type, see Sibson, 1977) in granitic rocks of the tail and trace of the Midge Creek fault (LeClair, 1988). WF=Waneta fault.
Figure 6. Photographs of strain fabrics in granitic rocks of the tail. (a) Outcrop of sheet D augen mylonite with parallel pegmatitic veins. Located immediately west of EMZ. (b) Photomicrograph of sheet D mylonite/ultramylonite in EMZ. (c) Hand sample of homogeneously foliated sheet A.

Figure 7. Microtextures from granitic rocks of the tail. (a) Photomicrograph from sheet A showing aligned plagioclase grains with igneous zoning and no evidence for solid-state strain. (b) Photomicrograph of mylonite/protomylonite from north-central part of the tail. Shows strain-free feldspar porphyroclast and relatively large, polygonal, highly recrystallized feldspar (Kfs2) indicating relatively high-temperature deformation. Photo is ~3.3 mm across. (c) Photomicrograph of mylonite/protomylonite from south-central part of the tail. Shows fine recrystallized quartz and feldspar grains and aggregates of fine recrystallized biotite (Bt2). Photo is ~2.1 mm across.

Figure 8. Photomicrographs of dextral shear-sense indicators in subhorizontal (XZ) sections. (a) δ-type recrystallized tails around K-feldspar porphyroclast in metre-thick ultramylonite within sheet C. Photo is ~2 mm across. Also shows asymmetric fold. (b) “C-S” protomylonite of sheet A.

Figure 9. Photomicrographs of east-side-up shear-sense indicators from subvertical (YZ) sections. (a) “Quarter”-structure (Hanmer and Passchier, 1991) with microfolds in upper-right quadrant indicating that layering was in the shortening field. Same layer is thinned in lower-right quadrant. Photo is ~52 mm across. (b) “C-S” fabric in mylonite of sheet D. Photo is ~26 mm across. (c) Oblique quartz grain-shape fabric in quartz ribbons from EMZ. Photo is ~3.3 mm across.

Figure 10. Kinematic-geometric model showing evolution of the Midge Creek fault from an E-directed thrust to a dextral and E-side-up fault recorded by the eastern mylonite zone (EMZ).
Figure 3

Structure Symbols
- foliation in gneiss
- stretching lineation
- bedding/compositional layering orientations
  - dips 80°-90°
  - dips 65°-79°
  - dips 45°-64°

Plutonic rocks
-  Tertiary
-  mid-Cretaceous
-  Jurassic

Tectonostratigraphic packages & terrane affiliation
- Island-arc (Quesnelia)
  - uTi - mTi
  - Rossland, Ymir Groups
- Marginal basin (Slide Mountain)
  - M - uTi
  - Stikine, Kaslo, Milford Groups
- NA parautochthon (Kootenay)
  - pC - O
  - Carrefour Group, Badshot Fm., Hamill Group
  - Mohican Fm.
- North American miogeocline
  - pC - O
  - Active, Nenay, Lahi, Reno,
    Quartzite Range Fms., Windermere
Figure 4
Figure 5
Figure 6
Figure 8
Figure 10