

# GEOLOGY OF THE GRANBY FAULT, AN EOCENE EXTENSIONAL FAULT IN SOUTHEAST BRITISH COLUMBIA

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**KEYWORDS:** *Southern Omineca Belt, Eocene extension, metamorphic core complex, Grand Forks Group, Granby fault, Knob Hill Group, Brooklyn Formation.*

## INTRODUCTION

The Grand Forks complex, northern equivalent to the Kettle dome in the United States (e.g. Cheney, 1977; Cheney, 1980; Rhodes and Cheney, 1981), is one of many exposures of high-grade metamorphic rocks of North

American miogeoclinal affinity in the southern Omineca Belt (Figure 1). These structural culminations bounded by Tertiary normal faults, often collectively referred to as the Shuswap complex, were rapidly exhumed by tectonic uplift during post-Laramide crustal extension in the Eocene (e.g. Lorencak *et al.*, 2001; Parrish *et al.*, 1988; Vanderhaeghe *et al.*, 1999). The western margin of the Grand Forks complex is the west-dipping Granby fault, which juxtaposes low-grade rocks of Quesnel Terrane to the west against the high-grade gneisses of the complex.

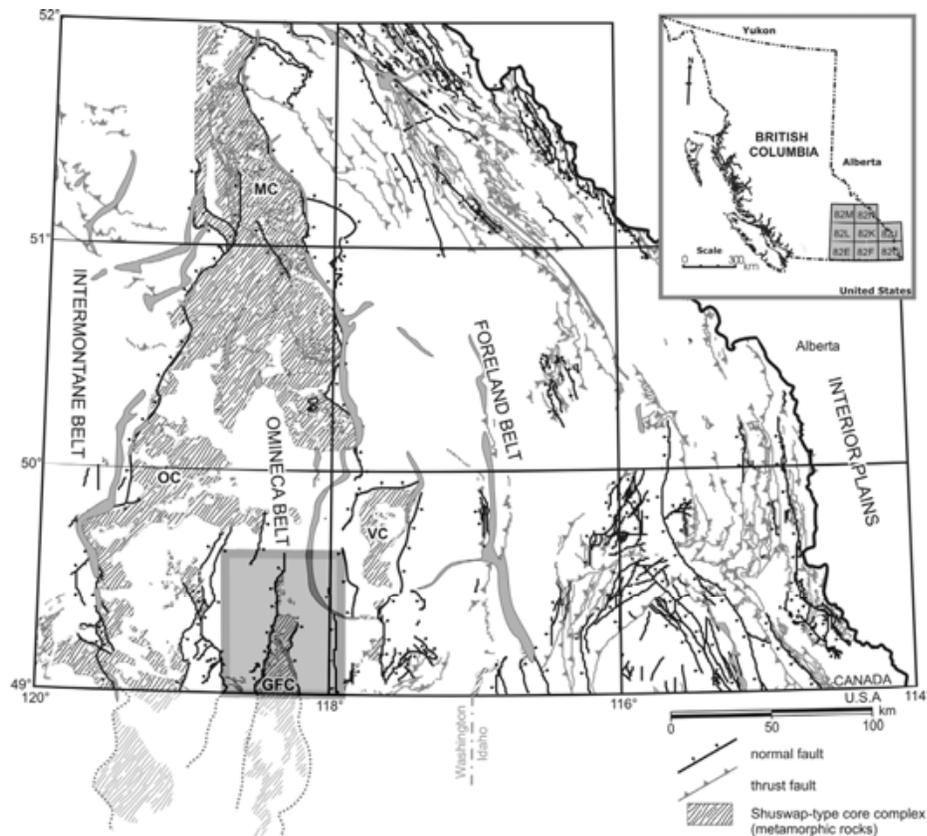


Figure 1: Map of the southeastern British Columbia showing the occurrence of the Shuswap-type metamorphic core complexes in the southern Omineca Belt. MC-Monashee Complex; OC-Okanagan Complex; GFC-Grand Forks Complex; VC-Valhalla Complex. Shaded box shows location of figure 2.

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This report describes the geology along 7 km of the Granby fault in the Volcanic Creek area, approximately 12 km north of the city of Grand Forks (Figure 2). The results presented here are based on one season of mapping

and a limited amount of petrography and mineral chemistry. This study is part of an on-going tectono-petrological study on the significance of the Granby fault in the denudation history of the southern Omineca Belt.

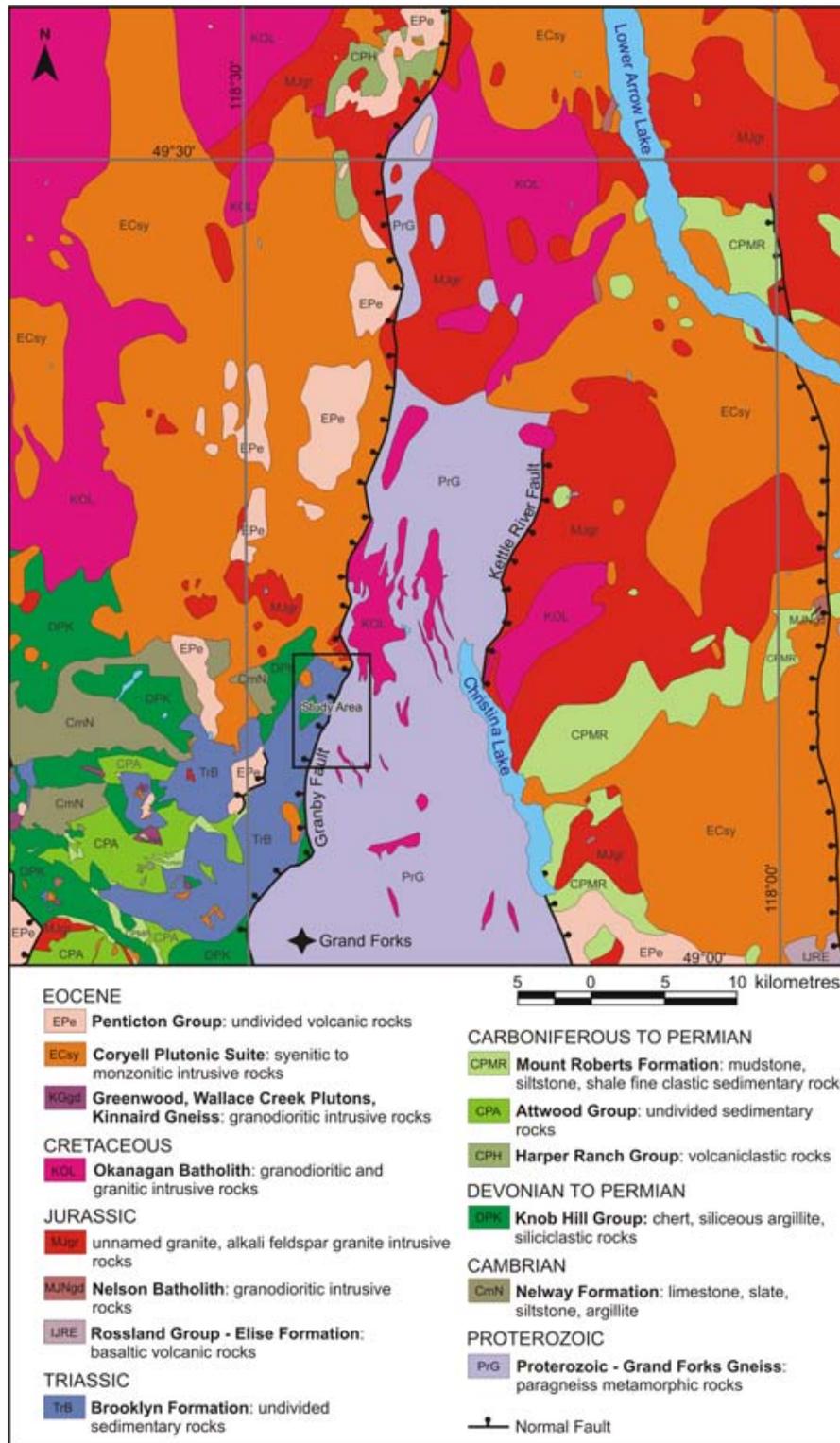


Figure 2: Regional geological map around the Grand Forks complex showing Paleozoic to Early Mesozoic units of the accreted Quesnel Terrane, and younger plutonic and volcanic suite (modified from Massey *et al.*, 2003).

## MIDDLE PROTEROZOIC

### REGIONAL GEOLOGY

The Grand Forks complex is bounded by outward dipping Eocene normal faults: the Granby fault to the west and the Kettle River fault to the east (Figure 2). In the hanging-wall of the Granby fault are sedimentary and volcanic assemblages of Quesnel Terrane, cross-cut by younger intrusions. Quesnel Terrane is generally interpreted as a package of allochthonous rocks accreted to the western margin of North America, characterized by Paleozoic to Mesozoic island-arc assemblages and associated intrusions (e.g. Acton *et al.*, 2002; Gabrielse *et al.*, 1991). The island-arc assemblage in the Grand Forks region consists of sedimentary and volcanoclastic rocks deposited during the Cambrian to the Triassic, with rare Jurassic volcanic rocks (Figure 2). Jurassic to Cretaceous plutons of granitic to granodioritic composition are also widespread within Quesnellia. Eocene plutonic rocks of the Coryell Suite and Eocene volcanic rocks of the Penticton Group are the youngest units in the area.

### LITHOLOGICAL UNITS

#### ***Footwall: High-grade metamorphic rocks of the Grand Forks Core Complex***

The Grand Forks complex is mainly composed of a high-grade meta-sedimentary succession described and mapped as the Grand Forks Group, occurring as paragneiss, schist, quartzite and marble (Preto, 1970a). Amphibolite, pegmatite, orthogneiss and granitoids are also present within the complex, as well as late, cross-cutting, north trending syenitic to monzonitic dikes.

Armstrong *et al.* (1991) dated the sillimanite-paragneiss (described below) from whole-rock Rb-Sr, whole-rock Sm-Nd and U-Pb in zircon. They obtained rather inconsistent results, with ages ranging from 1.6 to 2.0 Ga, concluding that the sillimanite-paragneiss is Early Proterozoic in age, with a strong Mesozoic to Early Cenozoic metamorphic overprint. Detrital zircons in this unit are interpreted as being derived from the North American craton to the east (Parrish *et al.*, 1989). Detrital zircons in the quartzite directly overlying the sillimanite-paragneiss have been dated as  $650 \pm 15$  Ma (Ross and Parrish, 1991), implying a major Proterozoic unconformity between the two units. The age of the high-grade metamorphism in the complex is still unknown.

Paleogene cooling ages of 50 to 67 Ma from K-Ar analysis in biotite and hornblende, respectively, have been obtained from the Kettle gneiss (Engels *et al.*, 1976), suggesting exhumation of the Grand Forks complex from moderate depths in the Paleogene.

#### ***Sillimanite-paragneiss (I)***

Coarse-grained sillimanite-paragneiss represents the structurally lowest meta-sedimentary unit of the complex exposed in the map area (Figure 3). It is the most widespread and thickest map unit. The unit contains more than 35% white leucogranitic pegmatite to very coarse leucogranite, inter-layered with the paragneiss.

The pelitic gneiss is migmatitic and stromatic (Photo 1). The mineral assemblages include some or all of K-feldspar, sillimanite, biotite, cordierite, garnet, quartz and plagioclase. Compositional banding is defined by thin, dark bands enriched in sillimanite, altered cordierite, biotite, Fe-oxide and locally garnet, alternating with coarse-grained leucosomes of plagioclase, K-feldspar and quartz. Sillimanite is acicular and is typically closely associated with cordierite. Samples rich in biotite contain rare sillimanite and vice versa. With the exception of one locality, cordierite is completely altered. Where present, garnet is anhedral and typically occurs within the altered cordierite.

The pegmatite bands and sills have apparent thicknesses of less than 15 metres, and are commonly ~5 metres thick. They are more resistant to weathering than the associated gneiss, and commonly form ridges oriented parallel to the gneissosity. They have a leucocratic granitic composition with biotite and rare sillimanite, garnet and tourmaline.



Photo 1: Migmatitic texture in sillimanite-paragneiss.

## LATE PROTEROZOIC TO CAMBRIAN

#### ***Quartzite (II)***

A quartzite unit ~200-300 metres thick occurs unconformably (on the basis of previously mentioned geochronological data) above the sillimanite-paragneiss. It is mainly composed of coarse-grained quartz, with up to

5% coarse white K-feldspar crystals, which are rounded and elongated within the gneissosity. Compositional banding is defined by modal variations in feldspar. Sillimanite rarely occurs within the unit. Some thin granitic pegmatite bands are locally inter-layered with the quartzite.

**Marble (IIa)**

Coarse white marble forms a thin (~100 m) lens within the quartzite. It is mainly composed of 3-5 mm crystals of calcite with euhedral black spinel, anhedral diopside and euhedral phlogopite as accessory metamorphic minerals.

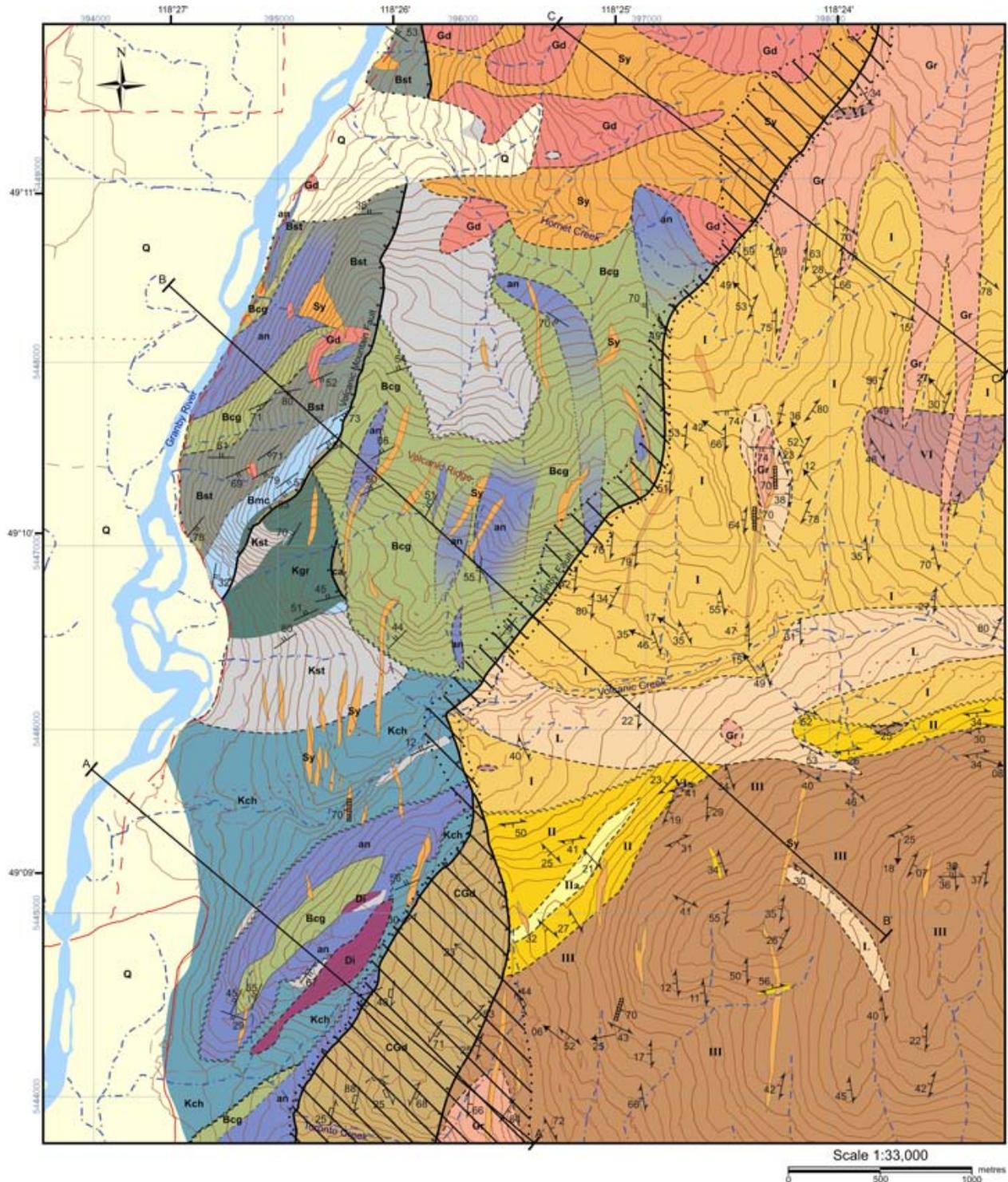


Figure 3a: Geological map of the western margin of the Grand Forks complex and bounding Granby fault, in the Volcanic Creek area. Universal Transverse Mercator Grid: Zone 11, NAD83; 20 metre contour intervals.

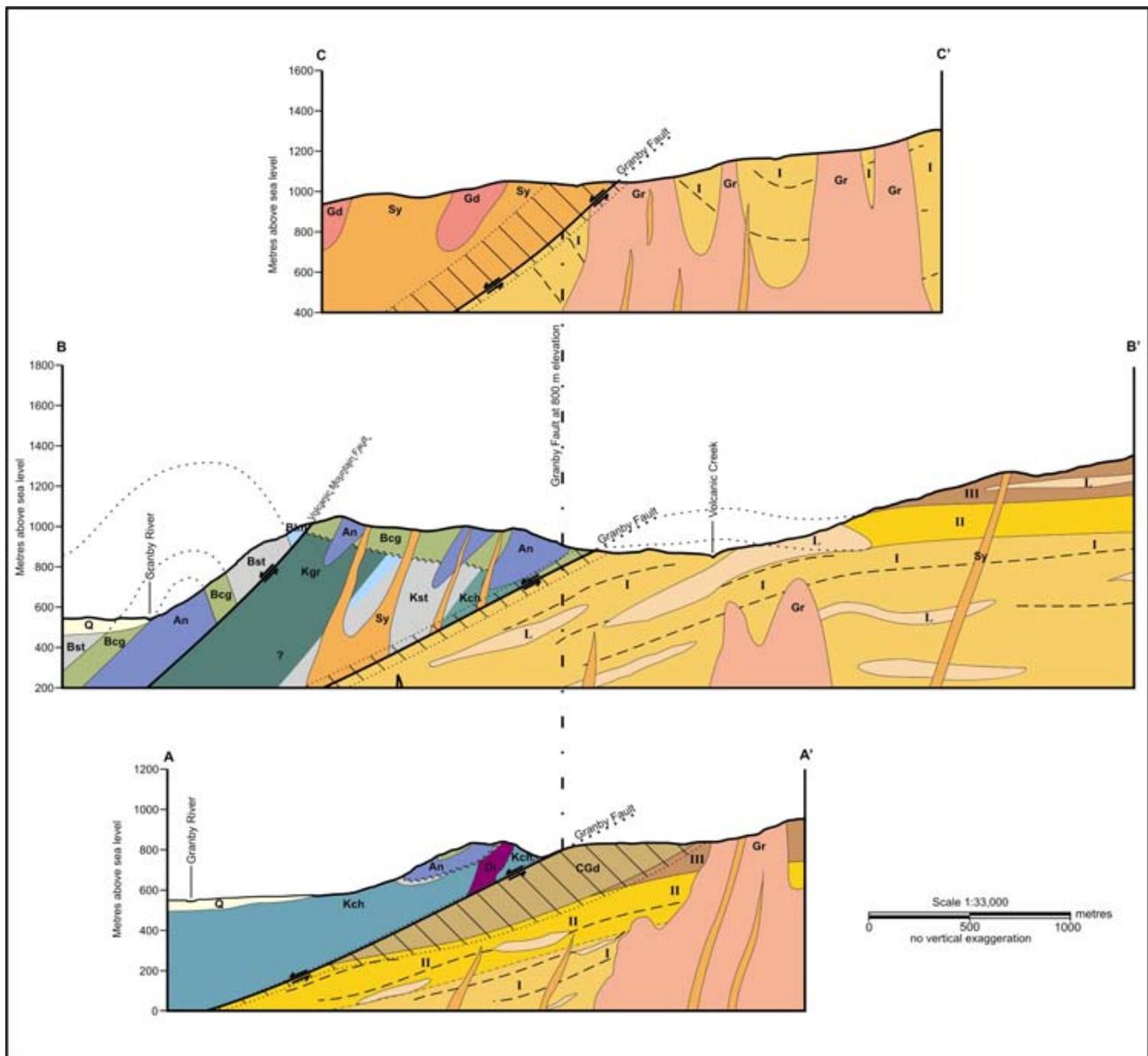


Figure 3b: Cross-section across the Granby fault, accompanying Figure 3. Geological boundaries, although assumed, are not dashed for clarity.

### ***Biotite-paragneiss (III)***

Biotite-paragneiss represents the structurally highest unit within the metamorphic core complex. It is widespread within the map area, but its thickness is unknown, as the unit is truncated by the erosional surface. The paragneiss is migmatitic with alternating biotite-rich layers and quartzo-feldspathic leucosomes defining the gneissic banding (Photo 2). Biotite, plagioclase and quartz (minor) are the main constituents while garnet and/or sillimanite are locally present but generally not abundant.

Clinopyroxene has been observed in one outcrop only (garnet- and sillimanite-free), on the northwest-facing slope south of Volcanic Creek. The mineral composition is suggestive of a semi-pelitic to psammitic protolith. Quartzo-feldspathic leucosomes a few millimetres to centimetres thick are common within the unit and locally contain garnet and sillimanite. The biotite-gneiss is interlayered with abundant pegmatite in a similar fashion to the sillimanite-paragneiss unit. The amount of coarse to pegmatitic leucogranite ranges up to 40% of the unit. Rare thin layers of quartzite (quartz + K-feldspar ± sillimanite) also occur within this gneiss.

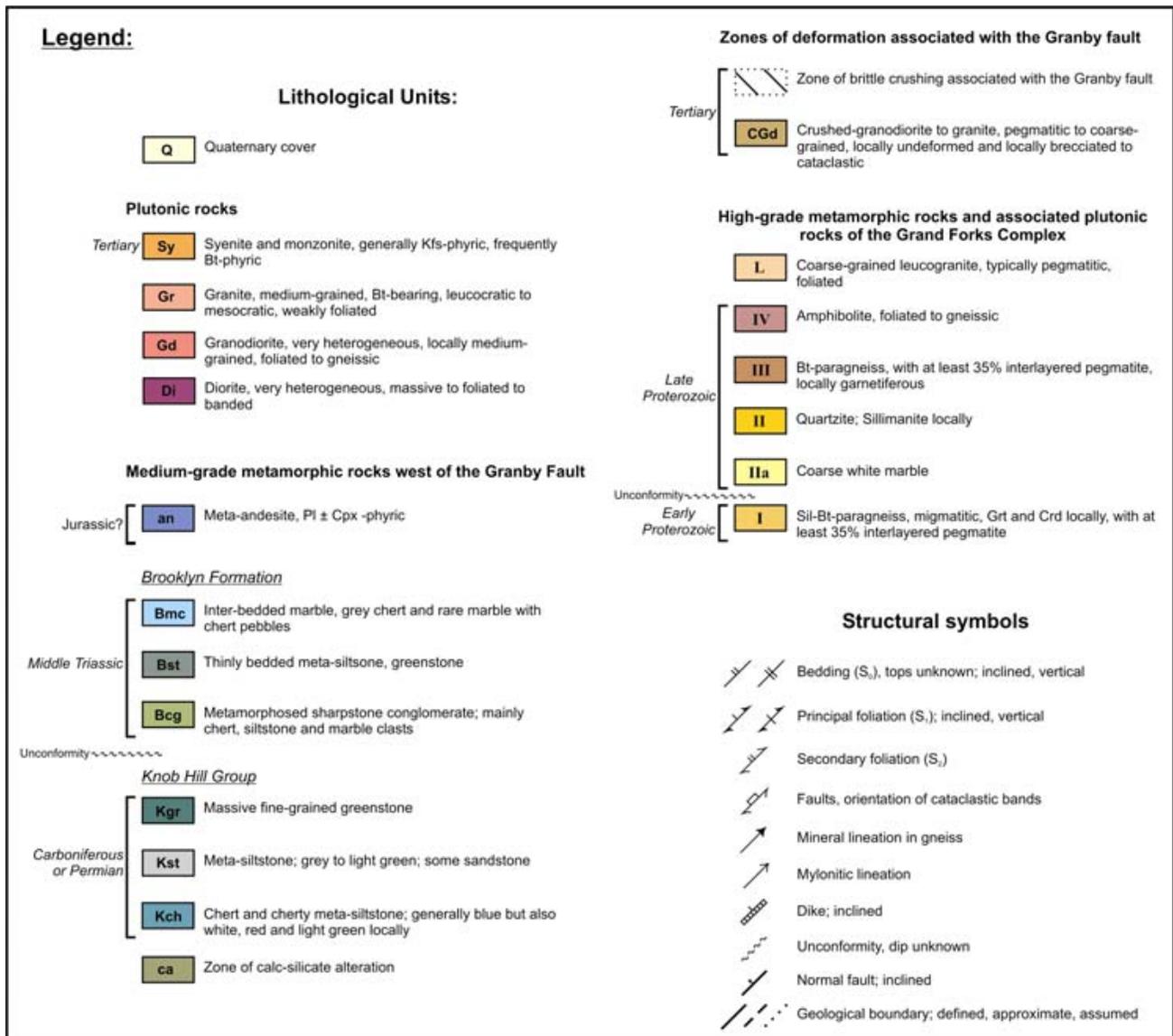


Figure 3c: Legend accompanying Figures 3 and 4.



Photo 2: Stromatic biotite-paragneiss.

### *Amphibolite (IV)*

Amphibolite is present throughout the metamorphic complex, generally occurring in small, discrete outcrops too small to be mapped individually. However, zones containing abundant amphibolite have been mapped (Figure 3a). The amphibolite is composed of hornblende, plagioclase, biotite, minor quartz, and rare clinopyroxene, and has a coarse-grained, foliated to gneissic texture. Alternating amphibole-rich and leucocratic bands are usually 1-4 millimetres thick. The amphibolite has been interpreted, on the basis of geochemistry, as metamorphosed Na-rich mafic plutons and dikes intruded into the meta-sedimentary sequence (Preto, 1970b).

### ***Coarse to pegmatitic leucogranite (L)***

Pegmatitic to very coarse-grained leucogranite is inter-layered within all meta-sedimentary units of the core complex but individual bodies are generally too thin (<10 metres) to be mapped. The map unit shown in Figure 3 therefore only represents the mappable portions of pegmatitic leucogranite. The leucogranite is white, with some biotite and rare sillimanite and garnet. The leucogranite appears massive, but is distinctly foliated when biotite is present. The textural continuum from leucosomes to pegmatite sills, and the local occurrence of sillimanite and garnet, suggest that the pegmatite represents leucogranitic melt locally derived from *in-situ* partial melting of the meta-pelitic to meta-psammitic rocks.

### ***Hanging-wall: Low grade metamorphic rocks of Quesnel Terrane***

The supracrustal rocks exposed west of the Granby fault include metamorphosed argillite, siltstone, sandstone, polymictic sharpstone-conglomerate, limestone and porphyritic andesite. The stratigraphy and inferred ages are based on the regional mapping and correlations of Little and Thorpe (1965), Preto (1970a) and Little (1983). These rocks range in age from Devonian to Jurassic and are part of Quesnel Terrane (Wheeler and McFeely, 1991). The exact age of the low-grade regional metamorphism is unknown.

### **KNOB HILL GROUP (CARBONIFEROUS OR PERMIAN)**

#### ***Chert (Kch)***

Massive chert represents a thick (>200m) unit in the southern half of the map area. It is almost entirely composed of microcrystalline quartz and varies in colour from dark blue to white, red and light green, and is locally silty. Near its upper contact, chert is inter-bedded within siltstone.

#### ***Meta-siltstone (Kst)***

Grey to greenish-grey meta-siltstone is generally quartz-rich, and contains the metamorphic minerals biotite, amphibole, plagioclase, quartz, epidote, muscovite and locally, small (<1 mm) euhedral garnet. It is generally massive to poorly-bedded and locally contains up to 5% sand-size clasts. Up to 15% of the unit is composed of medium-grained meta-sandstone. Pyrite and rare chalcopyrite occur in discrete zones throughout this unit, associated with minor faults. Mineralization is generally disseminated, with local centimetre-scale lenses of massive pyrite, that are generally associated with silicification of the host rock.

### ***Greenstone (Kgr)***

Greenstone exposed on the west-facing slope next to the Granby River is massive, light green and aphanitic.

### **BROOKLYN FORMATION (MIDDLE TRIASSIC)**

#### ***Meta-conglomerate (Bcg)***

Metamorphosed conglomerate and epiclastic breccias are widespread within the hanging-wall of the Granby fault (Figure 3a). They are physically and chemically immature, as revealed by angular to sub-rounded clasts and up to cobble-size sub-angular carbonate clasts. Clasts are polygenetic, consisting of chert, fine-grained quartzite, siltstone, marble and intermediate to mafic volcanic rocks (Photo 3). The metamorphosed matrix is relatively mafic, consisting mainly of biotite, actinolite, hornblende and secondary chlorite, giving the rock a greenish colour.



Photo 3: Bedding-parallel alignment of chert, siltstone and limestone clasts in meta-conglomerate.

#### ***Thinly bedded meta-siltstone (Bst)***

Overlying the sharpstone-conglomerate in the northwest is a laminated greenish siltstone, locally massive and grey. The transition between the two units is gradational as conglomerate and siltstone are inter-bedded at the contact. Most of the meta-siltstone is thinly bedded, with beds ranging from 2 to 15 mm, with slight compositional variations. Dark to light green beds are likely derived, at least partly, from greenstone or other volcanogenic sources. Grey to bluish-grey beds are silty to cherty. The south end of the unit (Figure 3) is in conformable contact with metamorphosed limestone and chert (Bmc).

#### ***Inter-bedded marble and chert (Bmc)***

This thin unit is composed of closely associated fine-grained light-grey marble and dark-grey chert. The unit is

well exposed on the west-facing slope north of Volcanic Creek, east of the Granby River. There it consists of thinly inter-bedded marble and chert, with beds ~10-20 cm thick, that are concentrically folded (Photo 4). Locally the unit occurs as marble with pods of chert and some beds with rounded chert pebbles (2 to 6 mm) in a carbonate matrix (Photo 5).



Photo 4: Folded inter-bedded marble and chert, with cross-cutting dikes and contact with meta-siltstone to the right.

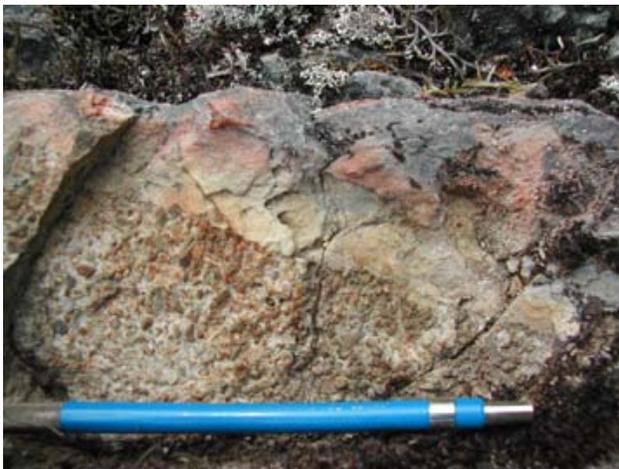


Photo 5: Bedding plane between fine-grained marble and chert-wackestone (conglomerate) within the inter-bedded marble and chert unit (pen for scale).

#### ***Calc-silicates, skarn (ca)***

Calc-silicate alteration of meta-sedimentary rocks occurs in two lenses within the hanging-wall, both associated with normal faults (Figure 3a). The northern one, in contact with the marble unit is a reddish brown siliceous rock (siltstone?) containing anhedral garnet. The other zone of calc-silicate replacement is observed within the meta-conglomerate at its contact with the underlying greenstone, and is marked by the development of garnet, diopside and calcite in the matrix.

## **UNCONFORMITY BETWEEN THE KNOB HILL GROUP AND THE BROOKLYN FORMATION**

Strata within the Knob Hill Group and Brooklyn Formation appear to be internally conformable. However, a stratigraphic or structural break must be present between the meta-conglomerate of the Brooklyn Formation and the underlying metamorphosed chert, siltstone and greenstone of the Knob Hill Group. The high angle between bedding in the Knob Hill Group and the contact between the Knob Hill Group and the Brooklyn Formation, combined with the observation that clasts in the very immature conglomerate/epiclastic breccia appear to be directly derived from underlying units, suggest that the stratigraphic break is an unconformity. This interpretation is consistent with the unconformable relationship between the Brooklyn Formation and Knob Hill Group in the Greenwood area (Little, 1983). On the western slope of Volcanic Ridge, marble and chert in higher levels of the Brooklyn Formation are also in contact with greenstone from the Knob Hill Group, but here the contact is represented by a northwest-dipping normal fault, which is interpreted to truncate the unconformity.

## **TRIASSIC TO JURASSIC?**

### ***Meta-andesite (an)***

Meta-andesite is fine-grained and generally porphyritic, containing small (<2 mm) plagioclase phenocrysts and locally large (2-6 mm) hornblende-actinolite pseudomorphs after clinopyroxene phenocrysts. Primary plagioclase laths are preserved in the matrix, along with metamorphic actinolite, hornblende, epidote, calcite and minor quartz as metamorphic minerals. Locally the composition appears to be more dacitic, as a few rounded quartz grains have been observed. These intermediate igneous rocks were likely emplaced as shallow dikes and sills within the sedimentary package, but because of limited exposure, the geometry of these bodies and their relationship with the surrounding rocks is poorly understood. The meta-andesite is closely associated with the Brooklyn meta-conglomerate. In the south of the map area, the meta-andesite underlying the conglomerate lens is interpreted here as being a volcanic flow, unconformably deposited on the Knob Hill Group. Some small intermediate to mafic dikes (<3 m thick) are also observed within the meta-siltstone and the inter-bedded marble units of the Brooklyn Formation. In the Greenwood area to the west, the only observed porphyritic andesites are interpreted to be of possible Jurassic age (Little, 1983).

## ***Plutonic Rocks***

### **JURASSIC?**

#### ***Hanging-wall granodiorite (Gd)***

A texturally heterogeneous biotite-granodiorite is exposed in the north of the map area, in the low-grade rocks west of the Granby Fault. It is generally medium-grained, foliated to gneissic and locally coarse-grained and massive, and varies in composition from leucocratic to mesocratic. This unit is older than the Coryell syenite as enclaves of granodiorite occur within the syenite.

### **CRETACEOUS-PALEOGENE?**

#### ***Footwall granite (Gr)***

A granitic body occurs in the footwall in the northern end of the map area, and gradually branches off and disappears to the south. Small bodies of similar-looking granite have been mapped elsewhere within the footwall. The massive to weakly foliated biotite-granite is medium-grained, leucocratic to mesocratic.

### **EOCENE**

#### ***Syenite and monzonite of the Coryell Suite (Sy)***

The syenite of the Coryell suite is mainly exposed as a pluton more than 2 km wide in the hanging-wall of the Granby Fault at the northern end of the map area. There, it occurs as a pink, coarse-grained, K-feldspar + biotite ± amphibole-phyric syenite, that may grade into a massive K-feldspar megacrystic (~1 cm) syenite. In the rest of the map area, the Coryell suite plutonic rocks occur as discrete dikes of monzonite and syenite, in both the hanging-wall and footwall of the Granby fault. They generally range from 5 to 20 metres in thickness and are limited to a few hundred metres in length, resulting in lens-shaped bodies. They are usually steeply dipping to the west but sometimes to the east. They frequently display dark, fine-grained chilled margins.

The dikes vary in texture across the fault. Within the hanging-wall, they are typically either very coarse-grained, or K-feldspar ± biotite ± amphibole-phyric in a fine-grained grey matrix (Photo 6). In contrast, within the footwall, the dikes tend to be massive and medium-grained, and frequently contain rounded grey enclaves of similar material with a higher mafic content.

These dikes represent the youngest unit in the map area. However, at least some of them are older than the latest movement on the Granby fault because the Granby fault cuts some of the dikes (Figure 3), and they are locally sheared and brecciated within the fault zone. On the other hand, the degree of cataclastic deformation in the dikes in the vicinity of the fault is much less than that of the host rocks, suggesting emplacement late in the fault

history. Emplacement of the dikes therefore may have been, at least in part, synchronous with the movement on the Granby fault, consistent with their trend sub-parallel to the fault zone and the variable amount of deformation in dikes close to the fault. A sample of the Coryell syenite collected 10.5 km north of the northwest corner of the map area yielded a zircon U-Pb age of  $51.1 \pm 0.5$  Ma (Carr and Parkinson, 1989). Movement on the Granby fault therefore both predates and postdates this age.

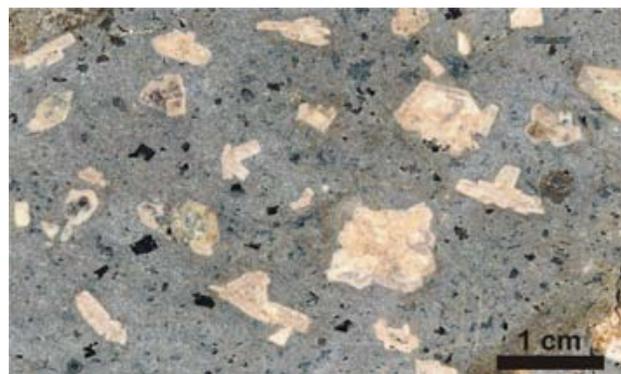


Photo 6: Slab of porphyritic syenite (trachyte) from a dike within the hanging-wall. Phenocrysts are K-feldspar, biotite and hornblende.

### **AGE UNKNOWN**

#### ***Sheared and crushed granodiorite along the Granby Fault (CGd)***

A medium- to very coarse-grained granodiorite occurs within the fault zone in the southern end of the map-area, near Toronto Creek. It is mesocratic (hornblende-biotite), locally with very coarse-grained leucocratic granitic fractions. The unit is sheared and highly fractured. Ductile shearing is expressed as an irregular foliation and lineation. Brittle brecciation of the unit occurs as thin chloritized zones (1-10 mm thick) containing crushed crystals. Light green outcrops of completely crushed fine-grained cataclasite occur locally on the western margin of the unit, near and along the Granby fault. Discrete mylonites occur within this unit but lack lateral as well as longitudinal continuity, suggesting that they have been reworked by subsequent brittle deformation. The intrusion occurs as a 300 m thick lens, with its long axis parallel to the fault trend. The overall shape and orientation of the body may suggest that it may have been intruded along the fault zone, and subsequently deformed brittly.

#### ***Hanging-wall diorite (Di)***

A coarse-grained, deformed and fractured hornblende-diorite is exposed just north of Toronto Creek. It is very heterogeneous, massive to foliated to compositionally banded. The diorite occurs as two thin lenses with long axes of 240 and 1100 m, oriented

roughly parallel to the Granby Fault. The observed foliation and shearing within this unit suggest that it may have been intruded during a deformation event. Because of textural similarity and comparable shape and orientation of the two units, the diorite (Di) could be genetically associated with the sheared granodiorite (CGd).

## STRUCTURAL GEOLOGY

### Footwall

Gneisses and other high-grade metamorphic rocks of the Grand Forks complex display a penetrative planar fabric represented by mineral foliation, leucosomes and gneissosity. This foliation is here termed  $S_1$ . Primary layering  $S_0$ , defined by the contacts between the various meta-sedimentary units, appears to be conformable with the regional foliation and gneissic layering, suggesting that it was transposed along the  $S_1$  surface. The  $S_1$  gneissosity within the western margin of the complex generally strikes north-south, with shallow dips to the west. This regional fabric controls the orientation of pegmatite sills and of larger bodies of coarse leucogranite.

The variation of the  $S_1$  foliation through the map area is presented on an equal-area stereographic projection (Figure 4). The distribution of the poles to gneissosity indicates an overall gentle dip-direction to the west and southwest, with a calculated mean  $S_1$  surface oriented 166/34W.

Small-scale folding of the  $S_1$  surface is observed throughout the complex. The style of the minor folds is variable, even within the same unit. They can range from similar to parallel, from tight to open. Wavelengths vary from a few centimetres to metres. Folding is typically cylindrical, with straight fold axes at the outcrop scale. The observed axial surfaces are parallel to the surrounding  $S_1$  surfaces (outside the hinge zone).

A mineral lineation defined by the alignment of sillimanite crystals can be observed in the gneisses. This lineation is also expressed by small crenulations in biotite-rich layers. The lineations are consistently parallel to the fold axis of the previously described minor folds. Since these lineations are always developed on the (locally crenulated)  $S_1$  surface, they are here termed  $L_2$ . The measured mineral lineations tend to be gently plunging ( $<45^\circ$ ), and generally trend to the northwest (Figure 4). The mean lineation, calculated from 13 relatively invariant measurements, is 310-41.

Although brittle deformation features are observed in the rocks close to the Granby fault (see below), the ductile fabrics noted above show no changes in the vicinity of the fault zone, suggesting that they represent deformation events that predate the Granby fault. Whether the structural features within the Grand Forks complex in the study area are the result of two distinct tectono-thermal

events, responsible respectively for the  $S_1$  foliation, and the  $L_2$  lineation and minor folds, or represent complexities in one main tectono-thermal event, cannot be determined at present. The gently west-dipping structures (i.e.  $S_1$ ,  $L_2$ ) are part of an overall dome-shaped structure of the Grand Forks complex (1970a) and Kettle dome (Cheney, 1980), in which the foliation and lineation gently dips toward the eastern and western margins of the complex, defining a large-scale antiform. Such doming could result from isostatic uplift of the core complex following its exhumation during crustal extension. Therefore, doming driven by Eocene normal faulting, which denuded the Grand Forks complex (Parrish *et al.*, 1988), could have led to the shallow tilting to the west (in the order of  $30^\circ$ , or dip of the mean  $S_1$ ) of the structural fabrics in the northwestern margin of the complex, assuming sub-horizontal  $S_1$  before faulting.

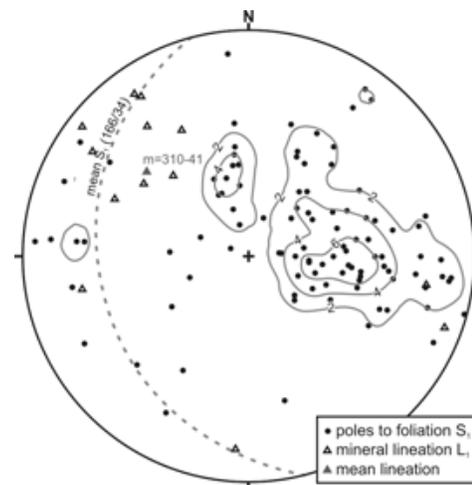


Figure 4: Equal-area stereographic projection of poles to foliation  $S_1$  (gneissosity) in the Grand Forks complex, and mineral lineation  $L_1$ . Calculations are based on 103  $S_1$  and 13  $L_1$  measurements. Contours for poles to foliation in percent, based on a spherical Gaussian grid with a weighting factor  $k=100$  (1% area equivalent) and a Gaussian minimum value of 0.05. The great circle represents the calculated mean foliation.

### Hanging-wall

Structural data in the hanging-wall of the Granby fault is limited by poor exposure and by the massive nature of most units. Scarce primary bedding or geological contacts ( $S_0$ ) were measured, but foliations or other penetrative fabric were not observed. Hanging-wall rocks are highly fractured, but the complexity and lack of consistency of the fracture sets has so far defied analysis.

Minor faults are present throughout the hanging-wall but are rarely clearly exposed. A hanging-wall fault of significant extent is however mapped in the northern half of the map area, and is herein named Volcanic Mountain fault (Figure 3). It is a normal fault striking north-

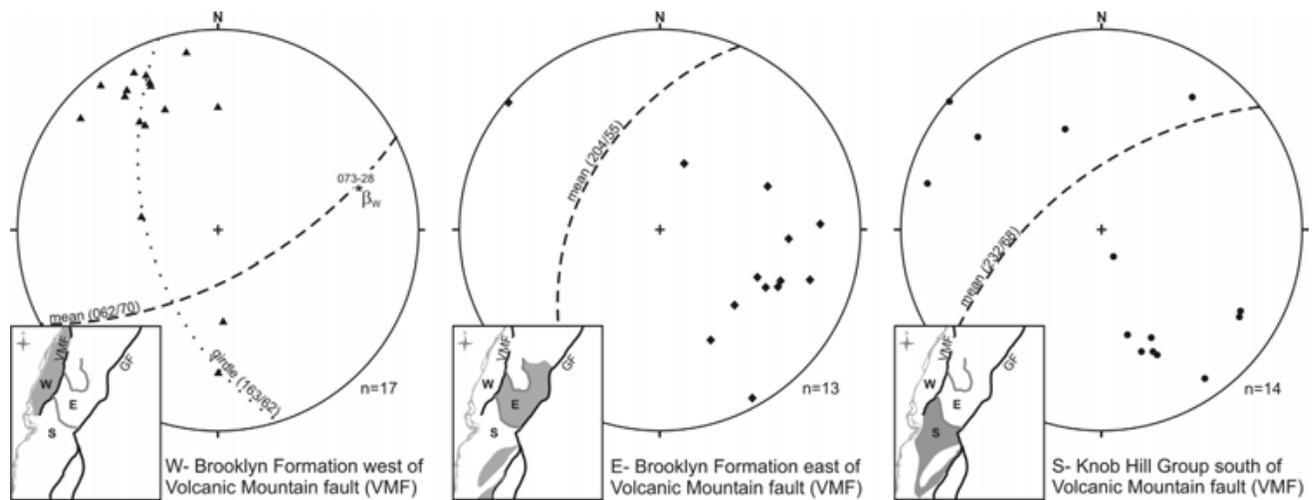


Figure 5: Equal-area stereographic projection of poles to bedding  $S_0$  west of the Granby fault (GF). Data has been separated in 3 structural domains bounded by the Volcanic Mountain fault (VMF) and the unconformity between the Knob Hill Group and the Brooklyn Formation. Granby Fault.

northeast and dipping  $40^\circ$  to  $50^\circ$  to the west, according to its trend across the topography. It is extended towards the north based on regional work by Fyles (1990). The fault's orientation suggests that it could be related to the Granby fault.

Ductile deformation in the hanging-wall of the Granby fault is rarely seen, with the exception of folding within one unit. Extensive parallel folding with wavelengths of a metre to tens of metres is displayed within the inter-bedded marble and chert unit on the steep west-facing slope next to the Granby River (Photo 4). The meso-scale folding in this unit is perhaps due to the favorable rheological properties (i.e. ductility) of the inter-bedded marble and chert compared to other units. Macro-scale folding is seen in a small overturned synform in the south of the map area, with meta-conglomerate in its core, and in a possible antiformal structure associated with the meta-conglomerate in the northwest.

Equal-area stereographic projections of poles to bedding are plotted in Figure 5. Three structural domains are defined: (1) a western domain within the Brooklyn Formation, west of the Volcanic Mountain fault, (2) an eastern domain within the Brooklyn Formation, east of the Volcanic Mountain fault, and (3) a southern domain within the Knob Hill Group. Each domain yields different overall bedding orientation, although in all domains there is a generally northeast-southwest strike. In the western domain, where folding has been observed at the outcrop-scale (Photo 4), poles to bedding suggest a fold axis gently plunging to the north-northeast, consistent with outcrop measurement of a fold axis of  $075-25$ . Although separated by an unconformity, the mean bedding plane in the eastern and southern domains have similar orientations.

### Granby Fault

The Granby fault separates low-grade metamorphic rocks of the hanging-wall (west of fault) from high-grade rocks of the Grand-Forks Complex in the footwall (east of fault). The trace of the Granby fault crosses the map area from south-southwest to north-northeast. The fault zone is characterized by a zone of brittle deformation (cataclasis) in which both hanging-wall and footwall rocks are brecciated and crushed. Fault zone rocks are cohesive breccias and cataclasites, suggesting recrystallization at moderate depths. Breccias are characterized by anastomosing shear zones up to a few millimetres in thickness, containing small angular crushed crystal fragments  $\pm$  chlorite, which cut through existing larger crystals (e.g. quartz and feldspars in pegmatite; clasts in conglomerate). Cataclasites are fine-grained, green, cohesive rocks, composed in part by recrystallized chlorite + quartz  $\pm$  fluorite, and locally containing remnant subrounded crystal fragments (usually quartz).

The zone of cataclasis and brecciation varies in thickness through the map area. In the central part, between Volcanic and Hornet Creek, the zone of brittle deformation is on average  $\sim 100$  metres thick and affects both hanging-wall and footwall rocks. In the North, the crush zone is up to  $\sim 230$  metres thick and is largely restricted to the syenite unit (Sy) in the hanging-wall. In the South, near Toronto Creek, the zone of brittle deformation is up to  $\sim 300$  metres in thickness, and is largely restricted to the crushed granodiorite unit (CGd) and some gneisses and pegmatite of the footwall.

The orientation of the fault in three dimensions can be estimated from its map trace. The Granby fault strikes south to south-southwest, and from its trace across topography, appears to dip  $\sim 35^\circ$  to the west. Some

outcrop surfaces of cataclasites and breccias observed along or near the fault plane display a similar orientation (parallel to the fault plane?), although others do not display any consistent planar fabric.

The latest displacement on the Granby fault is interpreted to be younger than 51.1 Ma, the age of the Coryell syenite, owing to deformation of syenite dikes in the fault zone. Accepting the biotite and hornblende K-Ar data for cooling of the Kettle gneiss (50-67 Ma, Engels *et al.*, 1976), displacement on the fault may have occurred over a period of tens of millions of years.

## METAMORPHISM

### Footwall – Grand Forks complex

The presence of garnet + cordierite + K-feldspar in the pelitic gneiss combined with the absence of orthopyroxene in the amphibolite (metabasite) implies that the core complex is in the transitional zone between upper amphibolite and granulite facies (Figure 6). Regional metamorphism affecting these rocks is therefore low to medium pressure (<7.5kbar) and moderately high temperature, between ca. 700 and 850°C.

The peak mineral assemblage of the metapelite is Sil + Crd + Grt + Bt + Kfs + Pl + Qtz + leucosome, the latter inferred to be partial melt (mineral abbreviations of Kretz,

1983). This assemblage lies on the model KFMASH univariant reaction  $Sil + Bt + Qtz + Pl = Crd + Grt + Kfs + L$  (Figure 6). The Fe/(Fe+Mg) ratio in the core of the garnet, assumed to preserve peak metamorphic conditions, is ~0.85 (see appendix), corresponding to a P-T condition of ~ 4 kbar at ~740°C (Figure 5 of Spear *et al.*, 1999). Assuming an averaged density for a mixed crust of 2.85 g·cm<sup>-3</sup>, or 3.6 km/kbar, this indicates a perturbed geothermal gradient of ~58°C/km (Figure 6).

### Hanging-wall – Knob Hill Group and Brooklyn Formation

The metamorphosed sedimentary and volcanic rocks in the hanging-wall of the Granby fault display a markedly lower grade of metamorphism than in the footwall. The presence of hornblende in meta-volcanic rocks (see appendix) combined with the occurrence of garnet in some meta-sediments, is an indication of lower amphibolite facies metamorphism.

Coexistence of actinolite with hornblende (Figure 7, see appendix) suggests that these rocks are close to the greenschist-amphibolite transition. The occurrence of Hbl + Act + Andesine puts this assemblage above the incoming of hornblende and oligoclase, and below the terminal stability of actinolite (Bégin, 1992, Figure 7). The occurrence of garnet and biotite in the meta-siltstone provides a further, albeit loose, constraint (Figure 6).

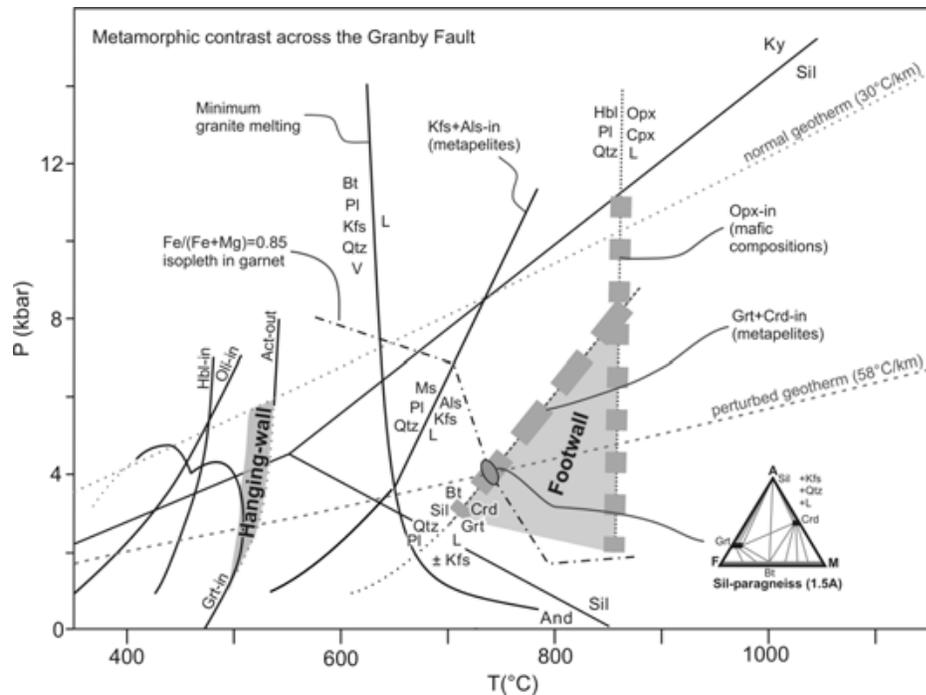


Figure 6: Pressure-temperature diagram showing the contrast in metamorphism across the Granby fault. Selected high-grade reactions are from Pattison *et al.* (2003). The Fe/(Fe+Mg) isopleth in garnet is from Spear *et al.* (1999). Mineral isograds for hornblende (Hbl), Oligoclase (Oli) and Actinolite (Act) in metabasites are from Bégin (1992). Grt-in isograd is from Tinkham *et al.* (2001). See text for discussion.

Combining the above constraints, the approximate stability zone for mineral assemblages in the hanging-wall of the Granby fault in the Volcanic Creek area is plotted in Figure 6. A maximum temperature of  $\sim 530^\circ$  is indicated, with pressure largely unconstrained. Further petrological work will be undertaken to improve these constraints.

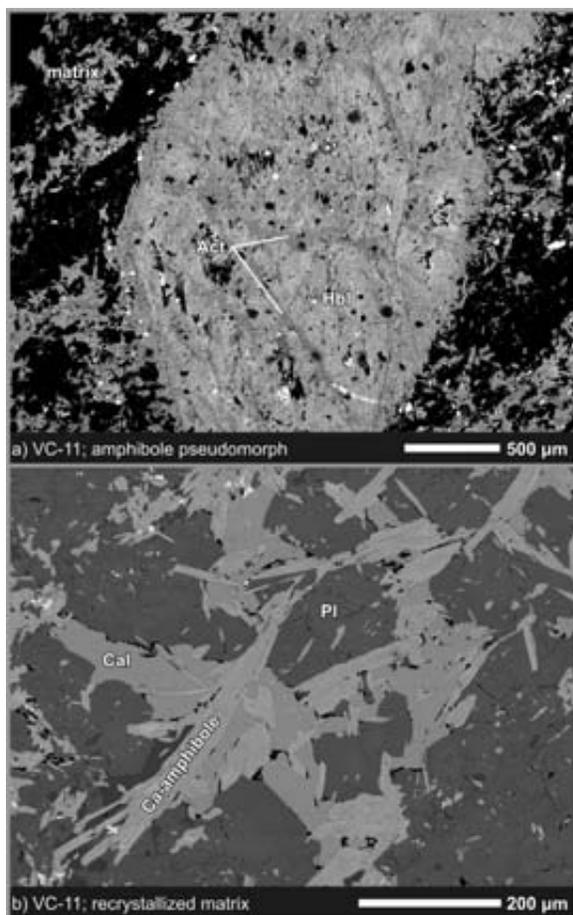


Figure 7: Back-scattered electron image of textural relationships and occurrences of amphiboles in the meta-andesite. a) Relict clinopyroxene phenocryst recrystallized as hornblende + actinolite; b) Recrystallized matrix with acicular amphiboles, calcite and plagioclase.

### ***P-T contrast across the Granby fault, and tectonic implications***

The above constraints indicate a minimum peak temperature difference of  $\sim 200^\circ\text{C}$  across the Granby fault, with pressure difference unknown at present (Figure 6). The timing of peak metamorphism on either side of the Granby fault has yet to be determined, so that the observed P-T contrast may or may not constrain the extent of movement on the fault. If it is assumed that peak metamorphism was synchronous in the hanging-wall and footwall, and that the rocks lay on the same geothermal gradient, a tentative estimate of the depth contrast across

the fault can be made. Using the estimated geothermal gradient for the footwall paragneiss of  $58^\circ\text{C}/\text{km}$ , a minimum temperature contrast of  $200^\circ\text{C}$  represents a minimum depth difference of  $\sim 4$  km. With a dip of  $35^\circ$ , the Granby fault could have therefore accommodated 7 km or more of horizontal displacement during Tertiary extensional events.

A composite cross-section drawn by Fyles (1995) suggests that the west side of the Granby fault consists of a succession, some 4-6 km thick, of thrust slices repeating the Knob Hill Group and overlying Brooklyn Formation. This would require at least 4-6 km west-side-down slip on the Granby fault near Grand Forks, supporting the estimated displacement suggested by the metamorphic contrast.

## **CONCLUSIONS**

The west-dipping Granby normal fault juxtaposes lowermost amphibolite facies rocks of Quesnel Terrane in its hanging-wall against transitional upper-amphibolite to granulite facies metamorphic rocks of the Grand Forks core complex in its footwall. The Grand Forks complex in the Volcanic Creek area consists of metapelitic gneiss, quartzite, marble and amphibolite, with significant volumes of granitic pegmatite interpreted to be due to *in-situ* anatectic melting. The rocks of the Quesnel Terrane consist of chert, siltstone and greenstone of the Knob Hill Group, overlain unconformably by sharpstone-conglomerate and related units of the Brooklyn Formation.

The Granby fault is a zone of brittle deformation tens to hundreds of metres wide, which dips gently ( $\sim 35^\circ$ ) to the west. Normal displacement along the fault appears to be synchronous, at least in part, with the emplacement of dikes related to the 51.1 Ma Coryell plutonic suite.

The peak metamorphic temperature contrast across the fault is at least  $200^\circ\text{C}$ , with pressure unconstrained. The age of metamorphism on either side of the fault is unknown. Assuming synchronous metamorphism and similar geothermal gradient across the fault, the Granby fault could have accommodated a minimum of 4 km of vertical displacement, or 7 km or more horizontally. Further P-T work and thermochronometry is required to better constrain the evolution of the Granby fault.

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## APPENDIX

Mineral compositions were acquired using wavelength-dispersive analysis on the JEOL JXA-8200 electron microprobe at the University of Calgary, using standard operating conditions (15 kV; 10 nA; focused beam) and a range of well-characterized natural and synthetic standards (e.g. DePaoli and Pattison, 1995). Quantitative analyses were subjected to matrix corrections based on the ZAF method. Results of analyses of garnet of the footwall and amphiboles of the hanging-wall are presented in tables 1 and 2, respectively. Estimates of  $Fe^{3+}/Fe^{2+}$  in amphiboles is the average between maximum and minimum estimates based on the method outlined by Schumacher (appendix 2 in Leake *et al.*, 1997). Amphibole names are based on the IMA nomenclature of amphiboles (Leake *et al.*, 1997).

Table 1: Average analyses of garnet in Sil-paragneiss (gran 1.5A). The numbers of cations calculated for the structural formulae are based on 12 oxygens.

	core	rim
SiO <sub>2</sub>	37.01	37.66
Al <sub>2</sub> O <sub>3</sub>	20.95	20.78
FeO	28.58	28.78
MnO	7.72	9.04
MgO	2.91	2.24
CaO	2.34	2.12
Total	99.51	100.63
<u>Cations based on 12 oxygens:</u>		
Si	2.99	3.02
Al	2.00	1.97
Fe <sup>2+</sup>	1.93	1.93
Mg	0.35	0.27
Mn	0.53	0.62
Ca	0.20	0.18
X Alm	0.64	0.64
X Prp	0.12	0.09
X Sps	0.18	0.21
X Grs	0.07	0.06
Fe/(Fe+Mg)	0.85	0.88

Table 2: Averaged representative analyses of amphiboles. The numbers of cations calculated for the structural formulae are based on 23 oxygen equivalents (O-F,Cl,OH).

	Meta-conglomerate (gran 6B)	Relict phenocryst in meta-andesite (VC-11)		Matrix amphibole in meta-andesite (VC-11)	
SiO <sub>2</sub>	44.88	50.79	47.27	51.88	48.37
TiO <sub>2</sub>	0.22	0.07	0.28	0.25	0.21
Al <sub>2</sub> O <sub>3</sub>	9.68	4.5	8.14	3.45	6.06
FeO	16.7	13.53	15.84	13.04	14.73
MnO	0.81	0.52	0.53	0.56	0.5
MgO	10.92	14.51	12.12	15.22	14.47
CaO	12.14	13.36	12.07	12.25	11.51
Na <sub>2</sub> O	0.85	0.42	0.97	0.44	0.52
K <sub>2</sub> O	0.41	0.16	0.27	0.08	0.16
F	0.04	ND	ND	0.02	ND
total	96.65	97.86	97.49	97.19	96.53
<u>Cations based on 23 oxygens :</u>					
Si	6.69	7.36	6.94	7.50	7.04
Al	1.70	0.77	1.41	0.59	1.04
Ti	0.03	0.01	0.03	0.03	0.02
Fe <sup>2+</sup>	1.47	1.36	1.51	1.25	0.85
Fe <sup>3+</sup>	0.61	0.28	0.43	0.32	0.88
Mg	2.43	3.13	2.65	3.28	3.14
Mn	0.10	0.06	0.07	0.07	0.06
Ca	1.94	2.00	1.90	1.90	1.80
Fe	0.00	0.00	0.01	0.01	0.07
Na	0.25	0.12	0.28	0.12	0.15
K	0.08	0.03	0.05	0.02	0.03
F	0.02	0.00	0.00	0.01	0.00
OH	1.98	2.00	2.00	1.99	2.00
cat. SUM	15.29	15.19	15.27	15.08	15.07
Fe/(Fe+Mg)	0.46	0.34	0.42	0.33	0.36
Mineral species	Magnesiohornblende	Actinolite	Magnesiohornblende	Actinolite	Magnesiohornblende

