# Mafic–felsic magma mingling in the Bow River batholith of the Halls Creek Orogen

by S. Sheppard


## Abstract

Textures indicative of magma mingling between granitoid and gabbro are extensively developed and spectacularly exposed in the Palaeoproterozoic Bow River batholith in the Halls Creek Orogen. There is no evidence that mixing and hybridization of mafic and felsic magmas took place at depth. The paucity of intermediate rocks, and lack of identifiable cumulates, precludes generation of the granitoids by crystal fractionation from mafic parent magmas. The compositional range in the batholith is primarily a function of the composition of the source rocks and the degree of partial melting. Simultaneous intrusion of mafic and felsic magmas from different sources was followed by limited crystal fractionation and mingling at high levels in the crust.


**KEYWORDS:** Halls Creek Orogen, Bow River batholith, granitoid, gabbro, magma mingling, hybridization

Mingling and mixing between coeval mafic and felsic magmas is very common in calc-alkaline granitoid batholiths worldwide (Didier and Barbarin, 1991; Pitcher, 1993). Mingling is defined as the physical interaction of two magmas where they retain their separate identities or produce heterogeneous rocks, whereas mixing results in a compositionally homogeneous hybrid melt (Sparks and Marshall, 1986; Frost and Mahood, 1987). Although commonly spectacular, magma mingling and mixing in the upper crust account for only limited variability in granitoid composition (Pitcher, 1993). However, some workers have suggested that the compositional range in calc-alkaline batholiths could result largely from mixing and hybridization of gabbroic and granitic magmas in the lower crust (Reid et al., 1983, 1993) with a secondary role for fractional crystallization.

The Halls Creek Orogen mostly consists of low- to high-grade metasedimentary and metavolcanic rocks, intruded by extensive granitoid and less voluminous massive and layered gabbroic intrusions (Tyler et al., 1995). All the contiguous granitoid and massive gabbro in the Halls Creek Orogen is grouped into the Bow River batholith (Fig. 1), which is subdivided into the 1865–1850 Ma Paperbark supersuite and the 1835–1800 Ma Sally Downs supersuite. These are equivalent to the ‘Bow River batholith’ and ‘Sally Downs batholith’, respectively, of Sheppard et al. (1995). Field relationships indicate broadly coeval intrusion of granitic and gabbroic magmas within each supersuite (Blake and Hoatson, 1993), although a range of field relationships is apparent between individual granitoid and gabbro intrusions. For instance, granitoid may intrude solidified or partially molten gabbro; gabbro and granitoid magma may be synchronous; or, gabbro may intrude solidified or partially molten granitoid. This paper deals with the Paperbark supersuite but many of the conclusions are also applicable to the Sally Downs supersuite.

## *Paperbark supersuite*

In the Halls Creek Orogen the Paperbark supersuite (Fig. 1) is about 25–30 km wide and over 300 km long, and consists of more than 20 I-type granitoid plutons and subordinate coeval gabbro intrusions. Most of the supersuite is composed of medium- to coarse-grained, porphyritic, biotite-bearing monzogranite, syenogranite and granodiorite, with subordinate tonalite. Rapakivi granite is common in the northern part of the supersuite. In general, the intrusions are homogeneous and show few indications of compositional zoning.

Coeval gabbro in the supersuite is massive and fine to medium grained, contains widespread biotite and quartz, and little or no olivine. The relationship to the layered mafic–ultramafic intrusions in the Lamboo Complex is unclear, although U–Pb SHRIMP dating by Page et al. (1995) indicates that at least some of the layered intrusions are the same age as the granitoid and massive gabbro.

### Description of field relationships between granitoid and gabbro

Widespread textures involving granitoid and gabbro in the Bow River batholith include net-vein complexes; extensive, irregular veins of granitoid cutting gabbro in conjunction with hybrid rock and xenocrystic gabbro; widespread

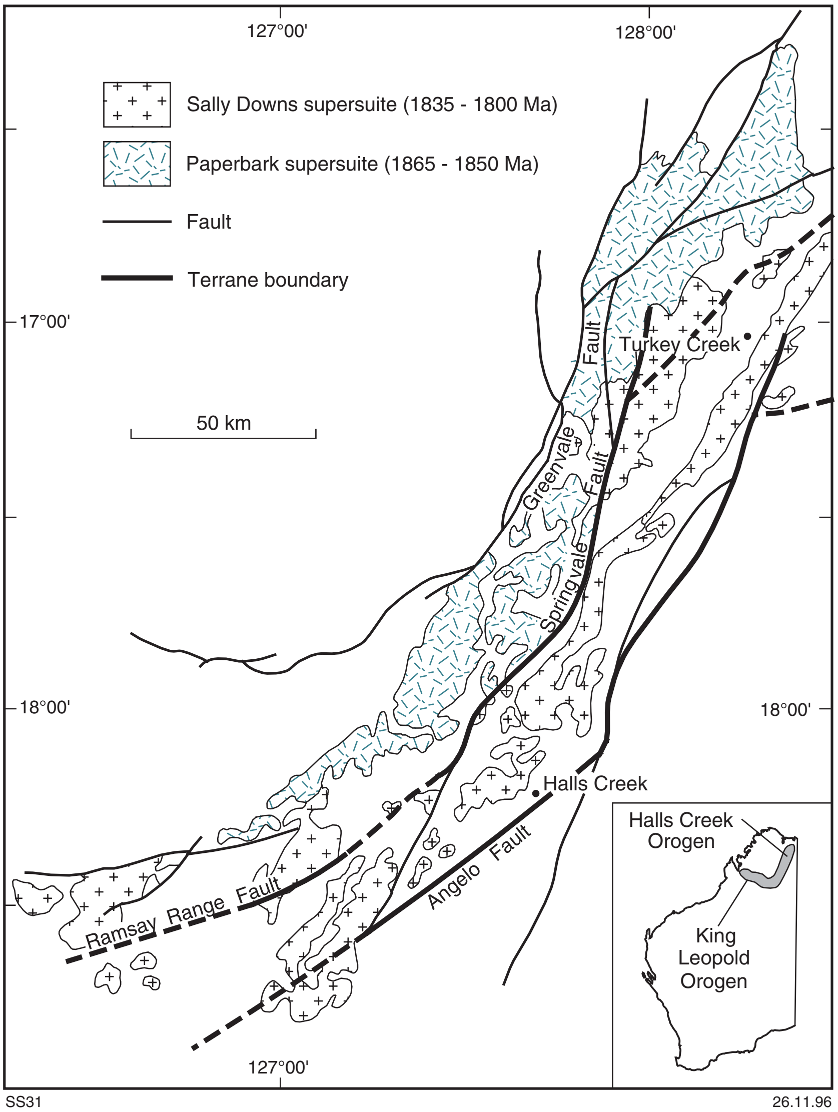


*Figure 1. Sketch map of the Bow River batholith, including coeval, massive gabbro intrusions*

rounded mafic inclusions in granitoid; and subvertical pegmatitic granitoid pipes in gabbro.

Net-vein complexes are present at the contact between many biotite-gabbro and granitoid intrusions (Blake and Hoatson, 1993). The complexes are up to 100 m wide, and consist of abundant rounded and angular inclusions of biotite gabbro enclosed and veined by heterogeneous biotite granitoid (Fig. 2). Mafic inclusions in the net-vein complexes are similar in composition and texture to rocks from the biotite-gabbro intrusions.

Mingled gabbro–granitoid consists of massive biotite- and quartz-bearing gabbro with veins and irregular patches of xenocrystic hybrid rock, both cut by irregular veins of biotite granitoid up to 30 cm wide (Fig. 2). Hybrid rocks are mafic to intermediate rocks that contain a component of both gabbro and granitoid; they have a mineralogy and grainsize (~1–2 mm) similar to those of the gabbros, but are more felsic and contain xenocrysts derived from the granitoids. Field relationships consistently indicate an order of intrusion, from oldest to youngest, of gabbro, hybrid rock, and granitoid. Contacts between hybrid veins and patches, and mafic rocks, are generally sharp (<0.5 cm wide) and curvilinear to cuspate, although more diffuse contacts are present. Most granitoid veins terminate abruptly, but some gradually merge into a trail of partially resorbed plagioclase xenocrysts within hybrid rock.

Granitoids in the Paperbark supersuite, and in particular the mafic varieties, contain widespread mafic inclusions with an igneous texture. Fine-grained mafic inclusions may be dispersed throughout the pluton, but are more numerous near the margins and especially close to net-vein complexes. Less abundant are fine- to medium-grained porphyritic inclusions that have an identical mineralogy to the host granitoid, but are more mafic.

Locally, biotite-gabbro intrusions contain cylindrical, subvertical pipes of pegmatitic biotite granitoid about 5–10 cm in diameter and 20–40 cm long, surrounded by a narrow zone of hybrid rock.

### Interpretation of field relationships

Igneous net-vein complexes form when mafic magma intrudes a cooler granitoid magma (Blake et al., 1965; Frost and Mahood, 1987; Didier and Barbarin, 1991), or a rigid granitoid at temperatures close to its solidus (Blundy and Sparks, 1992). The mafic magma chills against the granitoid, and is broken up into pillows of mafic rock enclosed by the granitoid. Owing to its much higher solidus temperature, the mafic magma solidifies, and melt derived from remobilization of the granitoid hydraulically fractures and veins the gabbro.

The textures in the hybrid rocks are consistent with incomplete mixing between mafic magma and small amounts of felsic magma. Xenocryst abundance in the hybrid rocks generally shows no spatial relationship to enclosing tonalite veins, indicating that most of the xenocrysts were incorporated at depth. The irregular nature of the granitoid veins, and exposures which show them merging into trails of plagioclase xenocrysts, suggest that the gabbro and hybrid rock were not entirely solid when veined.

The rounded shape of the mafic inclusions in the granitoids, the presence of phenocrysts straddling


*Figure 2A.* ***Irregular veins of porphyritic biotite monzogranite cutting massive biotite-bearing microgabbro in an intrusion of mingled gabbro–granitoid. Note hammer for scale***


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*Figure 2B.* ***Net-vein complex from the Paperbark supersuite. Numerous rounded to angular mafic inclusions are enclosed and veined by medium-grained biotite monzogranite. Note hammer for scale*** inclusion–granitoid contacts and widespread acicular apatite indicate that the inclusions represent mafic liquids quenched in granitoid magma (Vernon, 1983; Didier and Barbarin, 1991). Experimental and field studies on pegmatitic granitoid pipes (D'Lemos, 1992) indicate that they form by the diapiric intrusion of granitic magma into overlying gabbroic magma.

The field relationships outlined above indicate that granitoid and gabbro magmas in the Paperbark supersuite mingled extensively at high levels in the crust. However, to what extent did they mix and hybridize to form intermediate rock types?

### Geochemistry

In the Paperbark supersuite, samples of intermediate composition (~53–63 wt% $SiO_2$) are poorly represented, which reflects the predominance of felsic and mafic compositions. This contrasts with calc-alkaline granitoid batholiths in which intermediate compositions are abundant. The compositional gap between the mafic and felsic rocks in the Paperbark supersuite is illustrated in Figure 3. The gabbros and granitoids define two separate groups with the granitoids showing a roughly linear trend of sharply decreasing Sr with increasing $SiO_2$ (Fig. 3). The arrow shows the approximate trend expected from hybridization of gabbro and relatively mafic granitoid magmas, since hybridization is most likely to occur if the compositional contrast between the two magmas is ≤10 wt% $SiO_2$ (Sparks and Marshall, 1986; Frost and Mahood, 1987). The trend in the granitoids is at a high angle to that expected from hybridization with the mafic rock compositions. Only one granitoid sample, which plots midway between the two groups of rocks, is likely to be a product of hybridization.

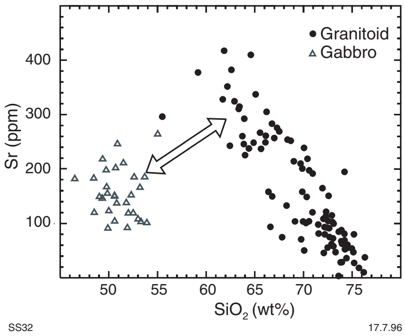


*Figure 3. Harker diagram showing the compositional gap between gabbro and granitoid of the Paperbark supersuite*

## *Discussion*

Several workers (Reid et al., 1983, 1993; Didier and Barbarin, 1991) have recently suggested that the compositional range in calc-alkaline batholiths is largely the result of hybridization between gabbroic and granitic magmas, rather than crystal fractionation or different degrees of partial melting of source rocks. In magmas of contrasting composition, hybridization is only possible where low melt viscosities, turbulent convection and large mass fractions of mafic magma are present.

Although intrusion of gabbro and granitoid was broadly contemporaneous in the Paperbark supersuite, they did not mix and homogenize to produce significant quantities of intermediate rock. Some of the scatter in the trends, particularly in the gabbros, could be produced by magma mingling, but hybridization is not the primary cause of compositional variation in the supersuite. The preponderance of siliceous rocks in the supersuite (and the batholith as a whole), in conjunction with an absence of cumulate rocks, indicates that the granitoids probably did not originate by fractional crystallization of mafic magma. Therefore, the primary granitoid magmas may have been quite siliceous (~70 wt% $SiO_2$), and thus would be unlikely to hybridize with a magma containing ~50 wt% $SiO_2$.

The homogeneity and restricted compositional range (typically ≤6–8 wt% $SiO_2$) of individual granitoid intrusions in both supersuites precludes extensive fractional crystallization in the upper crust. The fundamental controls on compositional variation in each supersuite are most likely to be variation in source rock composition and different degrees of partial melting.

## *Acknowledgements*

Tim Griffin, Paul Morris, John Myers and Ian Tyler are thanked for their reviews of the manuscript.

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