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Rheological controls on Grenvillian intrusive suites: implications for tectonic analysis

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Abstract—Studies of plutonic suites in western Grenville, along with the recent advances in understanding magma ascent and emplacement, and interactions between magma and their country rock, provide insights on the use of intrusive rocks to infer the accretionary history of deeply-exposed Precambrian orogens. In the Grenvillian Central Metasedimentary Belt of Québec, terrane juxtaposition was inferred to be late based on the distribution of 1.08 Ga potassic alkaline plutons. This view was questioned, however, upon recognition that magma ascent by dyke propagation can be stalled to enable the formation of plutons upon intersecting rheologically softer units, for example Grenvillian marble. In this context, preferential ponding of magmas in marble rather than tectonics can control regional distribution of plutons. The spatial association of plutons with marble and their contact relationships are, at the local scale, obscured by transformation of marble to skarn and by mechanical excision of marble from the paragneiss wall-rock sequence. In contrast, plutons and dykes of an older, 1.17 Ga, less alkaline magma association are shown by field and remote-sensing studies to be evenly distributed across the various lithotectonic domains of the belt. Their sheet-like emplacement along the belt boundary constrains Grenvillian tectonic assembly in the region to be early. Contrasting loci, type and degree of deformation of intrusive bodies illustrate that host-rock rheological differences influence the final characteristics of an intrusive suite. Consequently, the nature of the host is an important variable in inferring timing relationships and tectonic scenarios from intrusive suites in high-grade terranes. © 1998 Elsevier Science Ltd. All rights reserved

INTRODUCTION

As magma ascends through the crust, it leaves traces of its passage in the form of dykes and plutons. Traditionally, geologists extrapolate the spatial extent of a magmatic event from the distribution of plutons and dykes, and use their age, distribution and composition as aids in assessing tectonic settings and defining lithotectonic domains (Sengör *et al.*, 1993). They classify plutons as pre-, syn- or post-tectonic from their structural style and extent of deformation, and use their age to infer timing of regional deformation and metamorphism, facing problems due to ambiguous criteria, polyphase deformation and strain partioning across orogens (Paterson and Tobisch, 1988). The interpretation of temporal and spatial relationships between plutonic suites and their host rocks also contributes to unravelling orogenic history, contacts being either intrusive (often expected to be cross-cutting), uncomformable or faulted (Coney *et al.*, 1980). In reconstructions of deeply eroded Precambrian orogens, terrane analysis relies even most on intrusive relationships of specific igneous suites to delineate distinct rock packages and assess the relative timing of terrane assembly. In such geological contexts, mafic dyke swarms and their state of migmatization or deformation have long served as markers for inferring timing of regional metamorphism and deformational history (Bridwater *et al.*, 1973; Dimroth *et al.*, 1981; Hanmer *et al.*, 1997). The study of the Precambrian Grenville orogen also benefited, in the last decades, from advances in U–Pb geochronology, recognition of terrane/domain-bounding shear zones and LITHOPROBE seismic investigations (Davidson, 1984a,b; van Breemen and Davidson, 1988; Martignole and Calvert, 1996). A new impetus on such studies can now be expected from the significant breakthroughs in

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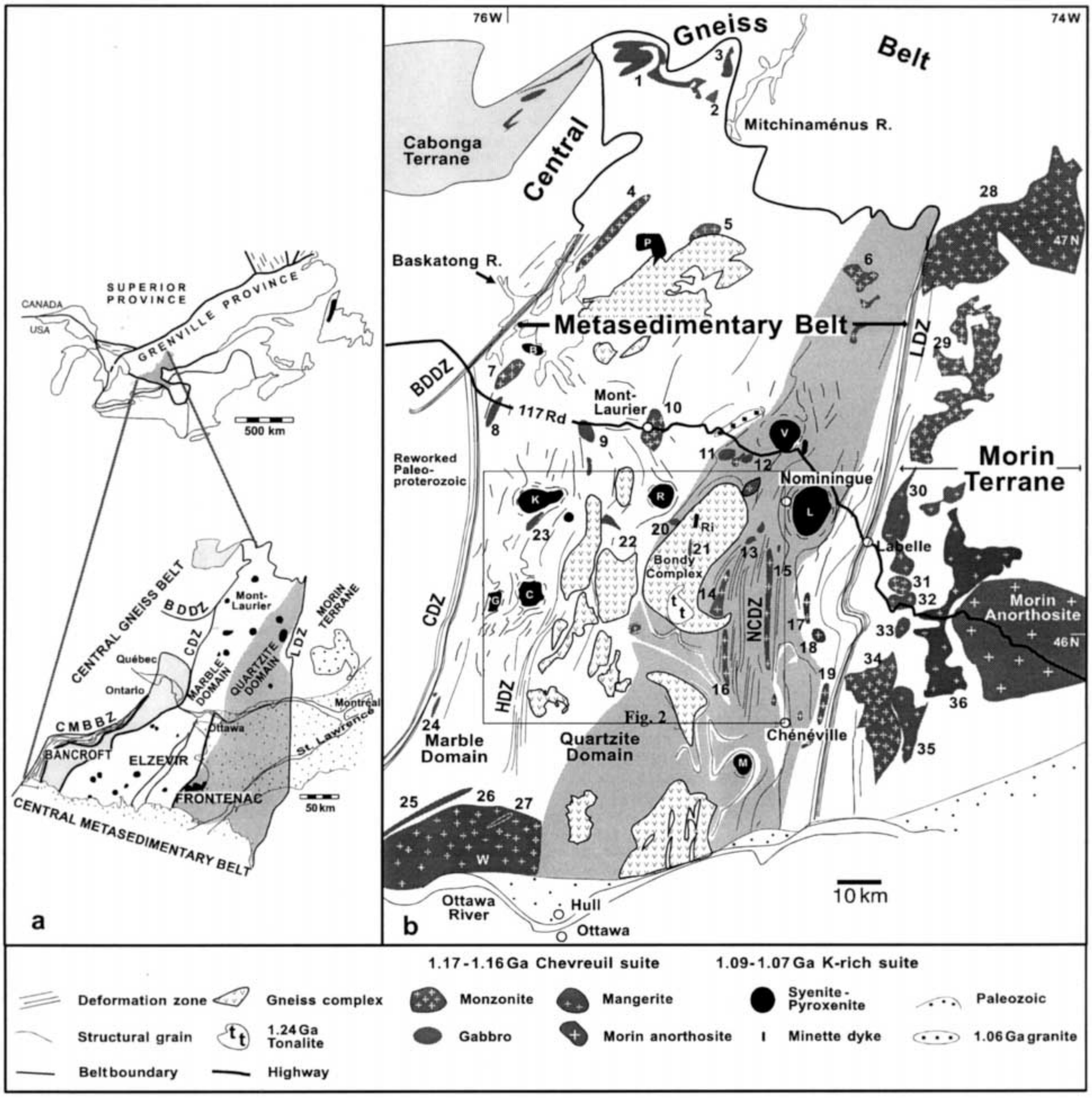

Fig. 1. (a) Terranes and domains in the Central Metasedimentary Belt and their location in the southwestern Grenville Province (modified after Corriveau, 1990; Davidson, 1995; and Corriveau and Rivard, 1997). (b) Distribution of plutonic rocks and gneiss complexes in the marble and quartzite domains of the Central Metasedimentary Belt of Québec (modified from Wynne-Edwards *et al.*, 1966; Corriveau *et al.*, 1996). Potassic plutons and dykes are: C, Cameron; K, Kensington; M, Montagne noire; Ri, Rivard; B, Baskatong; G, Gracefield; L, Loranger; P, Piscatosine; R, Lac Rouge; and V, Sainte-Veronique. Chevreuil plutons are numbered 1–27; Morin AMCG monzonite and mangerite are 28–36. Deformation zones are: BDDZ, Baskatong-Désert (Sharma *et al.*, 1995), CMBBZ, Central Metasedimentary Belt boundary zone (Hanmer, 1988); CDZ, Cayamant (Sharma *et al.*, 1995); HDZ, Heney (Langlais, 1991); NCDZ, Nominingue-Chénéville (Corriveau *et al.*, 1996); and LDZ, Labelle (Martignole and Corriveau, 1991).

the understanding of magma emplacement, mechanical anisotropies and rheological behaviour of orogenic belts (this issue of *Journal of Structural Geology*; Hatcher and Williams, 1986; Weijermars and Schmeling, 1986; Carter and Tsenn, 1987; Watson and Brenan, 1987; Lucas and Saint-Onge, 1995; Collins and Sawyer, 1996; Pavlis, 1996; Vigneresse *et al.*, 1996; Cosgrove, 1997; Tommasi and Vauchez, 1997; Brown and Solar, 1998). Such advances are applied here to re-evaluate inferences based on the use of plutons and dykes as temporal and tectonic markers in Precambrian orogens.

With its three discrete and mechanically contrasting lithological domains of marble, quartzite and felsic gneiss, the Grenvillian Central Metasedimentary belt of western Québec (CMB-Q; Figs 1 & 2) represents a microcosm of the crust to study the effects of rheology on processes governing sites of magma emplacement and final characteristics of intrusive suites during orogenesis at mid- to deep-crustal levels. The CMB-Q

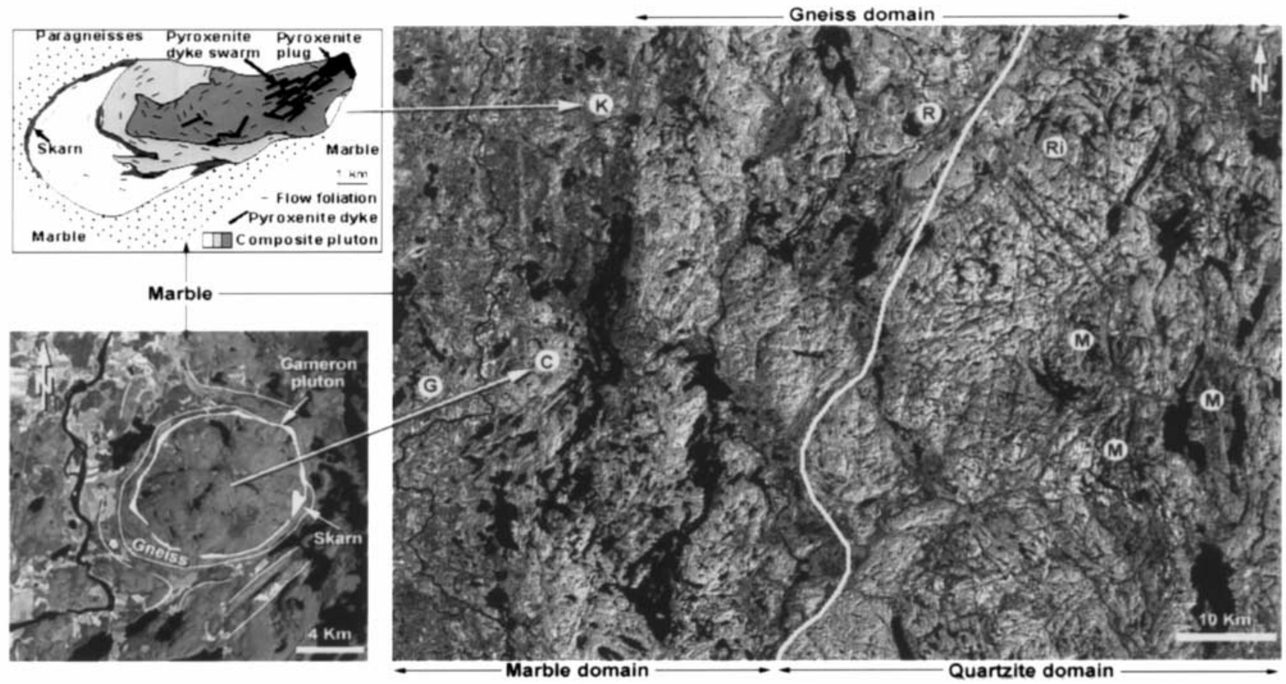

Fig. 2. LANDSAT Thematic-Mapper band 4 satellite imagery of the Central Metasedimentary Belt of Québec, south of Mont-Laurier. Marble-rich supracrustal assemblages exposed to the west are dark grey; quartzite-rich supracrustal assemblages to the east are light shades of grey with ridge-like topography most prominent in the Nominingue–Chénéville deformation zone in the eastern part of the figure; gneiss complexes form a train of light grey, fairly massive masses among the marble and quartzite domains. Monzonite and diorite sheet-like intrusive complexes of the Chevreuil suite, identified by M, are dark grey colour and have a flat topography. Location of K-rich alkaline plutons and dykes is indicated by C, G, K, R and Ri as described in Fig. 1. Note that no apparent bounding shear zone occurs between the marble and quartzite-rich domains (white line). The late deformation zones are preferential drainage pattern and correspond to the series of N–S-trending lakes. The schematic diagram of the mica–pyroxenite dyke swarm in the composite Kensington pluton is to the top left. The dykes cut across the flow foliation in the pluton. Marble comprises *c.* 80% of the country rock and is little observed along the wall rock (modified after Corriveau and Gorton, 1993; and Corriveau and Leblanc, 1995). The LANDSAT satellite image of the Cameron pluton (bottom left) shows the extent of marble, paragneisses in the wall-rock structural aureole, skarn and syenite (geology from Gauthier and Brown, 1986; and Corriveau and Gorton, 1993). Unusual asperities/bulges are observed along the otherwise smooth contact of the pluton as outlined by the thick white line marking the marginal skarn along the contact. Ridges shown by discontinuous, thin, white lines are paragneiss units among marble.

metamorphic rocks were intruded by three plutonic suites: the 1.17–1.16 Ga monzonite–gabbro Chevreuil suite (Corriveau and Rivard, 1997), the 1.09–1.075 Ga potassic alkaline Kensington–Skootamatta suite including minette dykes with exotic xenoliths (Corriveau *et al.*, 1990; Corriveau and Gorton, 1993; Morin and Corriveau, 1996) and the 1.06 Ga Guénette granite suite (Friedman and Martignole, 1995; van Breemen and Corriveau, 1995). All three suites differ significantly in their rock types, associated dyke swarms, apparent volume of magmas, mineral assemblages and textures.

The distinctive geochemistry, mineral assemblage and aeromagnetic signature of the 1.09–1.075 Ga potassic alkaline plutons allowed the Kensington–Skootamatta suite to be traced as a >450 km long, NE-trending train of plutons in the Central Metasedimentary Belt, from Ontario into Québec (Fig. 1 inset; Corriveau *et al.*, 1990). No such plutons were found in the southeastern part of the CMB-Q, in most of the Frontenac Terrane in Ontario, in the Central Gneiss Belt and in the Morin Terrane (Fig. 1 inset) (Corriveau, 1990; Davidson, 1995). Using the distribution of plutons, the concept of stitching plutonic suites and the striking arc geochemical signature of the suite, Corriveau (1990) proposed that the suite was related to a subduction regime. The area hosting the plutons was thought to constitute a terrane, distinct from the ones devoid of plutons and consequently that the terrane assembly in the western Grenville Province was post-intrusion, thus post-1.075 Ga. Easton (1992, p. 883) argued against an arc setting for the suite on the basis that arc magmatism would have generated a much more extensive suite than observed. A mantle inheritance for the arc signature was later demonstrated using isotopes (Amelin *et al.*, 1994; Corriveau and Amelin, 1994). We argue here that using the restricted distribution of this suite to negate the past existence of an arc is misleading. Following new mapping and U–Pb geochronology, post-1.075 Ga accretionary models (Corriveau, 1990; Martignole and Calvert, 1996) are refuted on the basis of: (1) the occurrence of older, 1.17–1.16 Ga, Chevreuil plutonic suite across the entire CMB-Q; (2) the discovery of

1.09–1.07 Ga plutons and ultrapotassic dykes (M and Ri in Fig. 1) (Amelin *et al*., 1994; van Breemen and Corriveau, 1995) in the domain previously considered devoid of ultrapotassic intrusions (the southern domain of Corriveau, 1990); (3) the lack of evidence for a bounding shear zone along the proposed terrane boundary (Corriveau and Jourdain, 1993); and (4) evidence for host rock rheological controls on pluton emplacement. Using the Kensington–Skootamatta suite, Corriveau and Leblanc (1995) presented a case example where the rheology of host rocks influenced the style and site of intrusive bodies at mid-crustal level and consequently the distribution of plutons. The limited distribution of this intrusive suite was determined not to reflect its restriction to a particular terrane element, but to be a consequence of trapping of magma at this crustal level by the rheologically softer marble sequences. Consequently, terrane amalgamation after emplacement of the suite could not be advocated for the area.

In this paper we first report critical field observations on the Chevreuil suite. This suite is one of a series of magmatic suites emplaced throughout the Grenville orogen between 1.17 and 1.16 Ga (Higgins and van Breemen, 1992; Davidson, 1995; Kargi and Barnes, 1995; Zhou *et al*., 1995). Interpretation of the extent, site and style of emplacement of the Chevreuil suite provides constraints on the accretionary history in western Québec and invalidates earlier models, including those derived from the distribution of the 1.09–1.075 Ga alkaline plutons. By contrasting the distribution, style of emplacement, type of intrusive relationships and extent of deformation of the Kensington–Skootamatta suite with the older Chevreuil suite, we illustrate: (1) that host rock rheological behaviour and reactivity can affect the final characteristics of intrusive systems; and (2) that rheological heterogeneities are intrinsic to the crust, their effects recurring throughout the orogenesis, and varying according to the tectonic events and the nature of the intrusive suite. The contrasts between the suites are imaged at local and orogen scale with remote-sensing LANDSAT and SEASAT data (Fig. 2). At the local scale, the processes taking place within the wall-rock envelope are shown to undermine our ability to recognize the true nature of intrusive contacts. At the regional scale, these characteristics can lead to misguided definitions of lithotectonic domains and suspect terranes (for definitions cf. Coombs, 1997 and references therein). This study of the influence of crustal rheology on establishing temporal relationships of orogenic events from intrusive suites provides a cautionary note on the use of routine markers in the tectonic analysis of now deeply exhumed Precambrian orogens.

GEOLOGICAL SETTING

The Mont-Laurier area comprises the northern, Québec, segment of the Mesoproterozoic Central Metasedimentary Belt (CMB-Q) in the western Grenville Province. These supracrustal rocks structurally overlie reworked grey gneisses of the Central Gneiss Belt along a major E-dipping, crustal-scale thrust sited along the western boundary of the belt (Fig. 1) (Wynne-Edwards, 1972; Indares and Martignole, 1990; Davidson, 1995; Sharma *et al*., 1995; Martignole and Calvert, 1996). To the east, the Morin Terrane features Grenvillian supracrustal rocks largely occluded by extensive 1.17–1.14 Ga anorthosite–mangerite–charnockite–granite–monzonite plutons (Morin AMCG suite in Fig. 1) (Wynne-Edwards *et al*., 1966; Emslie and Hunt, 1990; Doig, 1991).

The Mont-Laurier area is largely outside the tectonometamorphic imprint of the Morin AMCG suite and is composed of three discrete lithotectonic domains characterized by marble, quartzite and felsic gneiss, respectively. Marble dominates the western half of the CMB-Q with *c*. 80% marble within upper-amphibolite facies migmatitic paragneiss (Wynne-Edwards *et al*., 1966; Gauthier and Brown, 1986). The maximum metamorphic conditions preserved are ~750°C and 800 MPa, except near the western boundary of the belt where most conditions recorded are ~650°C and ~600 MPa (Kretz, 1980, 1990; Perkins *et al*., 1982; Indares and Martignole, 1990). Marble tectonites formed of coarse-grained, granoblastic marble and centimetre- to metre-scale fragments of paragneiss, amphibolite and pegmatite are ubiquitous in this domain. Within these tectonites, rocks which either originally cross-cut or were interlayered with the marble have been fragmented through differential strain, illustrating the extreme rheological contrast between marble and other rock types (Hanmer, 1988; Nadeau *et al*., 1994). Under similar conditions of temperature and differential stress, experiments indicate that marble is likely to flow at faster strain rates than most other rock types, estimates of the stress exponent (n) for power-law creep of marble at high temperature yields n values of around 8, in contrast to n values for other rocks (e.g. granite, amphibolite, quartzite) which are in the range 2–5 (Carter and Tsenn, 1987). Such ductile behaviour of marble is a potentially effective way to halt dyke propagation (Clemens and Mawer, 1992) and will probably influence the emplacement mode of magmas (Corriveau and Leblanc, 1995).

In the eastern half of the CMB-Q, quartzite is the dominant lithology ($>60\%$ by area) and occurs with migmatized upper-amphibolite facies paragneiss rocks. Marble is a minor component and occurs as metres to tens of metres thick units intercalated among quartzite layers (Corriveau and Jourdain, 1993; Corriveau and Madore, 1994).

The third lithotectonic domain forms domes in the marble and quartzite domains. It consists of a train of granulite-facies gneiss complexes in which granitoids and granitic to tonalitic gneisses of uncertain or of volcano-plutonic origin prevail. Metabasite occurs locally, whereas marble and quartzite are in trace amount (< 1%; Corriveau *et al.*, 1996). The Bondy gneiss complex is one of the largest gneiss complexes and contains hydrothermally leached Al–Mg gneisses with high-*P*, high-*T* metamorphic assemblages (e.g. cordierite–orthopyroxene–sillimanite in gneiss and cordierite–garnet–orthopyroxene in locally derived, post-fabric massive leucosomes). Metamorphic conditions attained ~950°C and ~1000 Mpa, recording thickening of the crust to about 35 km depth (Boggs, 1996). Three U–Pb ages on zircons inferred to be metamorphic and extracted from partially melted aluminous and quartzo-feldspathic gneisses suggest crystallization following peak metamorphism at 1.19 Ga (van Breemen and Corriveau, 1995; cf. Roberts and Finger, 1997). U–Pb cooling ages of 1.18 Ga or younger were obtained on monazite from metapelite and Al–Fe gneisses (Boggs, 1996). They record an initial stage of cooling or recrystallization prior to emplacement of the 1.17 Ga Chevreuil suite.

The area is traversed by four major N–S-trending, 5–15 km wide deformation zones that extend along most of the CMB-Q (Figs 1 & 2). The Cayamant (CDZ) and the Labelle (LDZ) deformation zones mark the western and eastern boundaries of the belt (Martignole and Corriveau, 1991, 1993; Sharma *et al.*, 1995). The Heney (HDZ; Langlais, 1991) and Nominingue–Chénéville (NCDZ; Corriveau *et al.*, 1996) deformation zones define the western and eastern limits of occurrence of gneiss complexes within the belt. In satellite imagery (Fig. 2), the gneiss complexes appear massive, lacking a predominant fabric, in contrast with the pronounced N–S compositional layering observed in the deformation zones (NCDZ seen in eastern part of Fig. 2).

RESEARCH METHOD

The plutons and dykes of the 1.17, 1.08 and 1.06 Ga magmatic suites serve as markers to discriminate the successive Grenvillian events. These markers were mapped and characterized across the entire CMB-Q using more than 7000 outcrops. The potassic alkaline plutons, their country rocks and the northern half of the Bondy gneiss complex were documented by mapping at 1:20,000 scale (Corriveau, 1989). A key area between Mont-Laurier, Labelle and Chénéville was mapped at 1:50,000 scale to search for the presence of a proposed terrane boundary, and to characterize in more detail all three lithotectonic domains (marble, quartzite and gneiss complexes), the various types of plutons and dykes (1.24 Ga tonalite, 1.08 Ga intrusions R, M and Ri, and 1.17 Ga intrusions 11–20 and 31–33 in Fig. 1), the Chevreuil suite and the eastern boundary of the CMB-Q (intrusions 1–34 in Fig. 1; Corriveau and Jourdain, 1993; Martignole and Corriveau, 1993; Corriveau and Madore, 1994; Corriveau, unpublished data). E–W and N–S reconnaissance transects were also conducted across the belt to characterize and define the regional extent of the various suites (e.g. along road 117, from 16 to 24, 25 and 26, and from 9 to 5 to 1 in Fig. 1). This step benefitted from photogeological interpretations of LANDSAT, SEASAT and RADARSAT images at the pluton to orogen scale (Rivard *et al.*, 1997), aeromagnetic maps (Hétu and Corriveau, 1995), as well as LITHOPROBE seismic data (Martignole and Calvert, 1996). The occurrence of glaciated outcrops, many recently uncovered and lichen-free, was instrumental in locating the various dyke swarms in this forest-covered area, the dykes commonly being only a few tens of centimetres in width. Dykes of the Chevreuil and Guénette swarms are the most common and can be traced systematically across the belt. In contrast, the Kensington–Skootamatta dykes are mostly restricted to their host cogenetic pluton; some occur in the wall rocks of these plutons and approximately five examples were observed away from plutons in the Bondy gneiss complex. Within each suite, cogenetic affinities were found between plutons and dykes, first through diagnostic field characteristics, field relationships, textures and structures, then through petrography and geochemistry. These affinities were finally tested with U–Pb geochronology of representative intrusive types (zircon, monazite, titanite and rutile; Corriveau *et al.*, 1990; Friedman and Martignole, 1995; van Breemen and Corriveau, 1995).

THE 1.17–1.16 Ga CHEVREUIL SUITE

Nature, timing of emplacement and spatial distribution

The Chevreuil suite consists of porphyritic monzonite plutons, vertically layered to massive gabbro stocks, mixed felsic–mafic sheet-like monzonite–diorite complexes and composite dykes commonly with comingling textures. K-feldspar megacrysts in monzonite (Fig. 3a) and dyke comingling textures (Fig. 3b), as well as their respective mineralogy, colour and texture, proved to be reliable markers for tracing this suite. The dykes and plutons of the Chevreuil suite are evenly distributed across the marble-rich and quartzite-rich domains of the CMB-Q and can be traced from the Central Gneiss Belt to the Morin Terrane. In the gneiss complexes, Chevreuil suite plutons are uncommon but dykes crop out systematically.

Cogenetic affinities between plutons and dykes of the Chevreuil suite are demonstrated by the systematic presence of mafic microdioritic dykes within and in the

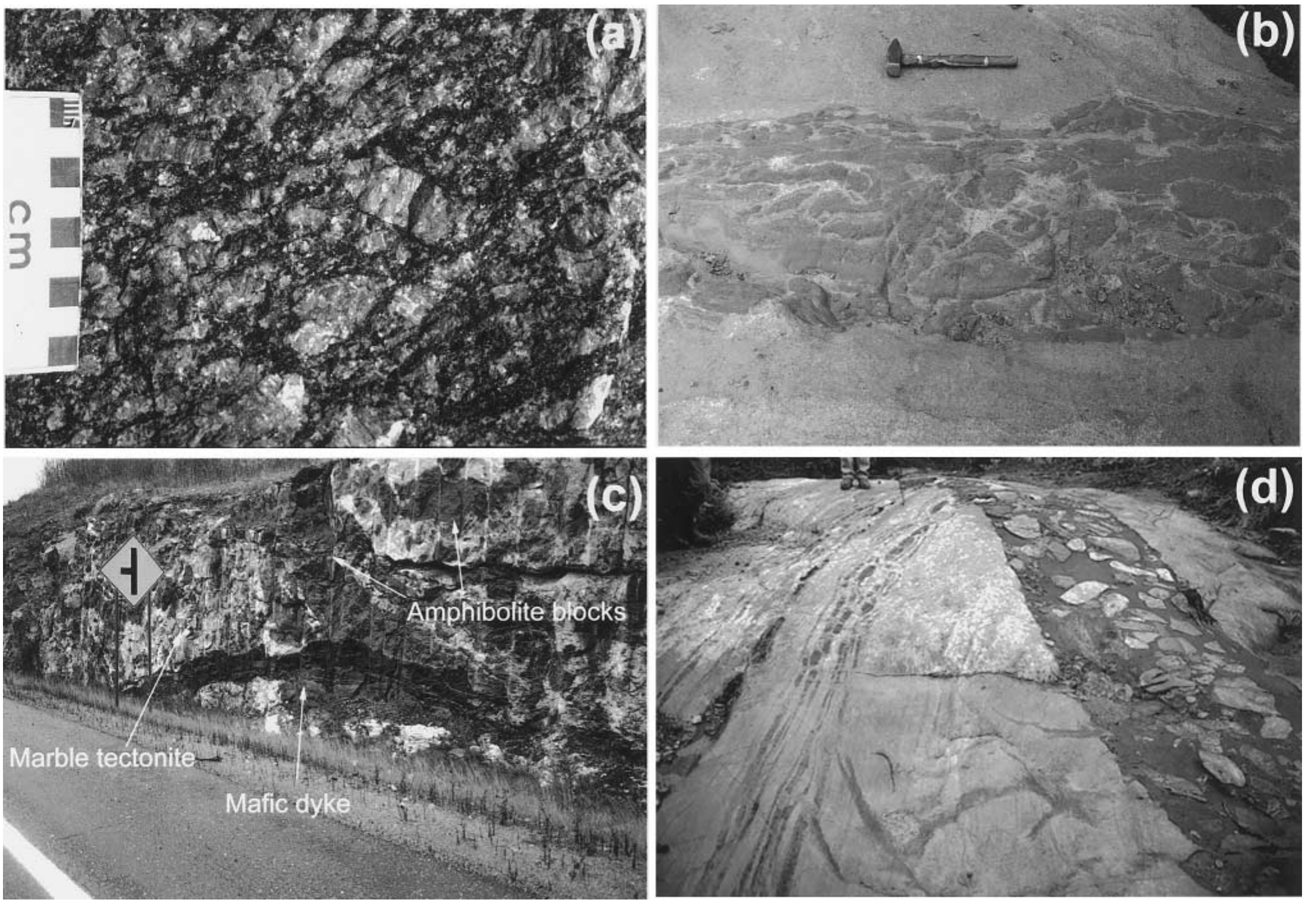

Fig. 3. Field photographs of exposed intrusive bodies of the Chevreuil suite. (a) Monzonite with a subtle igneous foliation defined by the preferred orientation of K-feldspar laths and mafic minerals. (b) Composite mafic dyke of the Chevreuil suite displaying intricate comingling between a mafic hornblende–biotite dioritic phase and a felsic phase. (c) Gently undulating mafic dyke in marble tectonite. (d) Photograph of the minette Rivard dyke. Rapid ascent of the magma through the lithosphere by fracture propagation is suggested by the diverse array of rock types and the size of the fragments (cf. Morin and Corriveau, 1996).

vicinity of the monzonite and gabbro bodies, as well as in the hornblende–biotite mafic mineral assemblage and the presence of comingling textures in both intrusive types. The microdiorite dykes are grey, fine-grained and commonly have a felsic (granitic to syenitic; aplitic to pegmatitic) phase with cuspate boundaries and intricate vein texture. U–Pb zircon dating of monzonite in sheet-like complexes, of a layered gabbro and of a mafic-felsic dyke, as well as U–Pb monazite dating of a pegmatite indicate that the Chevreuil magmatism took place from 1167 $+8/-4$ Ma (the oldest pluton dated) to 1156 ± 2 Ma (a cross-cutting pegmatite), confirming the field and petrographic evidence for their cogenetic character. Plutonic phases were emplaced first, followed by mafic and composite mafic–felsic dykes, and then by late-stage pegmatite dykes (U–Pb zircon ages of 1167 $+8/-4$, 1165 ± 2 and 1164 ± 3 Ma in monzonite 31, 16, 17; of 1175 ± 2 Ma in a pegmatitic gabbro pocket within the layered intrusion 12, and of 1161 ± 3 Ma in a pegmatitic phase of a composite dyke in the Bondy gneiss complex south of 21; and 1156 ± 2 Ma age from monazite inferred to be igneous in a late-stage pegmatite of the Nominingue–Chénéville deformation zone east of 15; Fig. 1).

Plutons and dykes of the Chevreuil suite cross-cut or include migmatitic paragneisses and felsic gneisses, and are not migmatized themselves. Hence, the suite post-dates the regional migmatization recorded by the gneissic rocks throughout the CMB-Q. Contemporaneous suites such as the monzonite and gabbro plutons of the Frontenac Terrane in the Ontario segment of the CMB, of the Central Gneiss belt (Fig. 1 inset) (Davidson, 1995) and of the Morin AMCG suite to the east (e.g. pluton 31; Emslie and Hunt, 1990), indicate that the migmatization event recorded in the CMB-Q was widespread. For the Chevreuil suite, there is a marked contrast in shape, nature and style of intrusive bodies between those sited within the deformation zones and those in the intervening domains (Fig. 1). This contrast is a key element in constraining the accretionary history of the CMB-Q in this part of the orogen. Furthermore, the extent of deformation displayed by the Chevreuil dykes and plutons varies systematically across the belt from none in those emplaced in the gneiss complexes to locally strong in those emplaced in the marble of the Cayamant deformation zone, providing constraints on timing and sites of late-stage reactivation.

Emplacement styles and degree of deformation across the belt

Outside deformation zones. Within the marble and quartzite domains between deformation zones, mafic and felsic magmas of the Chevreuil suite were emplaced separately, either as gabbro or monzonite plutons (e.g. intrusions 9–12, 20 and 23 in Fig. 1). Comingling of mafic and felsic magmas is only observed in the coeval dykes intruded into surrounding country rock. Monzonite plutons are homogeneous and characterized by a megacrystic texture, the presence of biotite and hornblende as mafic minerals, and by aligned K-feldspar crystals. Gabbroic rocks occur either in heterogeneous irregular plutons or as semicircular, steep-sided intrusions with modal layering of leucogabbro to melanogabbro. In all exposures of the four known layered intrusions (intrusions 11, 12, 13 and 20 in Fig. 1), modal layering, igneous foliation defined by tightly packed, euhedral plagioclase laths, and erosional troughs and surfaces in layered sequences are consistently subvertical. Their ubiquitous igneous texture indicates that the subvertical nature of the layering is primary and not due to tectonic rotation. Because these undeformed gabbros are scattered around the Bondy gneiss dome, it is clear that the Chevreuil suite post-dates the large-scale folding observed at the boundary of the Bondy gneiss complex. In the gneiss complexes, Chevreuil dykes systematically cut straight across the gneissic fabric and massive anatectic leucosomes. The dykes preserve intricate comingling textures. Thus, neither the dykes nor their host gneisses were penetratively deformed following emplacement of the Chevreuil suite. Dykes cutting across the marble (Fig. 3c) and quartzite domains outside of deformation zones are gently folded but retain their typical comingling igneous texture. These areas were slightly affected by post-Chevreuil overprinting.

Within deformation zones and CMB-Q boundaries. Within the Nominingue–Chénéville deformation zone, felsic and mafic magmas were repeatedly emplaced parallel to the structural grain resulting in trains of sheet-like plutonic complexes. Calc-silicate rocks (skarns) form with quartzite, the wall rocks of the intrusive sheets, their paragneiss septa and their country-rock xenoliths. Along-strike and away from the plutons, marble is more abundant than calc-silicate rock within the host quartzite-rich supracrustal sequence, supporting the inference that host marble was transformed to skarn adjacent to the plutons. In the host paragneiss, there is a marked difference between structures within and outside the deformation zone. Within the zone, the compositional layering and gneissosity are subvertical and oriented N–S with an *L–S* tectonite and S-plunging lineation rather than displaying fold interference patterns, and the leucosomes are commonly deformed, broken, porphyroclastic and foliated rather than massive. Chevreuil dykes cross-cut sharply the migmatized, porphyroclastic paragneisses, evidence that they post-date the strong transposition of their host paragneisses. The dykes are themselves folded and display a tectonometamorphic mineral lineation, also providing evidence for predating a late-stage reactivation event in this deformation zone.

The series of sheets within the plutonic complexes are compositionally distinct. Steep-sided plutonic sheets of megacrystic monzonite are concordant and alternate with subvertical diorite sheets and paragneiss septa both at the outcrop and map scales. The plutonic sheets are invaded by mafic, intermediate and felsic dykes (e.g. microdiorite, lamprophyre), and by numerous composite, co-mingled mafic–felsic dykes. K-feldspar megacrysts and mafic minerals, elliptical cogenetic enclaves and the preferred orientation of their phenocrysts, elongate mafic pillows in comingled phases, subrounded country-rock xenoliths, and the gneissosity in paragneiss septa and their wall are all parallel to the contacts of plutonic sheets, the microdiorite dykes in these sheets and the fabric of the country rock. In order to constrain the accretionary history of the CMB-Q, it is important to know whether parallelism of these structures is primary and if the subvertical sheets were emplaced along pre-existing fabric. The pluton fabric closely matches the essential observations favouring a magmatic origin for the foliation (Paterson *et al.*, 1989). The monzonite and diorite sheets are consistently concordant with the prevailing structural grain and to a large extent retain their igneous textures. A few intrusive sheets are mylonitized. Although the deformation history of plutons evolves from emplacement to cooling (cf. Pavlis, 1996), misinterpretation can be circumvented by thoroughly studying the style of cogenetic dykes. In the intrusive sheets, the early microdiorite dykes remain concordant with their host fabric whether the host sheets are deformed or not, and whether the dykes themselves are deformed or not with their host. In contrast, the late-stage felsic dykes cut across the igneous and/or solid-state fabric of the plutonic rocks consistently. Such felsic dykes are folded where they cross strongly deformed plutonic sheets and country-rock gneiss. This contrast between early and later phases strongly advocates that parallelism of sheets, dykes and paragneiss septa is primary and not an artefact of transposition through folding. Moreover, neither the long, thin paragneiss septa, nor the intraplutonic microdiorite dykes and the intrusive sheets show signs of folding. Trains of steep to subvertical, sheet-like intrusions concordant with the structural grain of their hosts also follow the eastern (LDZ), western (CDZ) and northern boundary of the CMB-Q (1–4, 7, 8, 17, 18, 19 and 24 in Fig. 1) (Wynne-Edwards *et al.*, 1966; Kretz, 1977; Kretz *et al.*, 1989; Corriveau *et al.*, 1996). The degree of deformation of these bodies and their cogenetic dykes differ between these boundaries. Chevreuil dykes that cut across the marble tectonites in the western, Cayamant deformation zone are folded isoclinally with a westward vergence. In contrast to the dykes in the Nominingue–Chénéville and Labelle deformation zones, these dykes commonly display a penetrative axial-planar biotite foliation parallel to the transposed fabric of the host marble tectonite. The felsic components in the comingled dykes are strongly transposed where this fabric is developed, obscuring the igneous origin of the felsic component. Contrary to the eastern side of the CMB-Q, the monzonite sheets are penetratively deformed, recording strong reactivation at amphibolite facies.

For the deformation zones and tectonic boundaries to serve as sites for magma emplacement, they had to predate or to have formed contemporaneously with the igneous intrusions (e.g. McCaffrey, 1990; Tobisch and Cruden, 1995; Brown and Solar, 1998). Thermal effects related to magma emplacement may act to localize deformation into belts (Tommasi *et al.*, 1994). The series of N–S-trending gneiss complexes, with their large scale and their strength contrast with surrounding paragneissic domains, were probably major factors in inducing strain localization across the belt. This resulted in partioning the late-stage deformation into N–S deformation zones (Corriveau and Rivard, 1997), a process well documented in Tommasi and Vauchez (1997). The presence of marble would exert a mechanical control on strain localization or enhance the thermal effect. However, emplacement of the Chevreuil suite post-dates the large-scale folding of the gneiss complexes (e.g. uniform subvertical fabric of the layered intrusions scattered around the folded gneiss of the Bondy complex). It also post-dates the development of widespread porphyroclastic and foliation fabric in the leucosomes of paragneisses in the host deformation zone. These textures are specific to the deformation zones, hence we infer that part of the deformation and strain localization along these zones took place prior to magma emplacement. Consequently, the deformation zones along the tectonic boundary of the CMB-Q in which mafic and felsic magmas were repeatedly emplaced were pre-existing. Emplacement was either controlled by the crustal anisotropy inherent to these zones following the model of Lucas and Saint-Onge (1995) or by coeval deformation (D'Lemos *et al.*, 1992; Brown and Solar, 1998).

THE 1.09–1.075 Ga KENSINGTON–SKOOTAMATTA SUITE

The 1.09–1.075 Ga K-rich alkaline Kensington–Skootamatta suite consists of more than 20 syenitic to pyroxenitic plutons with ultrapotassic to shoshonitic affinities (Corriveau *et al.*, 1990; Harris, 1991; Easton, 1992; van Breemen and Corriveau, 1995). Potassic alkaline members, undersaturated in silica, prevail except in the Loranger pluton, where all plutonic phases are shoshonitic and silica saturated to critically saturated. The plutons are subcircular in plan view and correspond to very strong positive aeromagnetic anomalies. Associated with the suite are dykes of carbonatite, diorite with biotite, clinopyroxene and/or plagioclase phenocrysts, and minette-type lamprophyres which occur mostly within related plutons (Corriveau and Gorton, 1993; Morin and Corriveau, 1996).

Even though the Kensington–Skootamatta magmatism post-dates and covers as large an area as the Chevreuil magmatism in Québec, the distribution of plutons differs significantly. The potassic plutons are in close spatial association with marble (except Loranger, Fig. 1). In contrast, the cogenetic dykes mostly occur within the plutons, a few cut across the gneiss and quartzite country rock but none crop out in marble. About five minette dykes, including the 1.07 Ga xenolith-choked Rivard intrusive breccia, occur in the Bondy gneiss complex (Fig. 3d). Corriveau and Leblanc (1995) attributed this contrast in intrusion styles to the rheological behaviour of the host during emplacement. Other potential factors, such as differences in magma viscosities and ascend mechanisms, were discarded as calculated viscosities for alkaline felsic to ultramafic phases were all very low indicating that magmas should ascend by dyke propagation (e.g. calculated viscosities of 1–100 Pa s for the mafic magmas assuming crystal-free melts at 1000°C and 700 MPa, with a minimum estimate of 2 wt% H_2O, and using the equations of Shaw, 1972; Corriveau and Leblanc, 1995; Morin and Corriveau, 1996).

The Rivard dyke combined with the abundance and the diversity of its xenoliths attest to magma ascent by dyke propagation with fracturing active over an extensive section of the lithosphere (Morin and Corriveau, 1996). Intersection with large-scale marble units is an efficient stopping mechanism for dyke propagation (Clemens and Mawer, 1992; Corriveau and Leblanc, 1995). At the local scale, the mica pyroxenite dyke swarm of the Kensington pluton serves to illustrate this mechanism. This dyke swarm cuts sharply across the igneous foliation of the pluton and in some areas comprises 50% of the exposure (Fig. 2). In contrast, not a single dyke is observed in surrounding marble of the wall rock. Upon intersecting wall-rock marble, the incoming magma was unable to penetrate this ductile host, and it coalesced at the pluton–marble interface to form the mica pyroxenite stock. Pluton contacts (Cameron, Gracefield and Lac Rouge plutons, Figs 1 & 2) display unusual asperities/bulges. These asperities along the otherwise smooth contact are well constrained by mapping and resemble the geometry of modelled dykes which have failed to extend from a magma body (cf. fig. 2 in Rubin, 1993). Considering that these K-rich alkaline plutons were also emplaced

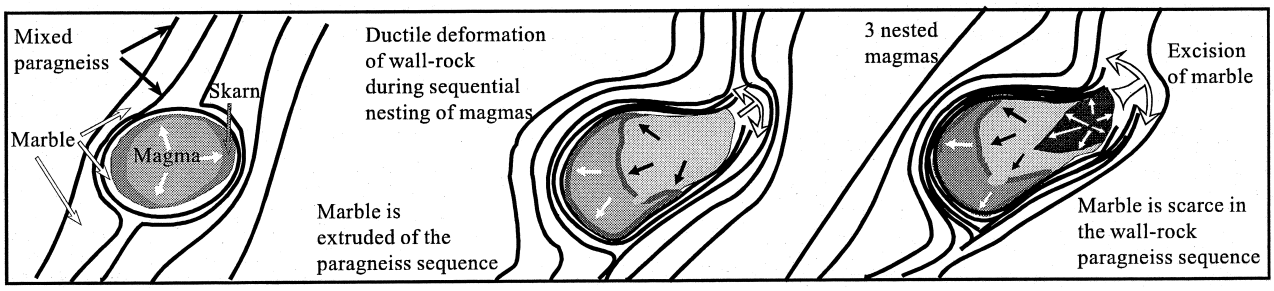

Fig. 4. Schematic representation of the mechanical excision of marble from the paragneiss sequence during emplacement of the Kensington pluton (the emplacement model is shown in fig. 6 of Corriveau and Leblanc, 1995).

in marble, the asperities are proposed to result from failed dyke propagation from a magma body within marble. At the regional scale, the marble acted as a soft unit, inhibited fracturing, trapped incoming magmas and served as a preferential ponding site thereby inducing the formation of plutons rather than throughgoing dykes, hence the spatial association of plutons with marble (Corriveau and Leblanc, 1995).

Ponding of alkaline magmas into marble led to the formation of thin (less than 100 m), discontinuous and highly heterogeneous marginal units of skarn. This process obscured the contact relationships of plutons with marble at the local scale. Moreover, marble is scarce in the wall-rock assemblage of the concentric, ⩽2 km wide, structural aureoles around the plutons (Figs 1, 2 & 4). Quartzite, calc-silicate rocks and mixed paragneiss are systematically present in the aureole, in contrast with the ubiquity of marble in the country rock. Where it occurs as wall rock, marble tends to be concentrated along the eastern contact of the plutons (e.g. Ste-Véronique, Cameron, Kensington; Corriveau and Gorton, 1993). Corriveau and Leblanc (1995) proposed that the marble-paragneiss wall rock was shouldered aside during pluton emplacement, the ductile behaviour being sustained by the successive heat input associated with sequential nesting of magmas and the high ambient temperature (*T* of magmas estimated at ~1050°C, *T* of country rock estimated at ~600°C based on titanite and hornblende cooling ages for the area; Corriveau and Gorton, 1993; Hanes *et al.*, 1994; Boggs, 1996; Morin and Corriveau, 1996).

Figure 4 illustrates how, during the sequential nesting of magmas to form the Kensington pluton, excision of marble from the marble–paragneiss sequence occurs resulting in a quartzite-rich sequence significantly different from the original host assemblage. During pluton emplacement, the extremely ductile marble was squeezed out of the paragneiss sequence, its flow probably eastward and channelled by the less ductile paragneiss layers. The remaining paragneiss piled up against the wall, forming a paragneiss aureole almost devoid of marble. Marble exposures at the eastern contact of the plutons are interpreted as the lateral outflow of marble.

EFFECTS OF CRUSTAL RHEOLOGY ON THE FINAL CHARACTERISTICS OF INTRUSIVE SUITES: PITFALLS AND KEYS TO TECTONIC ANALYSIS

Marked changes in the distribution of plutons, in magma emplacement sites and style, and in intrusive relationships across distinct lithological assemblages may be contingent on tectonics and magma ascent paths (e.g. Tobisch and Cruden, 1995) or on timing of terrane assembly. The observations presented herein on the style of emplacement and the spatio-temporal pattern of the Kensington–Skootamatta suite highlight the role of host-rock rheology on the final characteristics of an intrusive suite with: (1) the preferential siting of plutons within soft marble sequence; (2) the difficulty for dykes to propagate into marble; and (3) the absence of marble adjacent to plutons as a result of its extrusion and conversion to skarn. These observations impose constraints on the use of plutonic suites and extent of dyke swarm, both for delineating exotic terranes and for reconstructing their tectonic history. The relationship between magma emplacement sites and extent of deformation of the 1.17–1.16 Ga Chevreuil suite and tectonic boundaries, vs those in gneissic hosts are well suited for tectonic analysis at the orogenic scale.

Ponding at or escape of magma through lithotectonic assemblages: dependence on rheology

Many factors will influence the site, shape and size of intrusive bodies; some factors will be intrinsic to the magma (e.g. composition, temperature, fluid concentration, density, viscosity, driving pressure, volume, supply rate), others are tectonic or intrinsic to the host (e.g. lithostatic load, large-scale anisotropies, tectonic regime, crustal level; Hogan and Gilbert, 1995; Lucas and Saint-Onge, 1996). Potassic alkaline magmas most commonly reach the surface and erupt, or intrude the crust as lamprophyre dyke swarms (Foley *et al.*, 1989; Rock, 1991). In that respect, the train of potassic alkaline plutons in the CMB-Q and their high mafic to ultramafic components are unusual (Corriveau and Gorton, 1993; Blichert-Toft *et al.*, 1996). Considering the common occurrence of plutons and intraplutonic lamprophyre–diorite dykes, an associated lamprophyre dyke swarm across the belt would also be expected. Instead, extensive mapping has only revealed a few dykes. Under the conditions prevailing in the CMB-Q at the time of emplacement, it appears that these low-viscosity alkaline magmas left only a few dykes as trace of their passage through gneissic crust whereas the formation and siting of plutons was apparently governed by the location of large-scale marble units. From these observations, we suggest that pluton distribution can be easily misused as a criteria to define the spatial extent of a magmatic event in cases where the host rock exerts a rheological control on emplacement sites. The use of such criteria can lead to misleading interpretations of the tectonic setting during magmatic activity (e.g. Easton, 1992) and on the tectonic assembly of high-grade terrains (e.g. Corriveau, 1990).

Another criterion used in terrane analysis is the type of contact between intrusive suites and discrete lithotectonic domains or proposed terranes. The absence of apparent cross-cutting relationships of an intrusive suite in marble could be interpreted as the result of post-emplacement juxtaposition against marble by faulting or tectonic assembly (e.g. Hildebrand and Easton, 1995). The absence of dykes in one package of rocks and their presence in adjacent packages could be used to infer timing of tectonic juxtaposition of discrete lithological packages. However, the rheological controls on dyke propagation described in this study show that the lack of cross-cutting relationships in marble should not be used as evidence for assessing timing of magma emplacement across distinct supracrustal assemblages. The Kensington–Skootamatta suite is an example where rheology, not tectonics, controls the distribution of dykes and plutons.

The spatial association of K-rich alkaline plutons with marble is systematically obscured at the contact of plutons, marble having reverted to skarn or been squeezed out of wall-rock envelopes. In the quartzite-rich supracrustal sequence of the Nominingue–Chénéville deformation zone, marble was also converted to skarn during magma emplacement of the Chevreuil suite. The apparent lack of marble at or near the contact with plutons could be construed, with the absence of dykes in marble, as evidence that marble packages: (1) differ from the paragneiss wall rock; and (2) were absent during emplacement, leading to the interpretation of tectonically distinct rock packages. In marble-rich terrain, mapping marginal skarns and understanding the formation of structural aureoles may thus help in establishing the nature of the original wall-rock assemblage and consequently avoid misinterpreting the apparent lack of marble.

In gneiss complexes, stocks and plutons are scarce even though dykes, frequently subvertical, are common. As intrusion post dates regional large-scale folding and the formation of deformation zones, differences in structural levels and tectonic transposition cannot account for the difference in intrusion styles of the Chevreuil and Kensington–Skootamatta suites between the gneiss complexes and the surrounding supracrustal domains. We argue that without internal deformation to enhance magma emplacement, and in the absence of large-scale structural anisotropies or planes of weakness, the gneiss complexes are intrinsically poor sites for ponding of magma, their mechanically strong character favours fracture propagation instead.

Strain partitioning across lithotectonic domains: a diachronous record of orogenesis

Variations in the degree of deformation of the Chevreuil suite record strain partitioning across the CMB-Q and provide further constraints on the mechanical behaviour of each lithological assemblage after peak metamorphism. Polyphase deformation at high temperatures can severely overprint peak metamorphic assemblages and impair proper estimation of the tectonic evolution of orogenic belts. Although several amphibolite-facies deformation episodes overprint this Grenvillian supracrustal belt, the Chevreuil and Kensington–Skootamatta dykes display a variable degree of deformation across the belt. In the gneiss complexes, the dykes do not register pervasive deformation fabrics. They are straight and undeformed, illustrating that their host behaved as a rigid domain after *c.* 1.17–1.16 Ga. Because they escaped pervasive post-Chevreuil suite amphibolite-facies tectonometamorphic overprinting, these complexes provide a unique setting where the high-T–high-P, granulite-facies, peak-metamorphic assemblages are preserved. The maximum conditions of ~950°C and ~1000 MPa differ significantly from all previous estimates in the CMB-Q (cf. Boggs, 1996). The maximum metamorphic conditions preserved in the marble domain are ~750°C and ~800 MPa (Indares and Martignole, 1990). In this area, the Chevreuil dykes are slightly deformed. In contrast, near the western boundary of the CMB-Q, metamorphic conditions are much lower (~650°C and ~600 MPa, Kretz, 1980, 1990; Perkins *et al.*, 1982; Indares and Martignole, 1990). The Chevreuil dykes become penetratively deformed and recrystallized at amphibolite facies. We argue that the strong amphibolite-facies overprinting of the Chevreuil dykes in the Cayamant deformation zone reflects preservation in marble of the last gasps of orogenesis and the physical conditions recorded are interpreted as re-equilibrated. From the early events that first formed the marble tectonites to the late-stage Grenvillian intraplate reactivation that folded the dykes and refolded the marble tectonites, marble behaved as a very ductile material. The implication is that the metamorphic conditions preserved across the CMB-Q are diachronous, they do not belong to the same event. It follows that the complex tectonometamorphic pattern, the sharp changes in the metamorphic record and the differences in cooling or recrystallization ages cannot simply be interpreted in terms of differential unroofing or tectonic juxtaposition of blocks affected by a single event.

Dykes in the quartzite-rich domains, even within the Nominingue–Chénéville and Labelle deformation zones, are fairly well preserved even though they are folded and locally lineated. Overprinting of igneous fabric in the plutonic phases is, for the most part, minor. The mechanical behaviour of this mixed, quartzite-rich paragneiss sequence is, intermediate to that of the gneiss complexes and marble, resulting in a fairly good preservation of structures formed during magma emplacement as late-stage tectonometamorphic overprinting was for the most part minor.

In conclusion, the different mechanical strength of gneiss complexes and surrounding paragneiss assemblages, and the resulting rheological heterogeneities across an orogen can be influential during the orogenic history. Their effect may control the siting and the style of magma emplacement or the degree of deformation of intrusive bodies. Geologists can exploit these differences by adapting their study or even their mineral exploration programme accordingly.

Tectonometamorphic overprint of the Chevreuil dykes and the dating of mafic dykes

U–Pb ages from zircons in metamorphosed mafic dykes are commonly used to infer the age of peak metamorphism (e.g. Timmerman *et al.*, 1996). Meaningful dates, however, can only be achieved if the relationship between zircon growth and peak metamorphism can be established (Dirks and Hand, 1991; Roberts and Finger, 1997). Composite mafic dykes with a strongly transposed comingled felsic component can be misconstrued for transposed anatectic veins. In the CMB-Q, tracing of the Chevreuil dykes from their undeformed state in gneiss complexes to their strongly transposed and thoroughly recrystallized and foliated state in the Cayamant deformation zone illustrates the dangers of dating deformed mafic dykes to infer peak metamorphism. In the Cayamant zone, although both the dykes and the host gneiss and marble are strongly deformed at amphibolite facies, dating the mafic dykes to infer the age of regional metamorphism would be inappropriate, because their emplacement post-dates peak regional metamorphism altogether. Rather U–Pb zircon ages would date the later amphibolite-facies tectonometamorphic overprint.

The Chevreuil plutons: keys on terrane assembly

The western, northern and eastern boundaries of the Central Metasedimentary Belt in Québec served as emplacement sites for Chevreuil suite magmas. Consequently, the CMB-Q must have been already sandwiched between the pre-Grenvillian margin of the Laurentian craton (Central Gneiss Belt) and the Morin Terrane at the time of Chevreuil magmatism. This has broad tectonic implications because the timing of accretion of juvenile and exotic crustal domains to Laurentia during the Grenville orogeny is commonly obscured by successive intraplate reactivation events. Consequently, 1.18 Ga (Hanmer and McEachern, 1992; McEachern and van Breemen, 1993), 1.08–1.07 Ga (Corriveau, 1990; Timmermann *et al.*, 1997) and 1.0 Ga (Martignole and Calvert, 1996) ages have been proposed for terrane accretion in western Grenville. The Chevreuil suite post-dates the migmatite-forming regional metamorphism and associated structures, and can be traced across the CMB-Q from the Laurentian margin to the Morin Terrane. If a major collision had occurred after the emplacement of the Chevreuil suite, dykes and plutons would be deformed penetratively and migmatized like their host gneisses. Most plutons and dykes of this suite preserve their igneous textures. Those in the weaker, marble hosted, N–S-trending reactivation zones of the western boundary are strongly deformed but they are not migmatized. In contrast, the gneissic hosts are migmatized throughout the area and they record thickening of the crust to $\sim$1000 MPa with peak metamorphism and anatexis at *c.* 1.19 Ga. The pre- or syn-metamorphic setting previously attributed to monzonite bodies on the grounds that they are recrystallized (Wynne-Edwards *et al.*, 1966; Indares and Martignole, 1990) is thus reinterpreted as reflecting episodes of intraplate reactivation, not late accretion. Primary sheet-like emplacement of the Chevreuil suite along the boundary of the CMB-Q requires accretion of the Belt and adjacent Morin Terrane to the Central Gneiss Belt by 1.17 Ga. We place this accretion to Laurentia at about 1.21–1.22 Ga to account for thermal relaxation prior to the 1.19 Ga metamorphic imprint (that is, following the model of England and Thompson, 1984). The partitioning of the strain recorded across the belt indicates that inferences derived from specific sites cannot be generalized across the orogen.

CONCLUSIONS

1. Critical field observations are reported on trains of primary, sheet-like monzonite–gabbro intrusions of the 1.17–1.16 Ga Chevreuil suite along the tectonic boundary of the Central Metasedimentary Belt in western Grenville of Québec. The post-peak-metamorphic character of the suite, its spatial extent and the style of its intrusive bodies constrain tectonic assembly of this terrane against Laurentia to be pre-1.17 Ga. Dykes of this suite furthermore permit the recognition of distinct tectonometamorphic

overprinting events and tracing strain partitioning across the orogen.

2. For the younger 1.09–1.075 Ga Kensington–Skootamatta potassic alkaline suite, the distribution of plutons differs significantly in being preferentially associated with marble. Intersection with extremely ductile marble-rich assemblages stopped ascending dykes of the low-viscosity alkaline magmas, and acted as ponding sites for magmas. The distribution of plutons was predicated on the presence or absence of marble. Mechanically strong gneiss assemblages, in contrast, favoured magma ascent by fracture propagation and emplacement of small dykes; not only of the Kensington–Skootamatta suite, but also of the older Chevreuil suite.
3. It was shown that intrusive relationships of plutons can be obscured by the transformation of marble to skarn as well as by the mechanical extrusion of marble through the passage of magmas. The rock-type association of the host paragneiss sequence is thus altered during pluton emplacement. A knowledge of rock mechanical properties and processes that govern transport and ponding of magma to form dykes and plutons is necessary in order to infer whether contacts are intrusive or faulted, and whether discrete supracrustal assemblages were tectonically juxtaposed prior to or after specific intrusive suites.
4. This case study on contrasting final characteristics of magma systems at deep crustal levels illustrates that traditional spatial and temporal intrusive criteria for terrane analysis can be misleading, and that host-rock rheology is an important variable in regional tectonic interpretation derived from intrusive suites.

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