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Relationships between syn-tectonic granite fabrics and regional PTtd paths: an example from the Gander–Avalon boundary of NE Newfoundland

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Abstract—Syn-tectonic granitic plutons and their host rocks not only provide a potential wealth of information about the timing and nature of regional kinematics, but also record information about thermal conditions. Successive syn-tectonic plutons emplaced into the Gander Zone of NE Newfoundland preserve fabric overprinting formed during cooling to regional ambient thermal conditions. Ambient conditions have been approximated for each pluton by careful analysis of microstructures and consideration of potential cooling histories, and have illustrated regional exhumation during a tectonic reversal from Silurian–Devonian sinistral transpression to Devonian dextral transpression. Because the time period of emplacement is relatively short by comparison to orogenic events (typically by more than an order of magnitude), individual plutons may record a 'snap-shot' of the regional history. By combining information from a number of plutons emplaced sequentially during a period of regional orogenesis, a picture may be built up defining time–temperature–deformation (Ttd) paths. Such information may compliment regional metamorphic PT studies in helping to establish orogenic PTtd paths. © 1998 Elsevier Science Ltd. All rights reserved

INTRODUCTION

Close temporal and spatial links between emplacement of granite plutons and sites of active deformation (e.g. Hutton, 1988), in particular crustal scale shear zones (D'Lemos *et al.*, 1992, 1997), can be demonstrated from detailed comparison of fabrics and structures developed within syn-tectonic plutons with those in their host rocks (Hutton, 1988; Paterson *et al.*, 1989, 1991). Hence, precisely dated, proven syn-tectonic granites can be used to constrain the timing of regional tectonic events (e.g. Ingram and Hutton, 1994). Recent workers have also shown that syn-tectonic granites often record a history of decreasing-temperature fabric overprinting developed during pluton crystallisation and cooling (e.g. Paterson *et al.*, 1989; Miller and Paterson, 1994; Tribe and D'Lemos, 1996), and that the nature of developed fabrics is likely to reflect the ambient thermal environment of the host rocks during emplacement. Combined geochronological and fabric analysis of syn-tectonic plutons should therefore enable estimates of time, temperature and deformation (Ttd) conditions at the time of pluton emplacement. Time intervals for emplacement of individual plutons are likely to be in the order of 100,000 to a few Ma (Spera, 1980; Paterson and Tobisch, 1992) and, as such, one to several orders of magnitude shorter than regional tectonic events. Therefore each individual pluton will record a 'snap-shot' of ambient tectonothermal conditions. Where plutons have been emplaced successively over a protracted time period spanning the regional tectonic event, individual snapshots may potentially be combined to produce a tectonic 'time lapse movie'. In effect, the plutons potentially record a Ttd path which could compliment metamorphic PT studies in helping to establish regional PTtd paths. Moreover, study of syn-tectonic pluton fabrics to establish Ttd may prove useful in regions which are unsuitable for conventional thermobarometric interpretation of host rocks. In this contribution we present field and petrographic evidence from a suite of successively emplaced Silurian–Devonian syn-tectonic plutons from the Gander Zone of northeast Newfoundland, and use the above principles to estimate changing ambient country rock conditions and hence relate regional metamorphic and deformation histories.

CLASSIFICATION OF GRANITE FABRICS

Relationships between mineral microstructures in both igneous and metamorphic rocks deformed under differing temperatures have been elucidated from contrasting deformation processes of constituent mineral phases (e.g. Voll, 1976; Simpson, 1985; Tullis and Yund, 1985; Gapais, 1989). These have been established from laboratory experiments (e.g. Tullis and Yund, 1985, 1987), and from contrasting deformation styles for a variety of minerals from rocks which have well-constrained thermobarometric conditions (e.g. Simpson, 1985). In the case of cooling paths for syn-tectonic igneous bodies, it is necessary to establish the timing of deformation relative to the degree of crystallinity of the pluton (e.g. Hutton, 1988; Paterson *et al.*,

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1989, 1991). Paterson *et al.* (1989, 1991) defined two fabrics: those formed during magmatic flow where aligned crystals lie in an undeformed matrix, and those formed during solid-state deformation. These fabrics broadly correspond to the 'pre-full crystallisation' and 'crystal plastic strain' fabrics of Hutton (1988) and Ingram and Hutton (1994). Paterson *et al.* (1991) also defined fabrics formed during 'sub-magmatic' flow where enough melt still remains to allow only limited crystal sliding (c. > 500°C). Tribe and D'Lemos (1996) clarified these definitions by subdividing fabrics on the basis of the rheological divide (rheologically critical melt percentage: RCMP) which separates fabrics dominated by free rotation within a surrounding melt (pre-RCMP), and those where stress is transferred across grain boundaries, through a framework of touching crystals (post-RCMP). The post-RCMP fabrics include those formed entirely in a sub-solidus condition, and those with an estimated 10–50% melt remaining (e.g. Arzi, 1978; van der Molen and Paterson, 1979; Bryon *et al.*, 1994).

Temperatures for solid-state (post-RCMP) fabric formation are based upon deformation styles for various constituent mineral phases (cf. Tribe and D'Lemos, 1996). Although these are uncalibrated in detail, and dependant on strain rate and strain partitioning, broad values of high (c. > 550°C), moderate (c. 550–400°C) and low (c. < 400°C) temperatures are applicable, and are used here in the following discussion.

GEOLOGICAL BACKGROUND

The Gander–Avalon boundary of northeast Newfoundland is a fundamental structure separating two seismically distinct basement blocks of probable Gondwanan affinity (Marillier *et al.*, 1989; Stockmal *et al.*, 1990; D'Lemos and Holdsworth, 1996; D'Lemos *et al.*, 1997). The present-day surface expression of this contact is the Dover Fault (e.g. Blackwood and Kennedy, 1975; Blackwood, 1977; Holdsworth, 1991, 1994). To the southeast of the Dover Fault, the Avalon Zone (Williams, 1964) (Fig. 1) preserves Gondwanan Neoproterozoic tectonostratigraphy and Palaeozoic cover sequences (O'Brien *et al.*, 1993). The Gander Zone (Williams, 1964) which lies on the northwestern side of the Dover Fault (Fig. 1) comprises Late Precambrian to Lower Palaeozoic clastic sediments thought to preserve a segment of peri-Gondwanan passive continental margin (Williams *et al.*, 1988). The western part of the Gander Zone comprises metasedimentary rocks of the Gander Group (Fig. 1), typified by greenschist facies psammites and pelites deformed into dominantly E-vergent recumbent folds with superposed upright structures and penetrative fabrics (Holdsworth, 1994). The eastern margin of the Gander Zone comprises a 20 km wide zone of paragneiss and migmatite of the Square Pond and Hare Bay Gneiss (Blackwood, 1977) (Fig. 1) deformed into upright structures and sheath folds propagating parallel to a weak NE–SW-trending subhorizontal mineral lineation and formed under low pressure amphibolite facies conditions (King *et al.*, 1996). Upright fold structures are dissected by a network of broad retrograde sinistral shear zones which together are thought to reflect sinistral transpression during the Silurian–Devonian Acadian orogeny (e.g. Dunning *et al.*, 1990; Colman-Sadd *et al.*, 1992; Holdsworth, 1994) (Fig. 2). The Dover Fault itself comprises a 2 km wide zone of low temperature greenschist facies dextral deformation which largely cross-cuts the greenschist to amphibolite facies structures in the Hare Bay Gneiss and provides the focus for subsequent linked arrays of brittle dextral deformation (Holdsworth, 1994). The protoliths to the migmatites and paragneisses were intruded by 'granites' and basic sheets, preserved as poly-deformed granitic orthogneiss and amphibolite (Blackwood, 1977). A spectrum of megacrystic and non-megacrystic granites was sequentially emplaced during peak metamorphism, which includes the Wareham, Lockers Bay and Cape Freels granites (Fig. 1). These plutons are commonly deformed and associated with high strain zones, although they do not display penetrative prograde metamorphism. All these components have been intruded by extensive 'post-tectonic' Devonian plutons, including the Newport and Deadmans Bay granites (Fig. 1), which cross-cut regional structures and metamorphic isograds, and develop discrete contact aureoles typical of plutons emplaced at high structural levels (Jayasinghe, 1978; D'Lemos *et al.*, 1995).

FIELD RELATIONSHIPS AND MACROSCOPIC FEATURES OF MEGACRYSTIC GRANITES

In this study we focus on five plutons which are sufficiently extensive, well exposed and coarse grained to allow ease of study of developing fabric elements. Field relationships for the study plutons are outlined below.

Wareham Granite

The Wareham Granite is a medium to coarse grained, foliated megacrystic biotite–hornblende granodiorite–tonalite (Jayasinghe, 1978). The rocks of this pluton preserve a shallow NNE-plunging *L*-fabric defined by aligned megacrysts, prolate megacryst clusters (up to 3 m long) and rare enclaves of dioritic composition (Fig. 1). Contacts of the Wareham Granite are locally intimately mingled and mixed with regionally extensive migmatites of the Hare Bay Gneiss, or intercalated with sillimanite grade metasedimentary screens (Holdsworth, 1994) (Fig. 2). The contacts

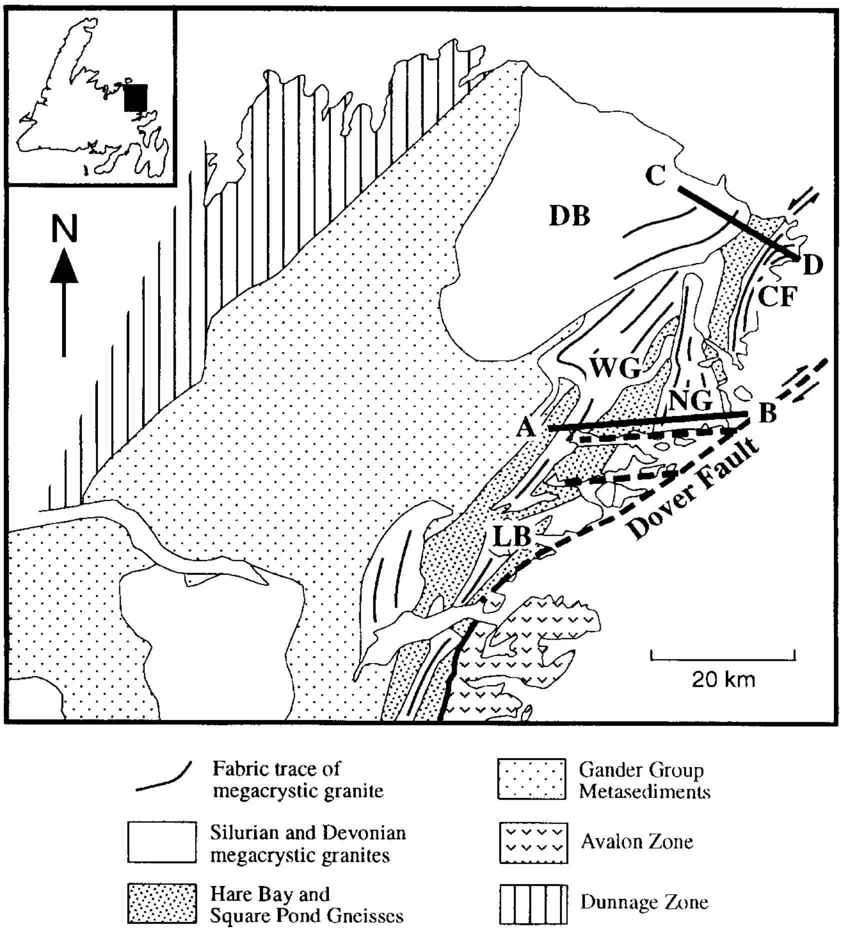

Fig. 1. Generalised geological map of the study region in NE Newfoundland (inset). CF—Cape Freels Granite; DB—Deadman's Bay Granite; LB—Locker's Bay Granite; NG—Newport Granite; WG—Wareham Granite. A–B, C–D location of schematic cross-sections (Fig. 2).

between the Wareham Granite and the metasedimentary screens are intensly folded, similarly the fabric within the pluton is colinear to both mineral lineations and fold azimuths developed in the folded metasediments and mingled rocks. Hence, the Wareham Granite is interpreted as being intruded synchronously with migmatisation, but prior to or during the formation of the dominant fold structures.

Cape Freels Granite

The Cape Freels Granite (Dickson, 1974; Jayasinghe and Berger, 1976; Jayasinghe, 1978) is a coarse grained, foliated megacrystic biotite granite–granodiorite. The megacrystic phase comprises approximately 80% of the exposure and toward the centre of the pluton a shallow NNE-plunging *L*-fabric develops, which is defined by alignment of megacrysts and microdioritic enclaves, which are cross-cut by a network of metre scale microgranite sheets (Fig. 1). Toward the NW margin of the pluton microgranite sheets become transposed into parallelism with the megacrystic granite fabric which progressively intensifies to form a protomylonitic *L–S* fabric associated with sinistral kinematic indicators. The NW margin preserves a syntectonic amphibolite facies contact aureole developed synchronously with sinistral transcurrent deformation. This suggests that the Cape Freels Granite was emplaced into an extensive sinistral transcurrent shear zone (Schofield *et al.*, 1996) continuous with those that locally dissect earlier upright fold structures (Fig. 2), and hence the Cape Freels Granite was probably emplaced subsequent to the Wareham Granite.

Locker's Bay Granite

The Locker's Bay Granite (Blackwood, 1977) is a foliated megacrystic biotite–hornblende granite lying approximately SSW along strike from the Cape Freels Granite (Fig. 1). The main megacrystic phase has a steeply dipping *L–S* fabric defined by alignment of megacrysts and dioritic enclaves. Local sub-solidus grain scale sinistral kinematic indicators are defined by strongly assymmetric megacrysts. Similarly, the Locker's Bay Granite is internally dissected by numerous sub-solidus anastomosing sinistral shear zones

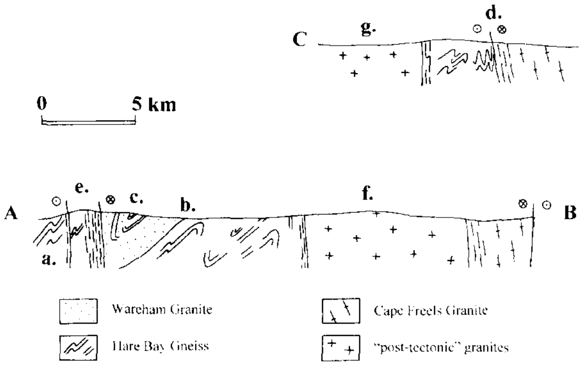

Fig. 2. Schematic cross-sections in Fig. 1. (a) Upright folding developed in the Hare Bay Gneiss. (b) Mingling of Wareham Granite and host Hare Bay Gneiss located at the structural base of the pluton. (c) Metasedimentary screens intercalated with the Wareham Granite. (d) Sinistral strike-slip high strain zone developed at the western flank of the Cape Freels Granite. (e) Sinistral hsz. dissecting earlier upright structures. (f) Newport Granite. (g) Deadman's Bay Granite.

suggesting that its emplacement may have been related to regional sinistral transcurrent deformation approximately coeval with emplacement of the Cape Freels Granite. Dextrally vergent fold structures and dextral *S–C* and *C–C′* fabrics are developed on the SE margin of the Lockers Bay Granite, which led Holdsworth (1991, 1994) to suggest that the pluton was emplaced during early dextral movement along the immediately adjacent Dover Fault. However, we consider that the internal predominance of sinistral fabrics indicate emplacement during earlier sinistral strike-slip and that dextral ductile structures and associated cataclasis represent subsequent overprinting.

Newport Granite

The Newport Granite (Strong *et al.*, 1974; Jayasinghe, 1978; Kerr *et al.*, 1993; D'Lemos *et al.*, 1995) is a weakly foliated megacrystic biotite granite. Internal compositional zones are defined by subtle changes in grain size and megacryst morphology, and the distribution of mafic micrograniti c enclaves. Contacts between compositional zones are either regular or gradational and typically defined by laterally continuous mafic-rich granitic bands (D'Lemos *et al.*, 1995). The Newport Granite has an overall N–S elongate wedge shape, with weakly developed N–S-trending *L* and *L–S* fabrics. The pluton has previously been interpreted as 'post-tectonic', as internal fabrics and pluton margins cross-cut the regional NE–SW-trending fabric developed in the host rocks (e.g. Colman-Sadd *et al.*, 1990; Kerr *et al.*, 1993) (Fig. 1). However, rooting of the pluton in a splay off the dextral Dover Fault, localised deflection of pre-existing fabrics at the contact and concentration of a complex array of brittle–ductile faults adjacent to the pluton suggest that its emplacement is controlled by active brittle upper crustal deformation (D'Lemos *et al.*, 1995).

Deadmans Bay Granite

The Deadman's Bay Granite (Jayasinghe and Berger, 1976; Jayasinghe, 1978) is a strongly composite pluton, predominantly comprising various facies of megacrystic granite (D'Lemos *et al.*, 1995). The dominant megacrystic phase shows abundant evidence of internal contacts and heterogeneity which D'Lemos *et al.* (1995) ascribed to interaction between sequentially emplaced magma bodies. Internal contacts between granite facies are sharp, gradational or diffuse but lie largely parallel to a NW-trending pre-RCMP, *S*-fabric defined by alignment of euhedral megacrysts (D'Lemos *et al.*, 1995). The western contact of the Deadman's Bay Granite is defined by inward dipping sub-solidus fabrics and cross-cutting brittle deformation, juxtaposing the pluton with migmatites developed in the aureole. The eastern contact with the Hare Bay Gneiss is defined by interlayered sheets of megacrystic granite and metasediment. The Deadman's Bay Granite cross-cuts the regional foliation and has a post-tectonic aureole defined by cordierite porphroblasts (Fig. 1). Such cross-cutting relationships have led previous workers to describe the Deadman's Bay Granite as post-tectonic (e.g. Colman-Sadd *et al.*, 1990; Kerr *et al.*, 1993), however D'Lemos *et al.* (1995) argued that while it is clearly post-tectonic with respect to ductile deformation, siting of the pluton is probably controlled by active brittle upper crustal deformation.

PETROGRAPHY AND MICROSTRUCTURES

Wareham Granite

Fabrics in the Wareham Granite are characterised by strong alignment of individual and clustered prismatic plagioclase and alkali feldspar megacrysts, alignment of decussate biotite mats, and ovoid interstitial pools of recrystallised quartz grains. These features are indicative of pre-RCMP fabrics (cf. Tribe and D'Lemos, 1996), or those formed during magmatic flow (cf. Hutton, 1988; Paterson *et al.*, 1989, 1991) (Fig. 3a). Quartz pools locally show weakly serrated or lobate grain boundaries, ductile bending indicated by undulose extinction and the formation of weak deformation bands (Fig. 3b). These features suggest weak sub-solidus deformation (cf. Voll, 1976; Tullis and Yund, 1987). At the structural top of the pluton, recrystallised biotite forms a penetrative fabric anastomosing around the megacrysts. Megacrystic plagioclase and alkali feldspar show marginal recrystallisation and are locally wrapped by mantles of fine-grained neoblasts. Plagioclase megacrysts also show rare ductile bending, deformation twins and development of recrystallised microshears (high to moderate temperature recrystallisation, c. >450°C, cf. Voll, 1976; Tullis and Yund, 1985; Simpson, 1985; Gapais, 1989). On

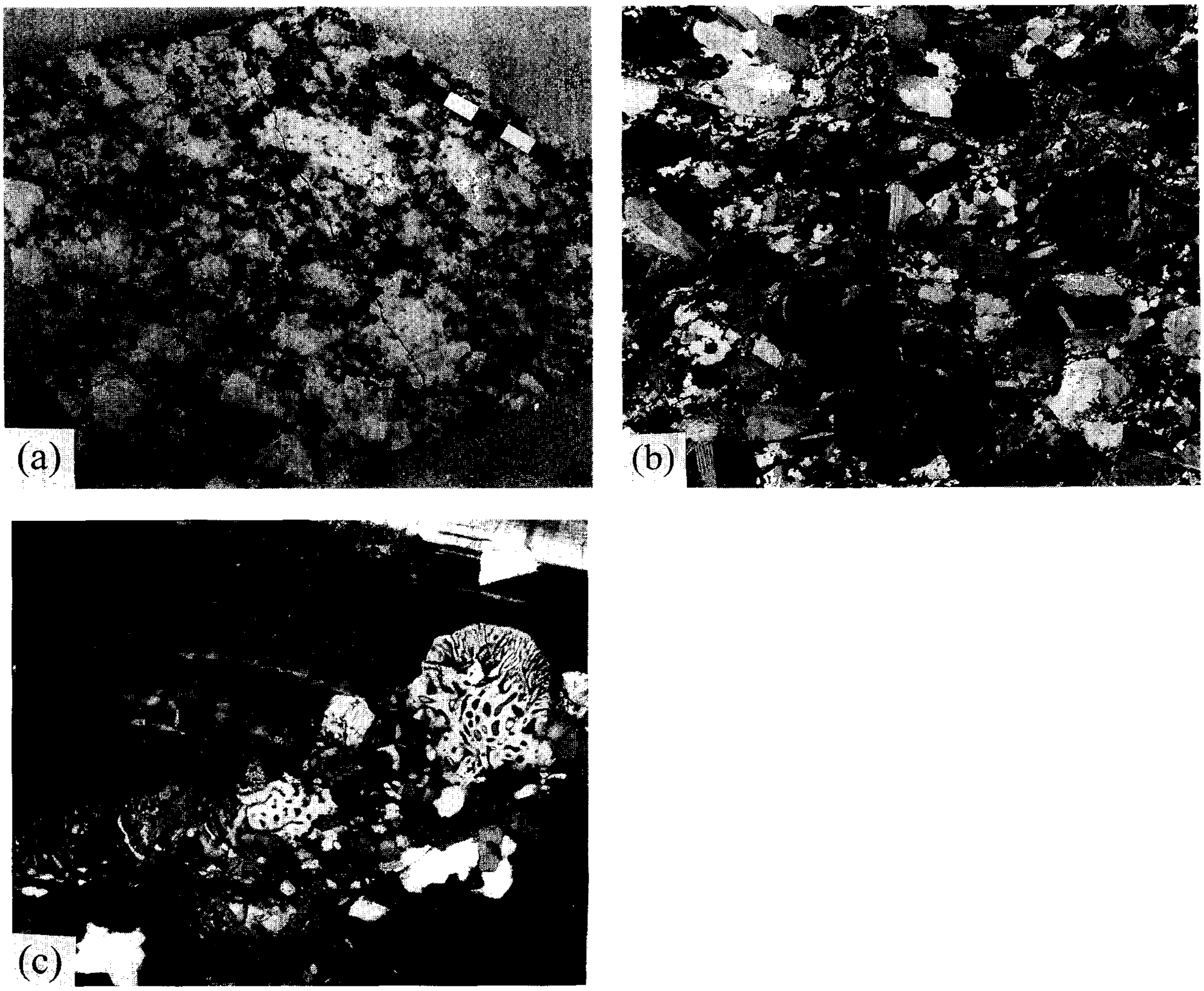

Fig. 3. Fabrics developed in the Wareham Granite. (a) Polished hand specimen showing the dominant pre-RCMP fabric, defined by strong magmatic alignment of alkali feldspar and plagioclase megacryst phases, and unaligned interstitial quartz, biotite and plagioclase. (b) Strongly partitioned moderate to low temperature sub-solidus fabric, with quartz and biotite recrystallisation concentrated into narrow, spaced shear zones. (c) Strain myrmekite developed between impinging alkali feldspar megacrysts. (b) and (c) photomicrographs, xpl. (b) Field of view is 3 x 2 cm. (c) Field of view is 5 x 4 mm.

some alkali feldspar crystals, lobate myrmekitic intergrowths (Fig. 3c) indent their long axes (high to moderate temperature recrystallisation, c. >500°C cf. Voll, 1976; Tullis and Yund, 1985; Simpson, 1985; Gapais, 1989). Fabric intensification and deformation under high to moderate temperature sub-solidus conditions are consistent with folding and development of a sillimanite-bearing axial planar fabric observed in the host rocks adjacent to the pluton.

Cape Freels Granite

The megacrystic phase of the Cape Freels Granite is characterised by aligned prismatic or tabular alkali feldspar megacrysts. Fabric elements defined by interstitial quartz and biotite domains intensify toward the pluton margin.

Toward the centre of the pluton pre-RCMP fabrics are preserved (cf. Tribe and D'Lemos, 1996), comprising aligned and tiled euhedral alkali feldspar and plagioclase megacrysts (Fig. 4a). Similarly, biotite occurs as decussate mats and discontinuous domains composed of only weakly aligned laths, and quartz forms ovoid interstitial pools of large roughly equidimensional grains, suggesting that they have not been subject to significant sub-solidus deformation (Fig. 4a). However, some plagioclase crystals show ductile bending of twin lamellae, and some alkali feldspar megacrysts show marginal recrystallisation between impinging megacrysts which indicate some recrystallisation at high to moderate temperature (c. >500°C sub-solidus deformation, cf. Voll, 1976; Simpson, 1985; Tullis and Yund, 1985; Gapais, 1989) (Fig. 4b & c). In some alkali feldspar megacrysts, brittle dilatant microcracks are developed at a high angle to the main foliation (moderate to

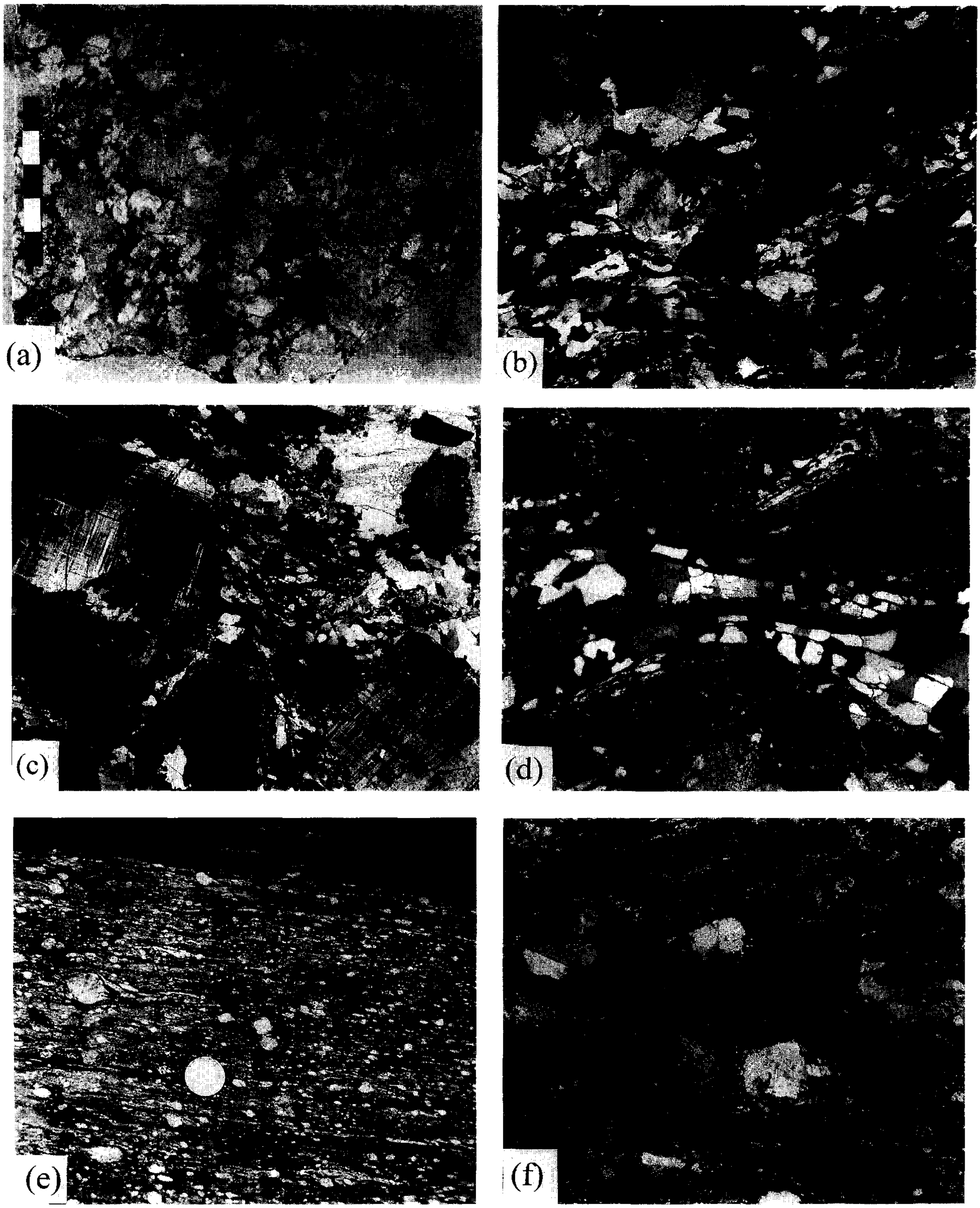

Fig. 4. Fabrics developed in the Cape Freels Granite. (a) Polished hand specimen showing pre-RCMP alignment of megacrystic alkali feldspar with ovoid interstitial quartz pools composed of recrystallised grains. (b) and (c) Moderate strain sub-solidus deformation at moderate temperature characterised by flattened quartz grains and recrystallisation between impinging alkali feldspar grains. (d) Quartz ribbon structures pinned by fine-grained recrystallised biotite domains. (e) Field photograph showing mylonitic Cape Freels Granite adjacent to the contact with its host rocks. (f) Increased low temperature sub-solidus strain approaching the western margin of the pluton, characterised by rounded alkali feldspar porphyroclasts surrounded by a strongly recrystallised chlorite-rich fine-grained matrix. (b), (c), (d) and (f) Photomicrographs, cross-polarized light. (b) Field of view: 1 × 0.7 cm. (c) c. 3 × 2 cm. (d) c. 5 × 4 cm. (f): c. 3 × 2 cm.

low temperature, c. < 500°C brittle deformation, cf. Burg *et al.*, 1984; Simpson, 1985; Tullis and Yund, 1985). Feldspar microcracks show no offset and are healed with strain-free granoblastic quartz, epidote and chlorite which is continuous with the annealed quartz pools, suggesting that recovery has taken place subsequent to brittle feldspar deformation. Individual quartz grains show undulose extinction, serrated grain boundaries and marginal neoblasts indicating recrystallisation subsequent to brittle alkali feldspar deformation. Where megacrysts impinge, quartz is more strongly deformed and occurs as pseudo-ribbon structures (cf. Boullier and Bouchez, 1978) (Fig. 4d). Biotite locally shows ductile bending and defines intercrystalline shears which pin quartz ribbons (moderate to low temperature recrystallisation, c. > 300°C cf. Voll, 1976; Simpson, 1985). Recrystallised biotite domains are transitional with less deformed mats, forming a poorly penetrative fabric anastomosing around the euhedral megacrysts. In this central part of the pluton, the main fabric elements were apparently formed during pre-RCMP flow, however localised development of subsolidus fabric elements indicates a continuum of non-penetrative, probably low strain deformation during pluton cooling.

Approaching the western margin of the pluton, alkali feldspar megacrysts become subhedral to rounded with perthite lamellae and twin planes oriented oblique to the main foliation, suggesting solid-state rotation during deformation. Abundant dynamic recrystallisation of the megacrysts forms broad rims of fine neoblasts. Dilatant brittle cracks lie at a high angle to the main fabric, or are offset and oblique giving an antithetic shear sense. Biotite is strongly recrystallised into fine-grained foliae defining a more penetrative anastomosing fabric.

Approximately 100 m from the contact, the megacrystic CFG occurs as a more homogeneously deformed protomylonite composed of lensoid or asymmetrical monoclastic alkali feldspar porphyroclasts (Fig. 4e & f). Concentration of strain into porphyroclast margins produces core and mantle textures, which coalesce into discontinuous gneissose bands. Recrystallised mantles truncate earlier formed strain myrmekite and pre-existing microcracks in the porphyroclasts, indicating a continuum of high strain subsequent to moderate temperature deformation and brittle deformation of alkali feldspar. Porphyroclasts occur in a fine-grained matrix in which planar quartz ribbons composed of largely annealed, strain free grains are pinned by planar biotite domains. Plagioclase is entirely recrystallised in strained, fine-grained plagioclase–quartz ribbons, and ductilely deformed biotite grains show marginal recrystallisation to fine-grained decussate biotite–chlorite mats. The fabric intensification and advanced recrystallisation observed toward the contact with the host migmatites suggest that development of microstructures becomes strongly controlled by increasing strain during subsolidus deformation.

Lockers Bay Granite

The main fabric elements in the Locker's Bay Granite are defined by strong alignment of lath-shaped alkali feldspar and plagioclase megacrysts, and undeformed biotite laths which are partially enclosed by magmatic plagioclase grains characteristic of pre-RCMP fabrics (cf. Tribe and D'Lemos, 1996). However, misoriented subgrains present on the short axes of alkali feldspar megacrysts, further rimmed by a mortar texture of fine neoblasts indicate widespread sub-solidus deforation (Fig. 5a). Strain myrmekite (Simpson, 1985) is abundant, and forms lobate intergrowths indenting long axes, or occurs between impinging megacrysts. Conjugate arrays of brittle microcracks are also present (Fig. 5a). Plagioclase shows little recrystallisation, although ductile bending is common, locally accommodated along recrystallised intergranular fractures which give rise to slight internal misorientation. Some plagioclase megacrysts also develop weak deformation lamellae and twins. Recrystallisation of feldspathic phases is interpreted as being indicative of sub-solidus deformation at high to moderate temperatures through to the brittle–ductile transition (c.500°C cf. Voll, 1976; Tullis and Yund, 1985; Simpson, 1985; Gapais, 1985). Quartz occurs as ovoid pools of medium grain size which are internally recrystallised and have a sub-granoblastic texture with lobate or serrated grain boundaries which indicate that deformation was dominated by grain boundary migration during near-solidus recrystallisation (cf. Gapais and Barbarin, 1986). Some grains are also weakly elongate parallel to the main foliation defining proto-ribbon structures, indicative of flattening during subsolidus deformation and recrystallisation (cf. Boullier and Bouchez, 1978). Some biotite grains show ductile bending or marginal recrystallisation into fine-grained rims of strongly aligned biotite (moderate to low temperature sub-solidus recrystallisation c. > 300°C cf. Voll, 1976; Simpson, 1985). These features indicate high to moderate temperature sub-solidus deformation throughout the Locker's Bay Granite, while preservation of strong pre-RCMP fabrics suggest that these represent decreasing-temperature overprint.

Within the main body of the Locker's Bay Granite, localised high strain zones preserve homogeneous sinistral grain-scale *S–C* fabrics or anastomosing cm–m scale sinistral shear zones. Within these shear zones alkali feldspar occurs as lensoid porphyroclasts (Fig. 5b) which show abundant marginal recrystallisation contiguous with a fine-grained quartz–feldspar–epidote matrix (high to moderate temperature recrystallisation c. > 500°C cf. Voll, 1976; Tullis and Yund, 1985; Simpson, 1985; Gapais, 1989) (Fig. 5b). Ductile antithetic micro-faults, defined by narrow zones of

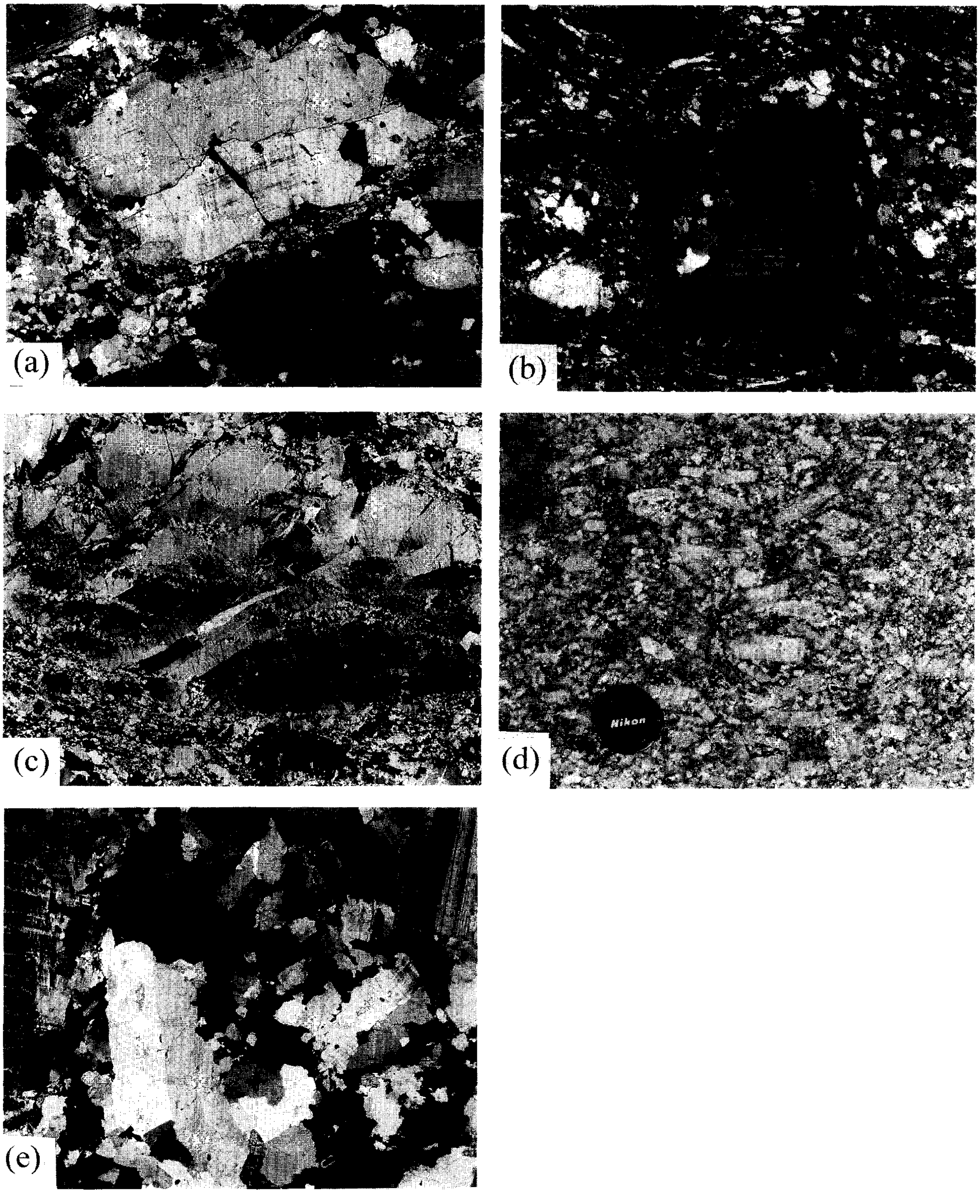

Fig. 5. Fabrics developed in the Locker's Bay, Newport and Deadman's Bay granites. (a) Typical pre-RCMP through to moderate temperature sub-solidus fabric developed in the Locker's Bay Granite, characterised by euhedral alkali feldspar megacrysts with narrow recrystallised mantles and internal brittle fracturing. (b) Mantled feldspar porphyroclasts indicative of sinistral shear from an internal sub-solidus shear zone within the Locker's Bay Granite. (c) Brittle disaggregation of a single alkali feldspar megacryst during cataclasis. (d) Field photograph showing pre-RCMP fabric developed in the Newport Granite, defined by strong alignment of alkali feldspar megacrysts with unaligned or ovoid interstitial phases (e) Deadman's Bay Granite showing typical pre-RCMP fabric with localised sub-solidus recrystalisation of interstitial phases. (a), (b), (c) and (e) Photomicrographs are in cross-polarized light; field of view; (a), (c) and (e) c. 3 × 2 cm. (b) c. 5 × 4 mm.

perthite offset and recrystallisation, and brittle microfaults defined by dilatant quartz healed cracks which are displaced to form domino-structures indicate shearing across the ductile–brittle transition for alkali feldspar (c. 500°C cf. Burg *et al.*, 1984; Simpson, 1985; Tullis and Yund, 1985). Quartz occurs in the recrystallised matrix and as sinuous ribbon-structures which have a granoblastic texture and have apparently undergone recovery crystallisation during strain partitioning into the intervening biotite domains (cf. Bell, 1985). Biotite also forms sinuous penetrative domains comprising strongly aligned fine-grained laths which locally wrap porphyroclasts and pin quartz ribbons. Biotite domains enclose larger relict grains and amphiboles with biotite-filled dilatant cracks indicating deformation of biotite across the ductile–brittle transition (c. 250°C, Stetsky, 1978). Textural features indicate that sinistral shearing and the formation of discrete high strain zones was operating during pluton cooling from high through to low temperatures (Fig. 5b).

At the eastern margin of the pluton adjacent to the Dover Fault, protomylonitic fabrics in the Locker's Bay Granite develop in cm–m scale high strain zones which lie either sub-parallel to the main foliation or cross-cut at a high angle. Within these zones alkali feldspar megacrysts preserve high to moderate temperature sub-solidus deformation textures. However, megacrysts also develop abundant flame perthite at grain boundaries, indicative of low temperature fluid enhanced deformation (c. 300–400°C, cf. Pryer and Robin, 1995). Alkali feldspar also develops broad ragged dilatant microcracks healed with strain-free quartz, and shows brittle disaggregation into angular grain fragments on the shorter axes of the megacrysts (Fig. 5c), or formation of polyclastic porphyroclasts which are consistent with cataclasic flow (low temperature deformation, c. <300°C, cf. Tullis and Yund, 1980; Tullis, 1983; Tullis and Yund, 1987). Plagioclase is strongly sericitised and the main penetrative fabric is defined by strongly aligned chlorite laths, also suggestive of fluid enhanced deformation at low temperature (Wintsch *et al.*, 1995).

Newport Granite

The dominantly megacrystic Newport Granite has a pre-RCMP fabric characterised by aligned prismatic-columnar alkali feldspar megacrysts which preserve numerous magmatic zoning and disequilibrium textures (D'Lemos *et al.*, 1995) (Fig. 5d). The matrix comprises coarse-grained unaligned plagioclase laths and equidimensional quartz grains which form a sub-granoblastic texture, with subordinate unaligned biotite and amphibole laths. Extremely weak sub-solidus deformation is indicated by localised myrmekite development between impinging alkali feldspar megacrysts and weak ductile bending of quartz.

Deadman's Bay Granite

The main pre-RCMP fabric in the Deadman's Bay Granite is defined by strong alignment of euhedral alkali feldspar megacrysts within a matrix of ducussate biotite mats and ovoid interstitial quartz pools (cf. Tribe and D'Lemos, 1996) (Fig. 5e). Pervasive ductile bending, formation of deformation bands and serrated grain boundaries within individual magmatic quartz crystals indicates that sub-solidus deformation has occurred. Similarly biotite shows localised ductile bending and marginal recrystallisation to form fine-grained neoblasts. Toward the margin of the pluton, a penetrative foliation is defined by unstrained medium-grained biotite laths which wrap rounded feldspar and quartz grains. Alkali feldspar locally develops strain myrmekite on the long axes of megacrysts (high to moderate temperature recrystallisation, c. >500°C, cf. Simpson, 1985), and plagioclase shows ductile bending offset by brittle microshears oblique to the main foliation indicating deformation in both ductile and brittle regimes.

CONDITIONS OF DEFORMATION

Figure 6 (after Karlstrom and Williams, 1995; Tribe and D'Lemos, 1996) illustrates speculative time–temperature evolution paths for three plutons emplaced, respectively, into high (c. 750°C, path 1), moderate (c. 550°C, path 2) and low (c. 400°C, path 3) temperature ambient host rock conditions. Initial gentle slopes of the hypothetical cooling curves reflect relatively slow cooling of the plutons during assembly and inflation as magma is still being added and crystallisation is taking place, releasing latent heat. Once solid, the plutons will cool toward the ambient country rock temperatures with greater thermal gradients giving rise to faster cooling rates, and hence exponential cooling vectors with different slopes for different country rock temperatures. Most importantly, the relative amount of time each pluton takes to cool through a given temperature interval is different. For example, a pluton emplaced at high ambient country rock temperatures will reside at above 550°C for a considerable period of time. If we assume continued deformation and constant strain rates during cooling, the pluton would be dominated by fabrics formed at pre-RCMP and high temperature (550°C) conditions. By comparison, a pluton emplaced at low ambient temperatures will reside for considerably greater time at low temperatures (<400°C), than in the high to moderate (e.g. sub-solidus—400°C) temperature interval, and would thus show mainly pre-RCMP and low temperature solid state fabrics, with little record of high and moderate temperature fabrics. Tribe and D'Lemos (1996) used such arguments to explain an apparent hiatus in the development of fabrics representitive of decreasing-

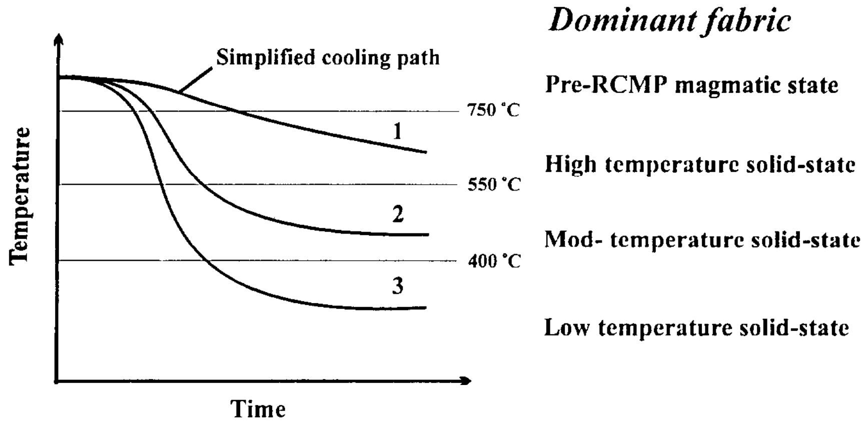

Fig. 6. Speculative time temperature cooling curves (after Tribe and D'Lemos, 1996), showing the decreasing-temperature evolution paths for three plutons emplaced into: (1) high temperature (c. 750–550°C); (2) moderate temperature (c. 550–400°C); and (3) low temperature (c. <400°C) host rocks.

temperature for plutons emplaced into low temperature ambient host rock, owing to the short interval of time that the pluton is deforming at high temperature solid-state conditions. Such a hiatus in decreasing-temperature fabric evolution seems to be at variance with previously proposed criteria for the recognition of syntectonic emplacement, which suggest that a continuum of magmatic to high temperature solid-state deformation should be observed (e.g. Paterson *et al.*, 1989; Miller and Paterson, 1994). However, Tribe and D'Lemos (1996) considered that such histories do reflect the fabrics in many plutons emplaced in the mid-upper crustal section. Here, we suggest that because of the cooling histories, the bulk fabric pattern of different plutons will be biased towards fabrics relating to the ambient country rock conditions.

Petrographic observations from the Wareham Granite indicate that the strongest fabric elements developed pre-RCMP and at high temperatures, indicative of high ambient country rock temperatures (Fig. 7). This interpretation, based on microstructural evidence, is consistent with field observations showing intermixing of the Wareham Granite with regionally extensive migmatites, with weak overprinting during subsequent deformation (cf. Holdsworth, 1994). The Cape Freels Granite preserves pre-RCMP fabrics toward the centre of the pluton, which are overprinted by solid-state microfabrics indicative of moderate to low temperatures (Fig. 7). Similarly, the Locker's Bay Granite also preserves a continuum of decreasing-temperature fabric development with an initial magmatic fabric largely overprinted by solid-state fabrics much of which are biased toward moderate temperatures. Hence the textural interpretation for both the Cape Freels and Locker's Bay Granites indicates moderate (550–400°C) ambient country rock temperatures. This interpretation is consistent with the parallelism of pluton fabrics with those developed in the aureoles which cross-cut amphibolite facies migmatisation, and preserve greenschist facies microstructures and mineral assemblages formed during regional sinistral transcurrent deformation (Schofield *et al.*, 1996). Low temperature, strongly partitioned deformation in both the Cape Freels and Locker's Bay Granite indicates either protracted cooling to lower ambient temperatures, or a subsequent deformation event. This latter interpretation is consistent with a reversal in the kinematics (sinistral to dextral) recorded in some cases (Holdsworth, 1994).

The Newport and Deadman's Bay granites are dominated by pre-RCMP fabrics, with an absence of solid-state decreasing-temperature fabric development other than at the Deadman's Bay Granite margins (Fig. 7). These features indicate emplacement in the absence of regional penetrative ductile deformation. This is either due to their emplacement late in the regional deformation history (suggested by their strongly cross-cutting contacts), and/or emplacement at high crustal levels where deformation is dominated by strongly partitioned brittle structures such that strain may be partitioned outside the pluton following emplacement. The latter may explain development of sub-solidus fabrics in the Deadman's Bay Granite margin, which represents a zone of high structural anisotropy. However in this instance weak marginal sub-solidus fabrics may also reflect post-emplacement ballooning structures (D'Lemos *et al.*, 1995).

IMPLICATIONS OF COOLING HISTORIES

Our data demonstrate how analysis of the dominant fabrics preserved in un-metamorphosed syn-tectonic granites, considered in the light of speculative pluton cooling histories, can be used to determine ambient country rock temperatures. In combination, the microtextural features of the sequentially emplaced (1) Wareham; (2) Locker's Bay and Cape Freels; and (3)

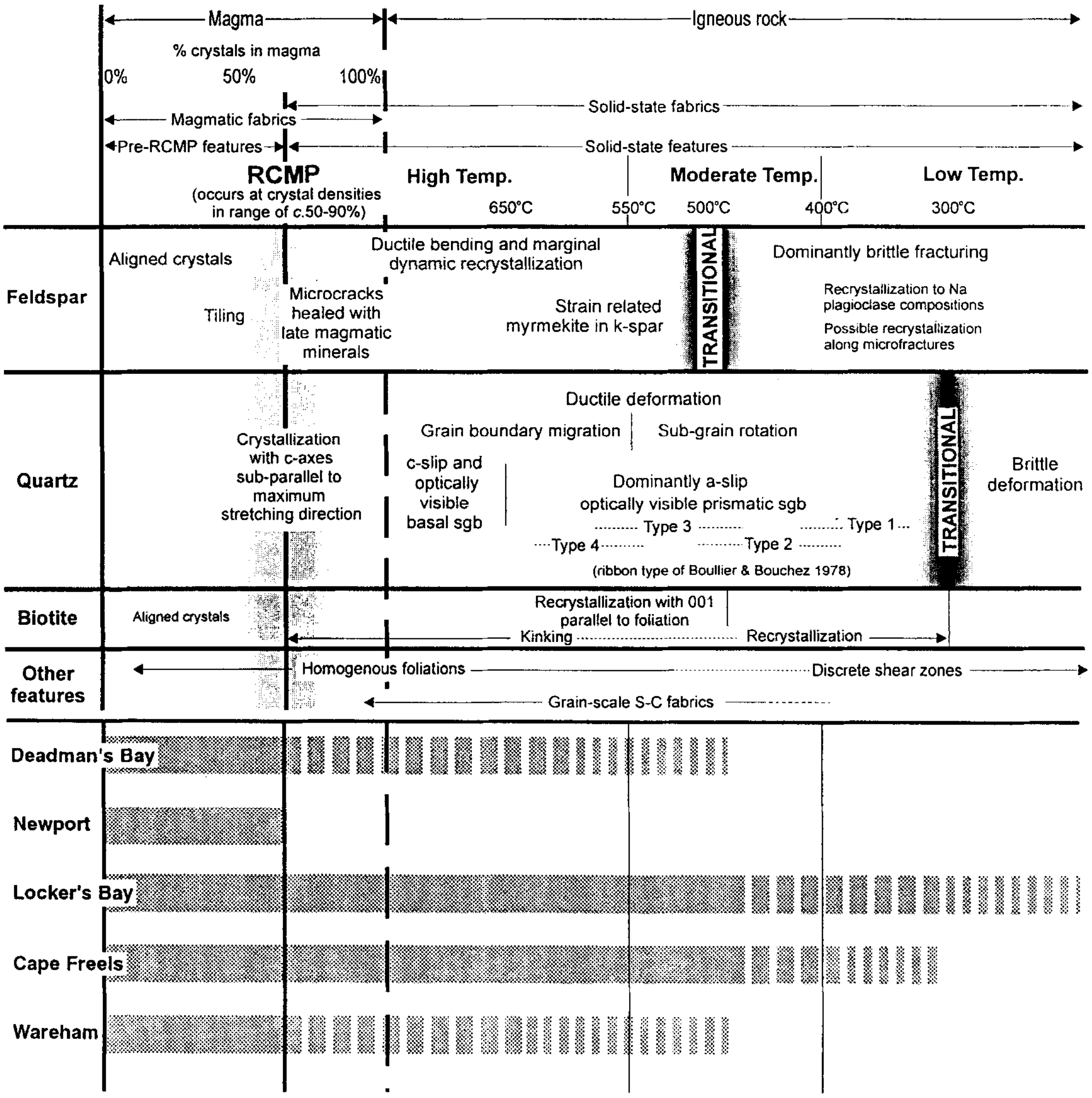

Fig. 7. Summary table showing the relationship between mineral microstructures, temperature and degree of crystallinity in a cooling syn-tectonic granite (after Tribe and D'Lemos, 1996 and references therein), also summarizing the microstructural styles preserved by the individual plutons as a result of their contrasting cooling.

Deadman's Bay and Newport granites record emplacement at amphibolite through to greenschist facies ambient country rock temperatures. Hence, we view the Wareham, Locker's Bay and Cape Freels granites as mid-crustal plutons. Subsequent exhumation, recorded by the successively lower ambient temperatures, and accompanying removal of the upper crustal section has allowed adjacent siting of the younger Deadman's Bay and Newport granites at high levels, possibly accommodated by strongly partitioned ductile–brittle fault systems (D'Lemos *et al.*, 1997). Importantly, the combination of sinistral transpression, exhumation and emplacement of mid-crustal plutons during the end Silurian, followed by kinematic reversal, continued exhumation and emplacement of high level plutons reflects tectonic processes resulting from the terminal collision of peri-Gondwanan tectonostratigraphic units against units with Laurentian affinity (cf. van Staal and de Roo, 1996) during the Silurian–Devonian Acadian orogeny (Dunning *et al.*, 1990).

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