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A microstructural and fabric study of the Galway Granite, Connemara, western Ireland

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Abstract – A detailed field and microstructural investigation of mineral fabrics in the late-Caledonian Galway Granite Batholith (∼ 400 Ma) provides insights into the relationship between emplacement-related deformation and crystallization state. These relationships are used to infer the regional instantaneous strain pattern at the time of intrusion. A Marginal Deformation Zone occurs in the granite along part of its northern sector, where planar fabrics are contact-parallel and dip steeply to the north. Within the Marginal Deformation Zone, the granite has similar patterns of pre- and post-RCMP (Rheologically Critical Melt Percentage) fabrics on either side of the NNE-trending Shannawona Fault Zone, which separates the Western and Central blocks of the batholith. Oblate pre-RCMP fabrics, which intensify towards the contact, are overprinted in a down-temperature continuum of deformation by co-axial post-RCMP fabrics that also become more intense towards the contact. At the southern edge of the Marginal Deformation Zone, deformation ceased before the granite reached its RCMP whereas, close to the contact, deformation ceased at ∼ 500 °C. Within the Central Block, oblate fabrics also developed parallel with internal granite facies boundaries. Throughout the batholith, the fabrics formed by co-axial deformation as a result of lateral expansion operating in successive magma batches at the emplacement level. These intrusion-related fabrics are consistent with other evidence that indicates the Galway Granite was emplaced into a transtensional setting at the end of the Caledonian Orogeny.

Keywords: granite, Caledonides, tectonics, emplacement, fabrics.

1. Introduction

The role of crustal lineaments and shear zones in controlling the position, ascent and emplacement of granitoid complexes is now well documented (Pitcher, 1979, 1997; Hutton, 1982, 1988; Jacques & Reavy, 1994; Dewey & Strachan, 2003 and references therein). Moreover, the temperature and timing of deformation throughout the crystallization interval and emplacement-related kinematics can now be assessed with confidence (Pitcher, 1997). These allow powerful constraints to be placed on the nature and conditions of crustal tectonics during magmatism. This paper presents new data and ideas for fabric development over significant tracts of the Galway Granite Batholith in western Ireland, and discusses the significance of the emplacement of the batholith in the regional setting of the Caledonides.

2. Geological setting of the Galway Granite

The late Caledonian granites (425–400 Ma) of Britain and Ireland are generally regarded as the anatectic product of thickened crust, usually with substantial evidence of mantle underplating, after the final Caledonian orogenic collision event during the Late Silurian, which is generally called Iapetus closure (Soper *et al.* 1992 and references therein). Much work (e.g. Jacques & Reavy, 1994; Hutton & Alsop, 1997) has emphasized the role of lithospheric lineaments and shear zones as dominant controls on the position, ascent and emplacement for plutons in the SW Scottish Highlands and Donegal, NW Ireland. The origin of these granites is unclear in that they post-date most of the terrane assembly of the Caledonides and intrude in very high-level sinistral settings across most zones of the Caledonides and are not obviously related to subduction or crustal thickening.

The Galway Batholith was emplaced at ∼ 400 Ma (Leggo, Compston & Leake, 1966; Feely *et al.* 2003): to the north into the 475–465 Ma Metagabbro–Gneiss Suite, a deformed arc complex that collided with the Laurentian margin during the Grampian event (Dewey & Mange, 1999; Friedrich *et al.* 1999; Leake, 1989; Leake & Tanner, 1994), and to the south into Lower Ordovician greenschist-facies rocks (The South Connemara Group) (McKie & Burke, 1955; Williams, Armstrong & Harper, 1988). A major fault, the Skerd Rocks Fault (Fig. 1), pre-dates intrusion of the batholith and brings the South Connemara Group against the

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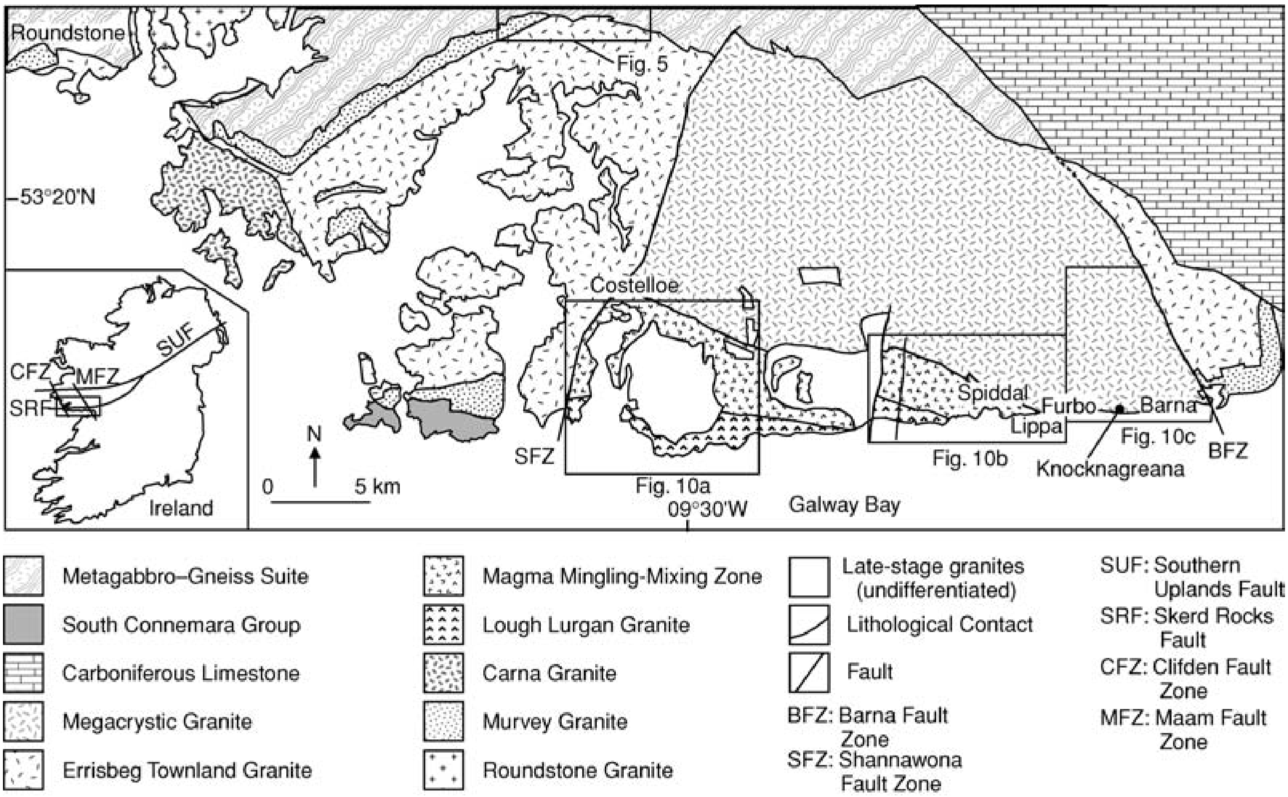

Figure 1. Regional geological map of the Galway Granite. Also shown are the locations of Figures 5, 10a,10b and 10c.

Metagabbro–Gneiss Suite (Leake, 1978). The fault is considered by Leake (1978) to be a splay of the Southern Uplands Fault and to have strongly influenced the siting of the batholith. Gravity and aeromagnetic studies have shown that the Galway Batholith extends south under Galway Bay to the northern Burren (Murphy, 1952; Max, Ryan & Inamdar, 1983; J. S. Madden, unpub. Ph.D. thesis, National Univ. Ireland, 1987) giving overall dimensions of 90 km by 35 km with the long axis oriented WNW–ESE, oblique to the Skerd Rocks Fault.

The granite is cut by two major faults (Fig. 1), the NE-trending Shannawona Fault Zone and the NW-trending Barna Fault Zone. These divide the batholith into Western, Central and Eastern blocks. Gravity studies by J. S. Madden (unpub. Ph.D. thesis, National Univ. Ireland, 1987) show that the Central Block is 3–4 km thinner than the Western Block and it is thought to represent a deeper erosion level through the complex (Leake, 1978). In the Central Block, there is a steep to moderate N-dipping zone of magma mingling and mixing in which complex silicic/mafic magma interaction has taken place (El Desouky, Feely & Mohr, 1996; Baxter & Feely, 2002). This zone probably continues at depth beneath the Western Block west of the Shannawona Fault Zone and may represent a deep-seated trans-batholithic shear zone that acted as an ascent site for much of the early magma, given the abundant evidence of mafic/silicic magma interaction (El Desouky, Feely & Mohr, 1996). The Megacrystic Granite of the Central Block and the Errisbeg Townland Granite in the Western and Eastern blocks are petrological equivalents; the Central Block Megacrystic Granite represents a more mafic, deeper level in keeping with upward movement of the eastern side of the Shannawona Fault Zone. Later granites cut the foliated Megacrystic Granite and/or the Magma Mingling–Mixing Zone (Crowley & Feely, 1997). These were emplaced at higher crustal levels and clearly cross-cut the earlier units; their emplacement may have been controlled by brittle block faulting.

Many previous studies (Kinahan, 1869; Kinahan, Leonard & Cruse, 1871; Burke, 1957; Leake & Leggo, 1963; Claxton, 1971; A. Plant, unpub. Ph.D. thesis, Univ. Bristol, 1968) have recorded mineral alignments that define the trace of a foliation in the Galway Batholith. This study presents the results of a systematic survey of macro- and microscopic structures that better constrain the geometry of the fabric in the batholith, and the timing and temperature of its development.

3. Methodology

Although it is recognized that a continuum of fabric formation exists in granites, it is important to identify and distinguish those fabrics formed through magmatic processes from those that have a tectonic origin (e.g. Paterson, Vernon & Tobisch, 1989). In this paper, we use the rheologically critical melt percentage (RCMP)

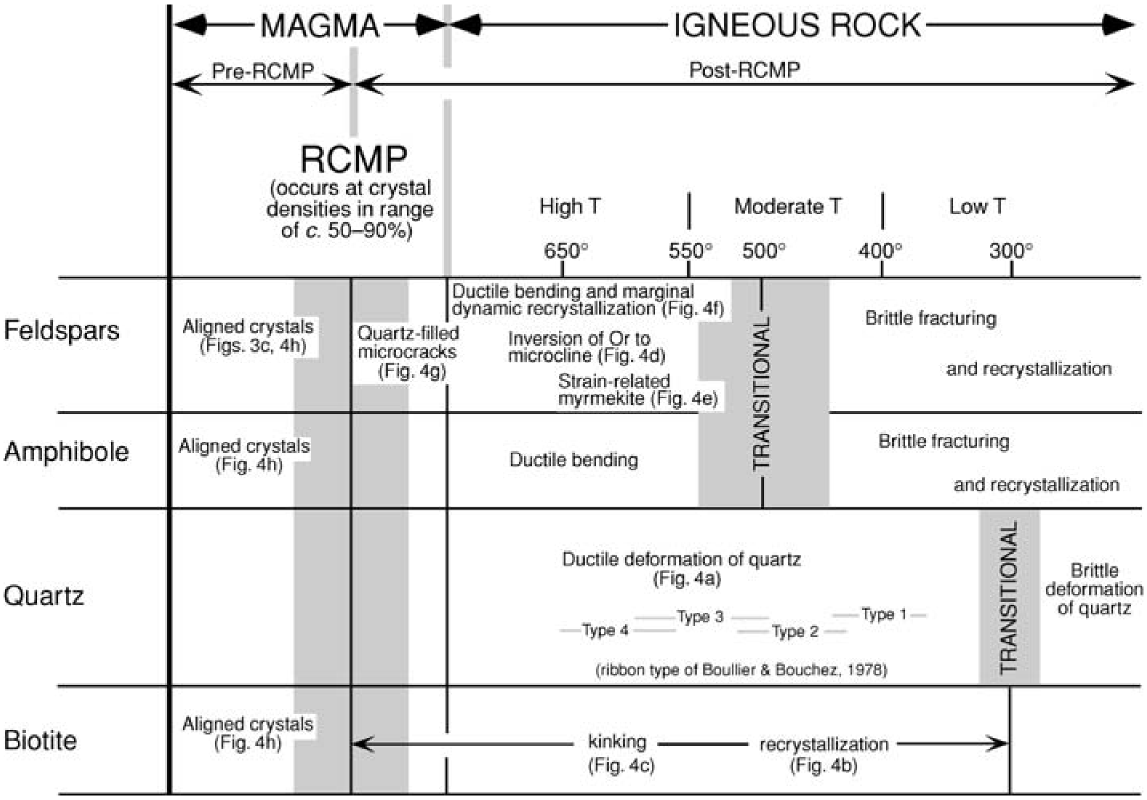

Figure 2. Microstructural criteria for the recognition and classification of fabrics in igneous rocks (after Tribe & D'Lemos, 1996).

to delineate a boundary zone between magmatic and tectonic fabrics. The concept of the RCMP was introduced by Arzi (1978); experimental and mathematical work since has defined the RCMP at 30–40 % melt (e.g. van der Molen & Paterson, 1979), a figure now widely accepted as the region in which partially melted rocks exhibit an abrupt change in viscosity (Fernandez & Barbarin, 1991; Rosenberg, 2001). The criteria compiled by Tribe & D'Lemos (1996), which we use in this paper (Fig. 2), allow for estimation of the temperature at which deformation occurred in the granite, and hence elucidation of the deformation history.

4. Fabrics of the Marginal Deformation Zone

To the west and east of the Shannawona Fault Zone, respectively, the Errisbeg Townland Granite and Megacrystic Granite facies are believed to be part of the same unit exposed at different depths. The contact between these granites and the country rock orthogneiss is generally sharp and unchilled (Fig. 3a) and no xenoliths or stoped blocks have been observed along the contact zone in the Central Block. Outcrops near the contact do not contain fractures or other indicators of cataclastic deformation, suggesting that contact-parallel faulting has not occurred. The dip of the contact is vertical or steep to the north in the Central Block and in much of the Western Block, although further west, as the contact changes to a SW–NE orientation, it decreases in dip and becomes more irregular and xenolithic. The distribution, intensity and textures of the contact-parallel fabrics are now described.

4.a. West of the Shannawona Fault Zone (northern Western Block)

Approximately 1 km from the northern contact, sporadic weak alignments of perthitic orthoclase megacrysts are present. Biotite, titanite and plagioclase are randomly oriented and quartz forms equant aggregates of grains in which weak undulose extinction is the only evidence for ductile deformation. Closer to the contact (at ∼750 m), the long axes of perthitic orthoclase crystals are aligned (Fig. 3c) and quartz aggregates are more oblate (Fig. 3b) ($X{:}Y{:}Z = 2.0{:}2.0{:}1.0$; $K \approx 0$). These aggregates comprise original grains that contain subgrains with sutured boundaries indicating grain boundary migration (Fig. 4a). Within 100 m of the contact, K-feldspars show the following microstructural changes: (a) orthoclase has inverted to microcline (Fig. 4d); (b) myrmekite is increasingly common on faces parallel with the foliation (Fig. 4e); and (c) marginal recrystallization increases, particularly at K-feldspar/K-feldspar contacts, with recrystallization grains (< 50 μm) forming core and mantle structures. Equant plagioclase (An_{25}) crystals do not appear to be aligned, but they do feature microstructures such as

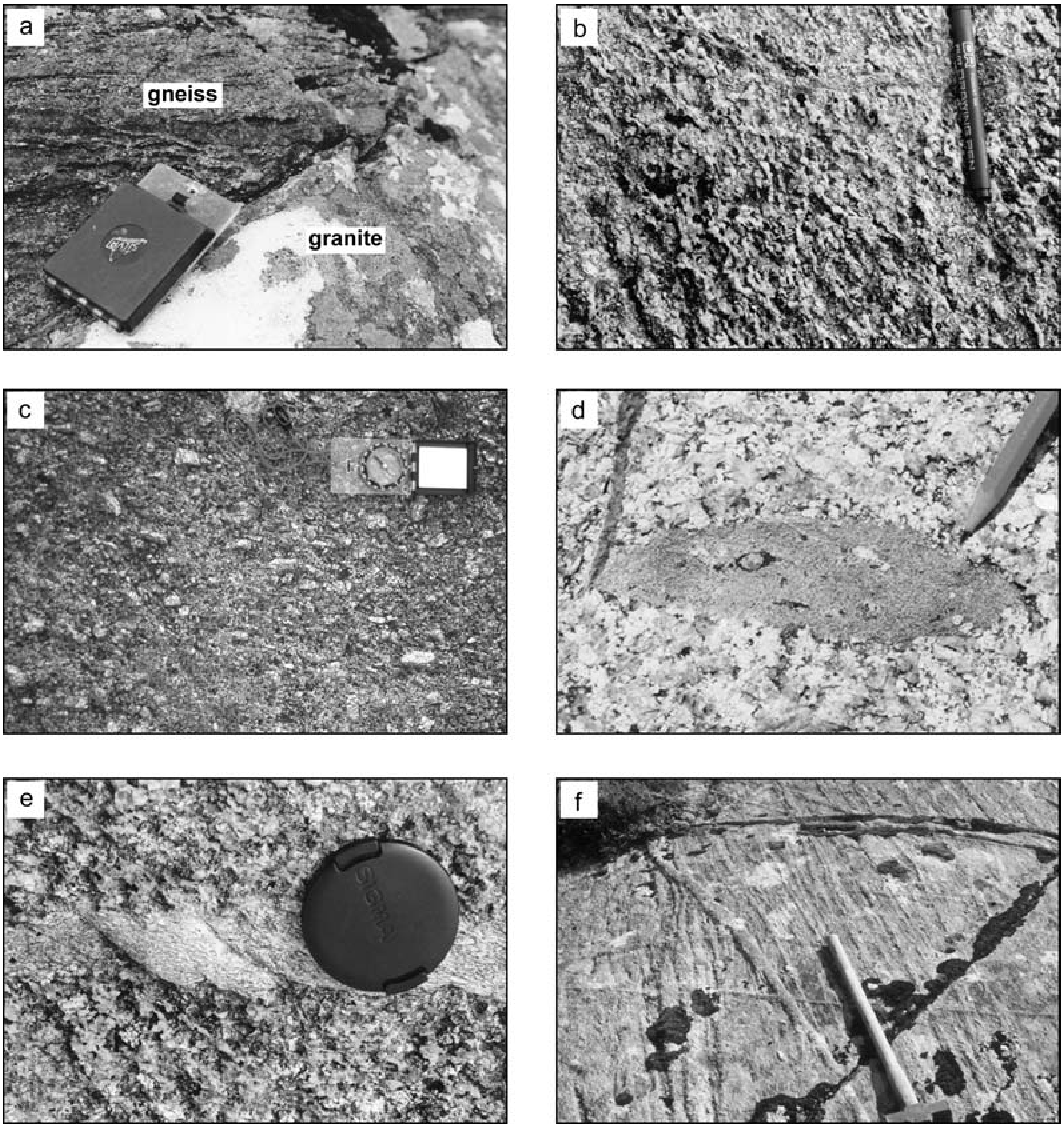

Figure 3. Field photographs of the Galway Granite. (a) Contact between the Errisbeg Townland Granite and strongly foliated orthogneiss of the Metagabbro–Gneiss Suite; note the obliquity between the strikes of the contact and the D3 foliation in the gneiss. Clinometer is 7 cm wide. (b) Strong quartz ribbon fabric in the Errisbeg Townland Granite from close to the contact with the orthogneiss. Pen is 1 cm wide. (c) Well aligned K-feldspar megacrysts in the Megacrystic Granite. Clinometer is 7 cm wide. (d) Mafic microgranular enclave from Megacrystic Granite. Note the mineral fabric in the enclave parallel to its long axis. Pencil is 8 mm wide. (e) Ductile shear zone from the marginal Errisbeg Townland Granite. Note the sharp boundaries and the strongly foliated interior. Lens cap is 4 cm in diameter. (f) Inland exposure of Magma Mingling-Mixing Zone. Note the strong banding apparent on this weathered surface. Hammer handle is 70 cm long.

bent multiple twins (Fig. 4f) and marginal recrystallization. Chloritized biotite commonly is smeared out in domains at the margins of the quartz ribbons (Fig. 4b) and unaltered biotite crystals are commonly bent (Fig. 4c).

4.b. East of the Shannawona Fault Zone (northern Central Block)

Poorly aligned K-feldspar megacrysts were first noted some 2.5 km from the northern contact set in a

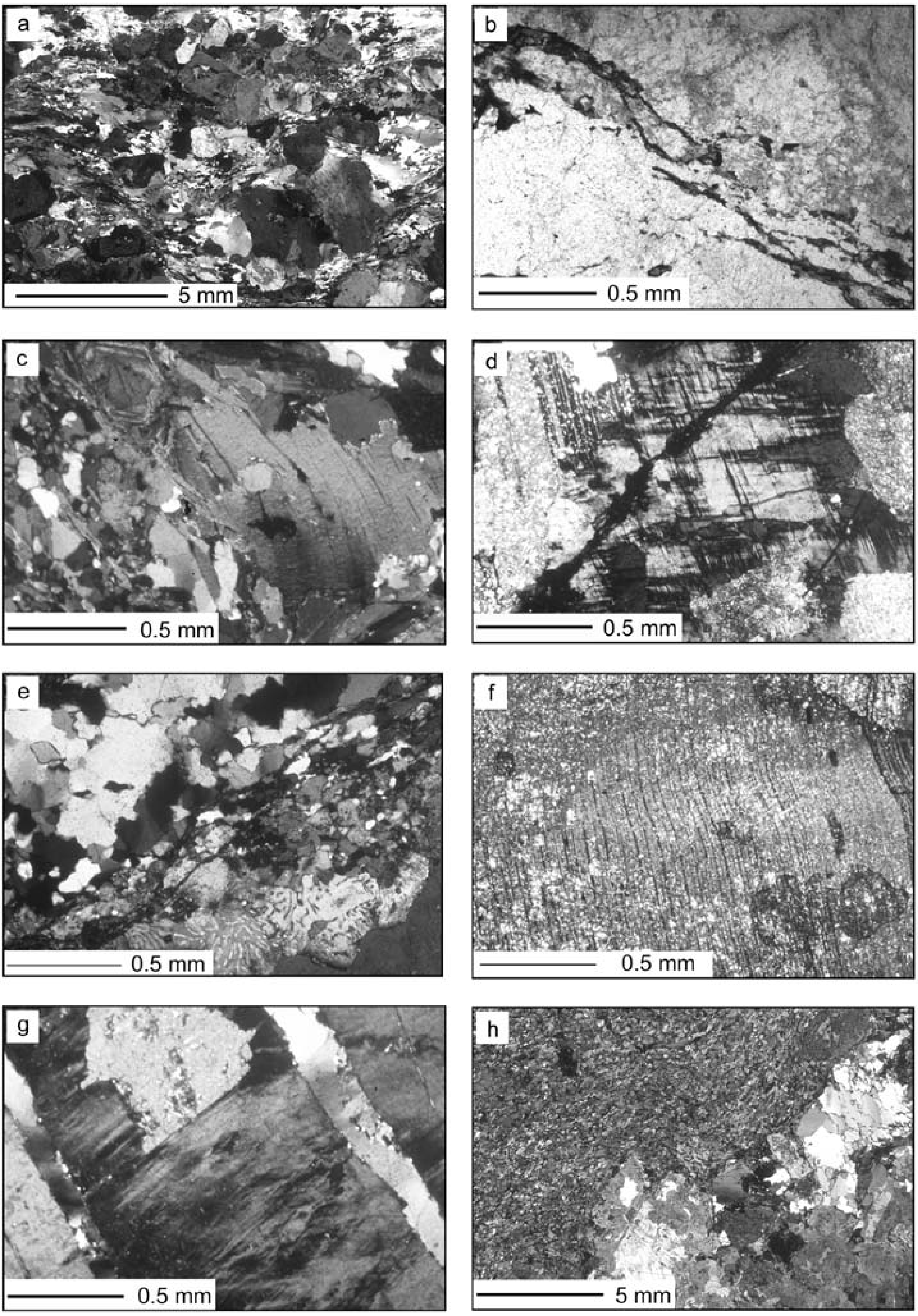

Figure 4. Thin-section views of microstructures in the Galway Granite: (a) well-developed quartz ribbons in Megacrystic Granite (XPL); (b) smeared-out biotite along the edges of a quartz ribbon, Megacrystic Granite, (PPL); (c) bending of biotite crystal, Megacrystic Granite, (XPL); (d) development of coarse microcline, Megacrystic Granite (XPL); (e) marginal development of myrmekite in K-feldspar, Megacrystic Granite, (XPL); (f) kinked twin planes in plagioclase, Megacrystic Granite, (XPL); (g) fractured K-feldspar infilled with quartz, Megacrystic Granite, (XPL); (h) contact between Megacrystic Granite and mafic microgranular enclave; note the pre-RCMP fabric in the enclave which parallels contact (XPL).

groundmass containing equant quartz aggregates. The first quartz SPO (shape preferred orientation) was observed within 2 km of the contact. Quartz aggregates are elongate on horizontal exposures (X:Z up to 4.5:1.0) forming ribbons that contain elongate sutured grains indicating that grain boundary migration processes were active. There is a similar progression in fabric intensity to that seen to the west of the Shannawona Fault Zone with the degree of preferred alignment of the K-feldspar megacrysts increasing to the north. Alignments of prismatic hornblende, biotite and titanite crystals are noted within 1 km of the contact. No ductile lattice bends or recrystallized margins are present in any of the minerals. Within 800 m of the contact, besides the strong alignment of the K-feldspar megacrysts, feldspars contain abundant microcracks normal to foliation. These are quartz-filled (Fig. 4g) in optical continuity with the aggregates outside the cracks, suggesting melt-present deformation (Bouchez *et al*. 1992). Alignments of titanite and hornblende are also noted, however, no systematic variation in the degree of preferred orientation has been observed. Plagioclase crystals are locally aligned but commonly contain ductile bends and recrystallized margins. Orthoclase is variably inverted to microcline and has abundant myrmekite on faces parallel with the foliation.

4.c. Mafic micrgranular enclaves east of Shannawona Fault Zone

Mafic microgranular enclaves (Fig. 3d) are abundant in the Marginal Deformation Zone east of the Shannawona Fault Zone. They contain strong alignments of prismatic titanite, hornblende, biotite and plagioclase (Fig. 4h). Orthoclase lacks marginal myrmekite, recrystallization or lattice bending. Quartz aggregates are weakly elongate with original grain boundaries only poorly sutured and, internally, the grains have weak undulose extinctions.

4.d. Ductile shear zones east of the Shannawona Fault Zone

These occur within 50 m of the contact east of the Shannawona Fault Zone. They are narrow, less than 2 cm wide, with sharp planar boundaries (Fig. 3e) and can be traced laterally for up to 5 m. They have, generally, a constant dip of about 30–40° S. Because of the geometry of the exposures, lineations are rarely observed, although a top-to-the-NE (reverse) shear sense has been deduced.

4.e. Interpretation of microstructures

The granite displays a similar fabric development pattern both east and west of the Shannawona Fault Zone. An early pre-RCMP fabric has been overprinted by post-RCMP deformation down to temperatures slightly below the solidus (~ 500 °C; Fig. 2) close to the contact. The presence of quartz-filled microcracks in feldspar crystals suggests that deformation continued during cooling and crystallization. Away from the contact, deformation ceased at a higher temperature, before the granite reached its RCMP. K-feldspar megacrysts show a progressively greater alignment concomitant with increasing quartz aggregate ellipticity as the northern contact is approached. Two explanations for this strain gradient are suggested: (a) the trend of increasing preferred orientation was developed in the pre-RCMP state and was subsequently overprinted by post-RCMP strains which also increased in intensity towards the contact, or (b) the alignment is a result of rotation and crystal growth in the post-RCMP state (analogous to porphyroblast growth). Deformed and undeformed samples alike are characterized by Carlsbad twins and zoning, suggesting that the feldspars are of igneous origin (Vernon, 1986) and that their alignment occurred in the pre-RCMP state. Fabric development in mafic micr247 granular enclaves shows them to have been deformed in the pre-RCMP state, with only minimal post-RCMP deformation. This contrasts with their host granite in which pre-RCMP deformation has been overprinted by post-RCMP fabrics, a feature noted in other granites (Fernandez & Gasquet, 1994) that indicates that deformation ceased at moderate temperature during the progressive cooling of both the enclaves and their host granite. The confinement of the ductile shear zones to a narrow section of the Marginal Deformation Zone suggests that they formed in response to local strain adjustments late in the crystallization history of the granite, rather than to regional deformation. Their formation was probably at relatively low temperature, because the shear zones clearly post-date the moderate temperature post-RCMP deformation in the granite. Their discrete nature further suggests that they formed at temperatures of less than 450 °C (Gapais, 1989).

4.f. Contact-parallel strain variations west of the Shannawona Fault Zone

Where mafic microgranular enclaves are uncommon in the well-exposed region west of the Shannawona Fault Zone, semi-quantification of the amount of post-RCMP strain was attempted using the shapes of deformed quartz aggregates from hand-specimens and thin-sections. A qualitative method of description for use on horizontal surfaces was adopted: weak quartz fabric (quartz aggregates are noticeably elliptical); moderate quartz fabric (intermediate between weak and strong); strong quartz fabric (quartz aggregates form elongate ribbons). It is believed that the collection of qualitative information from a large number of sites was preferable to the collection of detailed numerical data from fewer sites, given the area (8 km^2) over which the strain variations occur.

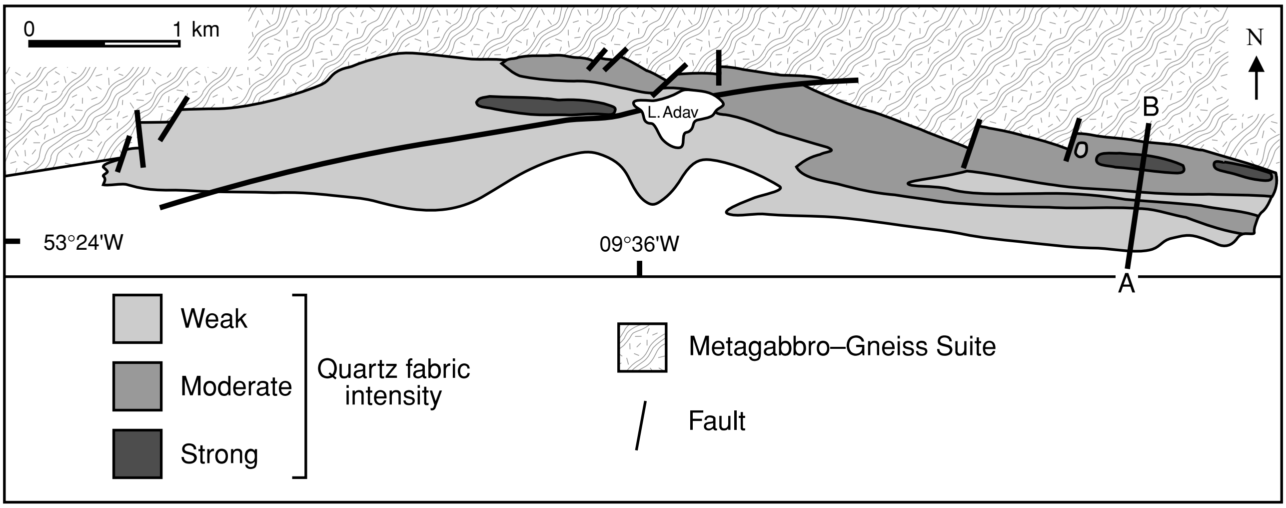

Figure 5. Contact-parallel strain variations in the intensity of the post-RCMP fabrics, defined by the ellipticity of quartz aggregates, in the Marginal Deformation Zone.

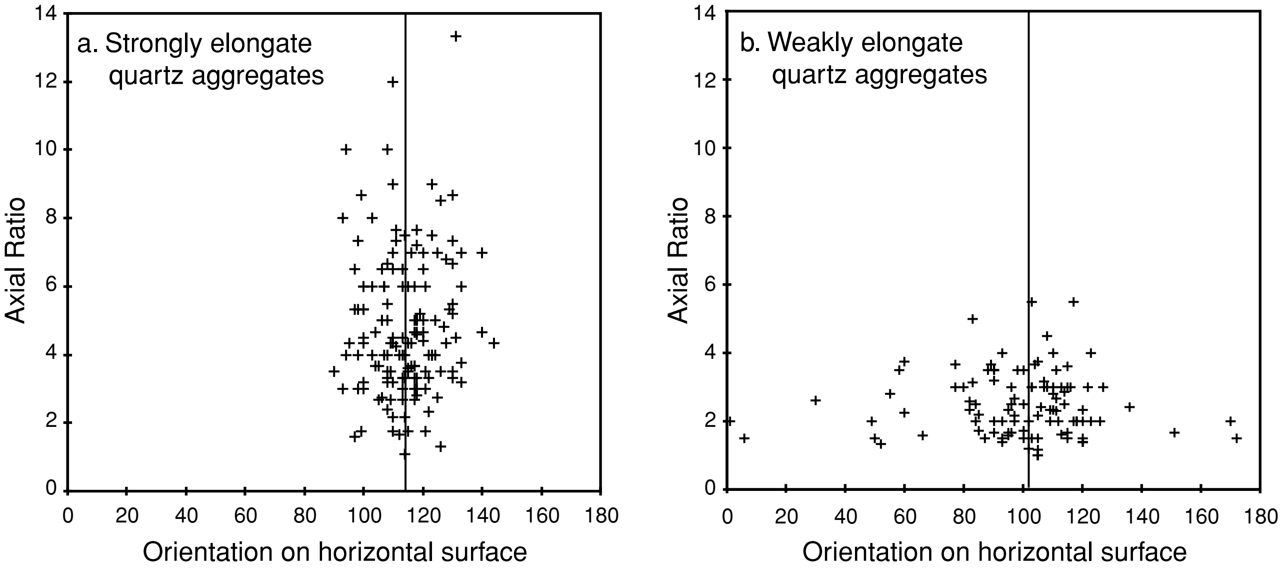

Figure 6. Axial ratio v. orientation of quartz aggregates from the Marginal Deformation Zone: (a) strongly elongate aggregates; (b) weakly elongate aggregates. Solid vertical line represents the foliation strike.

Within an overall pattern of increasing ellipticity of quartz aggregates both towards the granite–country rock contact and towards the Shannawona Fault Zone, there are contact-parallel zones of lower and higher strain (Fig. 5). Measurements of ellipticity and orientation of quartz aggregates at two representative localities were made to quantify their solid-state strain. In strong quartz fabrics (elongate ribbons), the long axes of the aggregates are oriented close to the foliation plane (± 30°) with the long axis of the most elongate ribbons (max. X:Z = 13.3:1.0, harmonic mean = 4.0) being closest to the foliation plane. In contrast, the orientation of the long axes of the quartz aggregates in weak quartz fabrics vary greatly, although the long axes of the most elongate aggregates (max. X:Z = 5.5:1.0, harmonic mean = 2.0) are aligned parallel with the foliation (Fig. 6). This pattern of increasing harmonic mean axial ratio along a traverse normal to the contact is illustrated in Figure 7a. On horizontal sections, the axial ratios increase towards the contact but, as is shown in Figure 7a, the increase does not occur at a constant rate. Axial ratios determined on vertical faces show a similar pattern (Fig. 7a). Assuming that the horizontal and vertical ellipses correspond to X/Z and Y/Z sections of the strain ellipse respectively, the values from Figure 7a were used to calculate the X/Y ratios with results plotted on Figure 7b demonstrating the oblate nature of the strain ellipse ($k \approx 0$). East of the Shannawona Fault Zone exposures are poor, but the zone of post-RCMP fabrics is about 2.5 times wider than west of the Shannawona Fault Zone. The pattern of increasing quartz ellipticity towards the contact is repeated, while

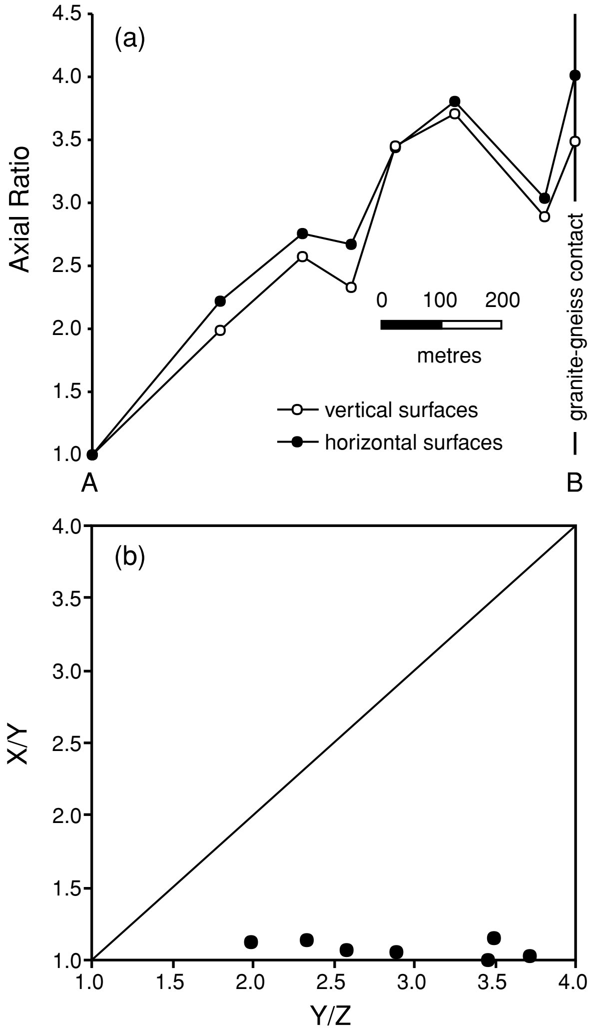

Figure 7. (a) Variation of the axial ratio of quartz aggregates on horizontal (filled circles) and vertical sections (open circles) along a contact-normal traverse (A–B in Fig. 5), from the point where post-RCMP fabrics are first noted, to the contact. Note that the values from horizontal sections are never less than the corresponding values from vertical sections (these values have been used to calculate the k-values plotted in Fig. 7b). (b) Flinn diagram demonstrating the oblate nature of the deformed quartz aggregates along traverse A–B in Figure 5.

the maximum mean quartz ellipticities of the quartz aggregates from either side of the Shannawona Fault Zone are approximately equal (∼ 4.0).

5. Fabrics in the granites of the southern Central Block

Field relationships for these granites (Megacrystic Granite, Magma Mingling–Mixing Zone Granodiorite, and the later Lough Lurgan Granite) have been described by El Desouky, Feely & Mohr (1996) and Crowley & Feely (1997). The Magma Mingling–Mixing Zone is a linear zone of vertical sheeting within the complex and may represent an important ascent site for magma batches. The field and microstructural aspects of the fabrics are used here to determine the relationship between deformation and crystallization.

5.a. Megacrystic Granite

Foliations are generally not apparent in the interior of the Megacrystic Granite. However, towards its contact with the Magma Mingling–Mixing Zone, alignments of perthitic microcline megacrysts occur with elongate quartz aggregates. Between Costelloe and Spiddal, these fabrics first appear inside the Megacrystic Granite about 1 km from the contact with the Magma Mingling–Mixing Zone. The elongate quartz aggregates (X:Y:Z = 2:2:1) are composed of individual equant crystals, with straight grain boundaries, although some have sutured margins indicating grain boundary migration. Individual grains contain only a few prismatic sub-grains and show weak undulose extinction. The K-feldspar megacrysts show a progressively greater degree of preferred alignment close to the contact with the Magma Mingling–Mixing Zone, and both titanite and hornblende crystals become aligned. Quartz aggregates become strongly elongate (X:Y:Z = 4:4:1). They are composed of a few original grains, sometimes made of equant sub-grain mosaics, but more commonly of fine aggregates of elongate recrystallized grains that have sutured boundaries and lack internal deformation features. The degree of quartz recrystallization is variable, and is most intense between feldspar crystals. Post-RCMP deformation features are also common in the feldspars and mafic minerals.

In the east, at Lippa (Fig. 1), where the faulted contact between the two granite types is exposed, the Megacrystic Granite contains strong preferred alignments of K-feldspar, hornblende, biotite and titanite. Quartz aggregates, however, are weakly elongate, composed of original grains that contain sporadic prismatic subgrains. No ductile bending or marginal recrystallization has been observed in any mineral.

5.b. Magma Mingling–Mixing Zone Granodiorite

At the contact with the Megacrystic Granite, the Magma Mingling–Mixing Zone Granodiorite exhibits strong alignments of K-feldspar megacrysts, hornblende and titanite. However, plagioclase laths are poorly aligned and biotite is randomly oriented. Quartz aggregates are weakly oblate (X:Y:Z = 2.0:2.0:1.0), composed of elongate grains with sutured boundaries and occasional recrystallization. K-feldspars have myrmekite on faces parallel with the foliation although much less commonly so than in the adjacent Megacrystic Granite. Mineral clots composed of fine-grained (0.2–0.4 mm) interlocking aggregates of hornblende and magnetite (± chloritized biotite and titanite) are a common feature in the Magma Mingling–Mixing Zone Granodiorite. In undeformed rocks, these clots are roughly spherical in shape whereas in deformed

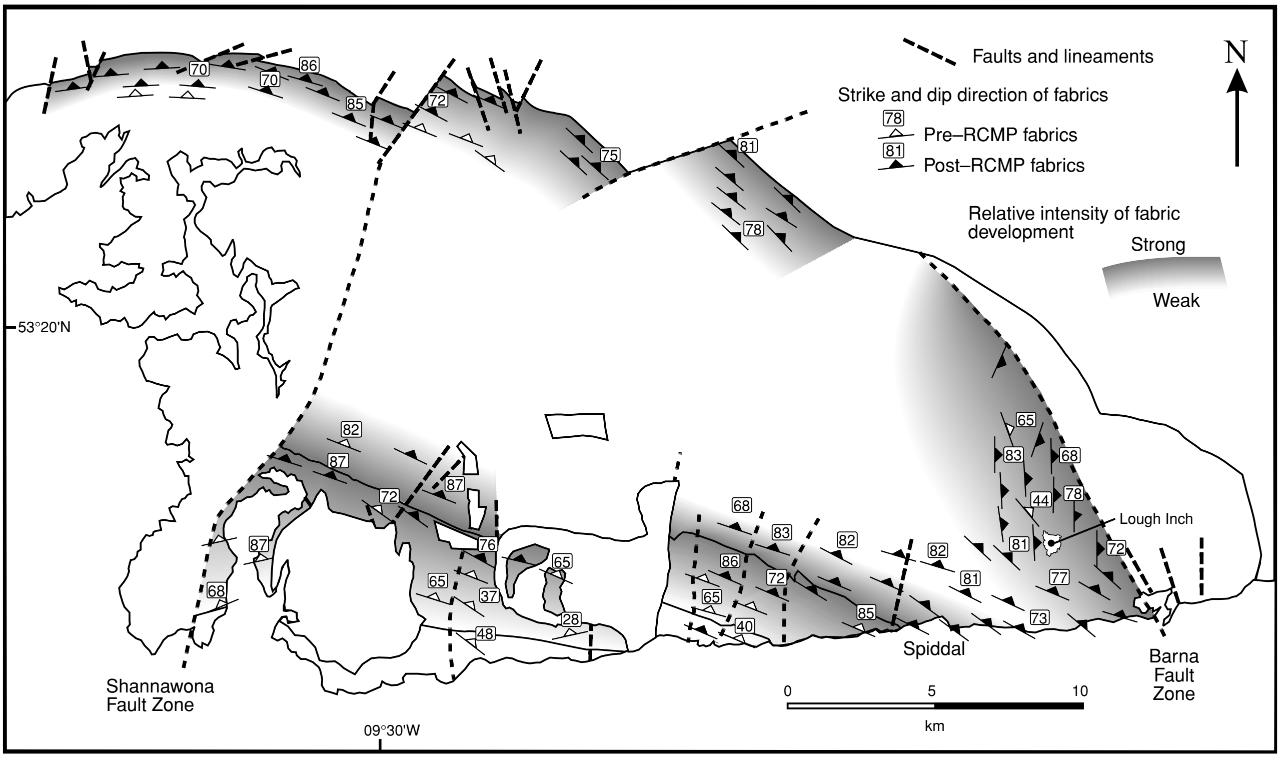

Figure 8. Planar fabric map of part of the Galway Granite. The intensity of the shading indicates the overall fabric intensity.

samples they are commonly oblate. The hornblende lacks ductile bends and recrystallized margins. The southern margin of the Magma Mingling–Mixing Zone Granodiorite in the Costelloe area, near its contact with the Lough Lurgan Granite, displays only weak alignments of minerals and mafic microgranular enclaves.

5.c. Lough Lurgan Granite

The Lough Lurgan Granite in the Costelloe area has only occasional alignments of biotite, titanite and hornblende close to the Magma Mingling–Mixing Zone Granodiorite (Fig. 1). In contrast, in the Spiddal area it contains stronger alignments of hornblende, titanite and biotite within 400 m of the Magma Mingling–Mixing Zone contact, although they are less well developed than in the adjacent Magma Mingling–Mixing Zone Granodiorite. Quartz aggregates are not elongate and no ductile microstructures have been recorded.

5.d. Mafic microgranular enclaves and mafic bands

Mafic microgranular enclaves and microdiorite sheets are abundant in the Magma Mingling–Mixing Zone Granodiorite. Their compositions range from medium-grained quartz-diorite to meladiorite (El Desouky, Feely & Mohr, 1996), indicating complex mixing processes during ascent.

Spherical or irregularly shaped enclaves do not contain mineral alignments. In contrast, ellipsoidal enclaves exhibit mineral alignments (hornblende, titanite, biotite, plagioclase, clots of hornblende) whose intensity is related to the degree of enclave ellipticity. The degree of preferred alignment of the minerals in elongate enclaves is always markedly more intense than that of the host granite. Within the enclaves, quartz aggregates are always sub-rounded and lack internal ductile deformation features.

5.e. Interpretation of microstructures

The Megacrystic Granite shows increasing pre- and post-RCMP strain towards its contact with the Magma Mingling–Mixing Zone. Post-RCMP deformation ceased at temperatures close to the solidus away from the contact, but continued to ~500 °C at the contact. The presence of equant mosaics of square sub-grains in relict grains of quartz suggests that deformation was continuous from the pre- to the post-RCMP states. Deformation of the granite at Lippa appears to have been only under pre-RCMP conditions, ceasing at a near-solidus temperature.

5.f. Strain variations in the Costelloe and Spiddal sectors

The mineral foliations in granites of the Central Block generally dip to the north. In the Costelloe and Spiddal areas, both the pre- and post-RCMP fabrics in the Megacrystic Granite are close to vertical (Fig. 9a,b) but, in the Magma Mingling–Mixing Zone (Fig. 9c,d) and Lough Lurgan Granite (Fig. 9e,f), the foliation has a broad range of dips decreasing to the south (Fig. 8). The fabrics defined by the mafic microgranular

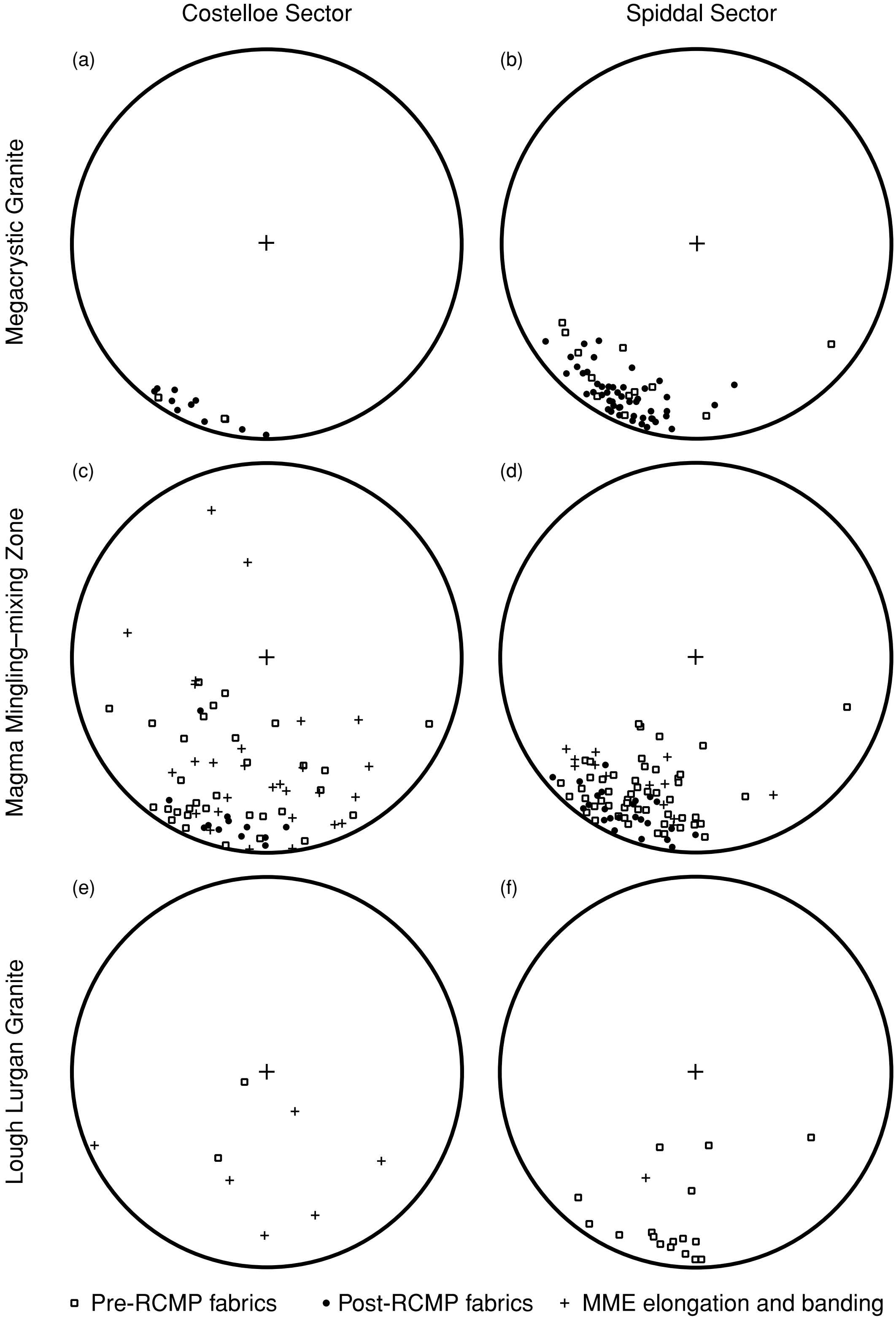

Figure 9. Lower-hemisphere, equal-area plots of poles to pre-RCMP fabrics (open square), post-RCMP fabrics (filled circle), and the fabrics defined by mafic microgranular enclaves (MME) and microdioritic bands (crosses). Plots are from the Costelloe Sector (a, c, e) and the Spiddal Sector (b, d, f). Granites are the Megacrystic Granite (a, b), Magma Mingling–Mixing Zone (c, d), and the Lough Lurgan Granite (e, f).

enclaves and mafic bands usually parallel those in the host granites although, in several places, the bands dip steeply to the south (Fig. 9c). In several localities mafic microgranular enclaves provide the only obvious indication of fabric development. The pre-RCMP fabrics in the granites have no apparent linear element, suggesting oblate strain. The shape of the post-RCMP ellipse may be determined

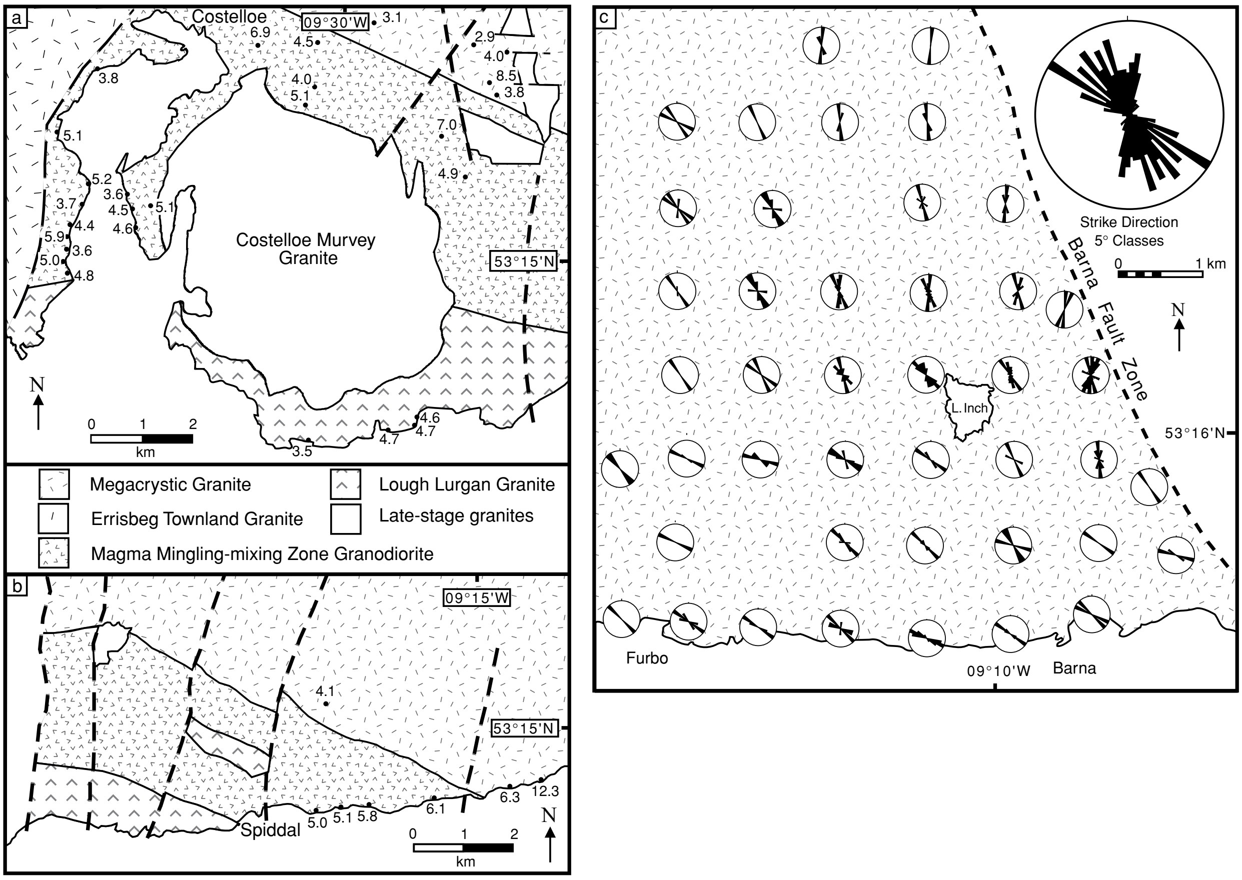

Figure 10. Maps of the (a) Costelloe and (b) Spiddal sectors of the southern Central Block, showing the axial ratios of enclaves; (c) map showing the strike of foliations in the eastern Central Block. Each rose diagram records measurements within a 1 km^2 area (divisions based on the National Grid). The large rose diagram combines all the data from the area.

from the ellipticity of quartz aggregates. On horizontal surfaces ellipticity increases from north to south towards the Megacrystic Granite/Magma Mingling–Mixing Zone contact where the maximum ellipticities ($X/Z \approx 4.0$) occur. On 3D sections, the aggregates are oblate ellipsoids. The microstructural features of the granite indicate that coaxial oblate strain was continuous from the pre- to the post-RCMP states. The abundance of mafic microgranular enclaves in the granites facilitates a detailed study of strain variation across the area and provides insights into the early deformation history of the granites. Measurements (on horizontal sections due to the lack of suitable 3D exposures) of the axial ratios and orientations of 10–28 enclaves were made at 39 localities between Costelloe and Spiddal, and the harmonic mean axial ratio calculated (Fig. 10a). In the western part of the area, axial ratios range from 2.9 to 8.5, the highest values in the Megacrystic Granite some 400 m from the Magma Mingling–Mixing Zone. In contrast, the axial ratios of the mafic microgranular enclaves in the Spiddal area increase eastwards from 5.0 in the centre of the Magma Mingling–Mixing Zone, to 12.3 in the Megacrystic Granite some 1300 m east of the Magma Mingling–Mixing Zone contact (Fig. 10b). At each locality the enclaves are aligned roughly parallel with the foliation in the host granite (Fig. 11), suggesting that their alignment results from elongation and rotation during oblate strain rather than alignment of already elongate enclaves.

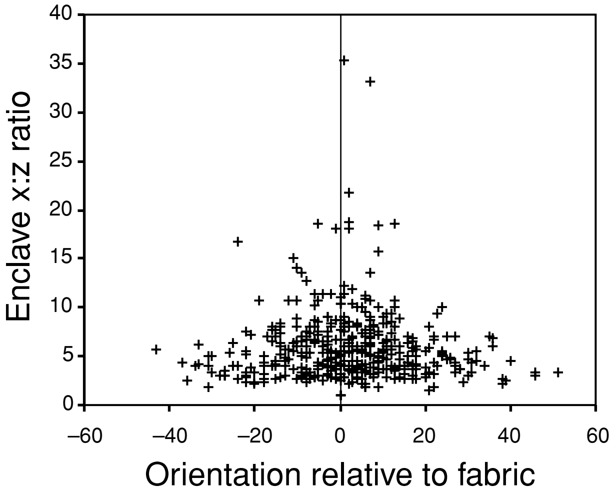

Figure 11. Axial ratio v. orientation of mafic microgranular enclaves from horizontal surfaces at 39 localities in the southern Central Block. Orientations are relative to the foliation (solid line) at each locality.

6. The granite of the eastern Central Block

We describe here the spatial variations in intensity of these fabrics in west to east traverses (a) in the south of the area, and (b) to the north of Lough Inch (Fig. 10c).

6.a. Microstructures

For approximately 2.5 km east of Furbo, along the coast, the Megacrystic Granite has only weak alignment of hornblende and biotite in a groundmass of randomly oriented feldspars and equant clots of quartz. Further east, the alignments of the mafic minerals become better-developed and K-feldspars are occasionally aligned. At Knocknagreana, quartz aggregates (X:Y:Z = 2:2:1) are elongate and composed of grains that have occasional sutured boundaries and weak undulose extinction. Towards Barna, the mineral alignments become more pronounced. The K-feldspars (orthoclase perthites) have intensely recrystallized margins; they also exhibit ductile bends and have abundant myrmekite on faces parallel with the foliation. Quartz-filled microcracks are orientated normal to the foliation. The quartz aggregates are more oblate (X:Y:Z = 3:3:1) and are composed of elongate sutured grains that contain prismatic sub-grains aligned parallel with the foliation.

The most intense NW–SE-striking fabrics occur to the northeast of Barna where the Megacrystic Granite contains strong alignments of titanite, biotite, hornblende and K-feldspar. The K-feldspars are predominantly microcline perthites and have extensive myrmekite and recrystallization at their margins. Quartz-filled foliation-normal microcracks are occasionally present and, in several samples, microcline megacrysts contain randomly oriented networks of narrow (< 0.01 mm) microcracks, suggesting cataclastic deformation at T < 500 °C (Tribe & D'Lemos, 1996). Quartz clots are highly oblate (X:Y:Z = 4:4:1) and contain mosaics of fine (< 0.1 mm) equant recrystallized grains.

The deformation history of the Megacrystic Granite in the north of the area is similar to that described above. In the west, fabrics are very weak or absent from the Megacrystic Granite but, eastwards, titanite, hornblende and biotite clots are weakly aligned. Microcline megacrysts are occasionally aligned and have only sparse myrmekite and recrystallized margins. Quartz aggregates are composed of coarse grains that have weakly sutured boundaries (indicating grain boundary migration) and contain a few prismatic subgrains and weak undulose extinction. North of Lough Inch, the Megacrystic Granite contains stronger mineral alignments. Recrystallized margins are common on aligned microclines as is myrmekite on faces parallel with the foliation. Quartz aggregates are more flattened (X:Y:Z = 3:3:1) with constituent grains having weakly sutured boundaries and many internal prismatic sub-grains. East of Lough Inch, the Megacrystic Granite displays more intense mineral alignments. Microcline megacrysts contain foliation-normal quartz-filled microcracks, recrystallized rims and abundant myrmekite on faces parallel with the foliation. Quartz aggregates are highly oblate (X:Y:Z = 4:4:1) and contain abundant elongate sutured grains that have fine recrystallized rims, kink bands and prismatic sub-grains. Of note in the area to the north and northeast of Lough Inch is the non-coaxial overprinting of the early magmatic fabric by a secondary post-RCMP fabric, where aligned K-feldspar megacrysts are augened by well-developed quartz ribbons striking in a more northerly direction.

6.b. Interpretation of microstructures

The intensity of both the pre- and post-RCMP deformation increases as the Barna Fault Zone is approached. Post-RCMP deformation continued during crystallization and cooling and ceased at progressively lower temperatures to the east. As seen elsewhere, deformation appears to have been continuous from the pre- to the post-RCMP states, but the non-coaxial overprinting of the pre-RCMP fabric by the post-RCMP fabric has not been recognized elsewhere in the batholith. N. T. Graham (unpub. Ph.D. thesis, Univ. Oxford, 1997) suggested that the post-RCMP fabrics might have formed as a response to the intrusion of a now downthrown intrusion to the east of the Barna Fault Zone. We believe that the orientation of the fabrics (they dip to the east) does not support this theory but rather that they are related to syn-emplacement movement on the fault zone. The juxtaposition of Megacrystic and Errisbeg Townland granites across both the Barna and Shannawona fault zones suggests that displacement on the fault zones is similar. Syn-emplacement movement on the Shannawona Fault Zone is believed to have been ~ 3 km (B. H. Callaghan, unpub. Ph.D. thesis, NUI, Galway, 1999).

6.c. Strain variations in the eastern Central Block

Along the coast between Furbo and Barna, mafic microgranular enclaves are present in sufficient quantities for accurate strain determination. Enclaves are aligned parallel with the foliation and have a discoidal shape (K = 0) indicating that the early pre-RCMP deformation path affecting the granite–enclave system was oblate. The ellipticity of quartz aggregates (measured on horizontal surfaces) increases to the ENE and, on 3D exposures, the aggregates are always discoidal (K = 0) with no obvious linear fabric element. Therefore, it appears that the deformation affecting these rocks from early crystallization through to moderate post-RCMP temperatures (~ 500 °C) was entirely oblate.

7. Summary of microstructures and interpretations

Examination of the microstructures in the Galway Batholith shows that similar patterns of fabric development occur on either side of the Shannawona Fault, although the Marginal Deformation Zone is ∼2.5 km wide on the east of the Shannawona Fault in contrast to ∼1 km wide to the west. Oblate pre-RCMP fabrics occur up to 2.5 km from the granite's northern contact, and are overprinted by lower temperature oblate post-RCMP fabrics. Both fabrics become more intense northwards, and the temperature at which deformation ceased decreased towards the contact. Oblate pre- and post-RCMP fabrics in the Megacrystic Granite of the southern Central Block increase in intensity towards the contact with the Magma Mingling–Mixing Zone, where deformation ceased at ∼500 °C. Pre-RCMP deformation in the Magma Mingling–Mixing Zone increases in intensity northwards towards the contact with the Megacrystic Granite, where it is overprinted by weak post-RCMP deformation. The Lough Lurgan Granite contains a weak pre-RCMP fabric near its northern contact but has no apparent fabric in the south. Both pre- and post-RCMP fabrics increase in intensity towards the Barna Fault Zone, and occasional strongly developed N–S oriented post-RCMP fabrics in the area contrast with the general WNW–ESE fabric trend in the Central Block. It is a characteristic feature of all mafic microgranular enclaves in this study that deformation occurred in the pre-RCMP state only and ceased at temperatures above the RCMP, a feature noted in other studies (Fernandez & Gasquet, 1994).

8. Discussion and conclusions

The studies presented above show that fabrics both at the northern contact of the batholith and inside the batholith formed during oblate coaxial deformation. Along the northern margin there is a westward decrease in the width of the Marginal Deformation Zone, and also in the ellipticity of quartz aggregates within it. However, contact-parallel heterogeneities exist within the general pattern of increasing deformation towards the contact (Fig. 5). The effect of the intrusion of the granite on its host rock (the Metagabbro–Gneiss Suite) seems to have been minimal: no granite-emplacement-related ductile structures in the gneiss have been recorded, and the contact and fabrics in the granite are oblique to the S3 fabric in the gneiss.

Oblate (K = 0) strains are an uncommon result of regional deformation resulting from relative plate motion across plate boundary zones. Few kinematic regimes allow such strains, with the exception of transform/transform/transform triple junctions and transient 'bouncing points' for deformation paths where the transpressive convergence angle is at less than 20° to the deformation zone boundary (Dewey, 2002). The oblate strains in the Galway Granite vary substantially and cannot, therefore, be the result of regional transpression. It is thought that lateral spreading of successive batches of magma at the emplacement level caused oblate strain in earlier batches leading to deformation which can be interpreted as a ballooning fabric (Burov, Jaupart & Guillou-Frottier, 2003). It is important to note that ballooning or inflating plutons can have a tabular geometry, rather than the 'balloon' shape that is implied by the term (Saint Blanquat *et al*. 2001).

The westward narrowing of the Marginal Deformation Zone, and a corresponding decrease in the ellipticity of quartz aggregates within the zone, are likely to be related to the decrease in the depth of exposure to the west (Leake & Ahmed-Said, 1994). Block stoping at the western end of the batholith (Leake, 1974) is consistent with the shallower level of exposure in this area. Other studies (e.g. Paterson & Vernon, 1995) have also suggested that at shallow levels, brittle rather than ductile emplacement processes are important. The Galway Batholith would therefore appear to span the brittle–ductile transition, an observation consistent with hornblende geobarometry studies which indicate the depth of crystallization at the current exposure level to vary between 8 and 18 km (Leake & Ahmed Said, 1994; B. H. Callaghan, unpub. Ph.D. thesis, National Univ. Ireland, Galway, 1999), with the deeper levels now exposed in the Central Block.

The pattern of high and low strain zones illustrated by Figure 5 is one more typically associated with non-coaxial deformation. A possible explanation for this, and for strain variations at outcrop scale, may be that deformation acted on a crystallizing granite with spatial viscosity heterogeneities. Small-scale (decimetric to metric) variations in properties such as temperature, crystal content or water content (especially in the sub-solidus state) would have greatly affected the mechanical behaviour of the granite. The apparent compatibility problems, caused by the large strain variations across zone boundaries, are solved if successive magma batches acquired their strain independently and sequentially.

Many workers (e.g. Leake, 1990; Jacques & Reavy, 1994; Ryan *et al*. 1995) have stressed the fundamental control of crustal structures on magma ascent and emplacement. El Desouky, Feely & Mohr (1996) proposed emplacement of the Galway Batholith between a dextral shear couple with a pull-apart component formed by the NNW-trending Maam and Clifden fault zones (Fig. 1). In their model, the dip-slip displacement on the Shannawona Fault is colinear with the long axis of the strain ellipsoid and the Magma Mingling-Mixing Zone marks a line of crustal shortening. The stoping at the western end of the batholith (Leake, 1974) is also consistent with extension of the crust in the direction of elongation of the batholith. Crowley (Q. G. Crowley, unpub. Ph.D. thesis, National Univ. Ireland, Galway, 1997) envisaged ascent of partial melts along the Skerd Rocks

Fault followed by emplacement by ballooning within the strain regime envisaged by El Desouky, Feely & Mohr (1996).

Given the lack of ductile deformation in the host rocks, and the presence of intrusion-related rather than tectonic fabrics in the Galway Granite, it is believed that emplacement of the Galway Granite took place in a transtensional setting, either within the pull-apart envisaged by El Desouky, Feely & Mohr (1996), or in the regional sinistral transtensional regime identified by Dewey & Strachan (2003) during the period of intrusion of the Galway Granite (~410–380 Ma; Feely *et al.* 2003). Jacques & Reavy (1994) concluded that plutons of the Argyll suite in Scotland intruded in tensional voids at the intersections of major crustal lineaments. It is proposed that interaction between the E–W Skerd Rocks Fault and the Clifden and Maam fault zones was the controlling factor in the siting and emplacement of the Galway Granite, and the fabrics in the granite are evidence for continuous, intrusion-related, co-axial deformation during cooling and crystallization.

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