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Contrasting magma emplacement mechanisms within the Rogart igneous complex, NW Scotland, record the switch from regional contraction to strike-slip during the Caledonian orogeny

H. KOCKS*, R. A. STRACHAN‡†, J. A. EVANS§ & M. FOWLER‡

*Kocks Consult GmbH, Stegemannstr.32–38, Koblenz, Germany
‡School of Earth & Environmental Sciences, University of Portsmouth, Burnaby Rd, Portsmouth, PO1 3QL, UK
§NERC Isotope Geosciences Laboratory, Kingsley Dunham Centre, Keyworth, Nottingham, NG12 5GG, UK

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Abstract – The Rogart igneous complex is unique within the northern Scottish Caledonides because it comprises an apparent continuum of magma types that records a progressive change in emplacement mechanisms related to large-scale tectonic controls. Syn-D_2 leucogranites and late-D_2 quartz monzodiorites were emplaced during crustal thickening and focused within the broad zone of ductile deformation associated with the Naver Thrust. In contrast, emplacement of the post-D_2 composite central pluton was controlled by development of a steeply dipping dextral shear zone along the Loch Shin Line, interpreted as an anti-Riedel shear within the Great Glen Fault system. The mantle-derived nature of the late-to-post-D_2 melts implies that the Naver Thrust and the Loch Shin Line were both crustal-scale structures along which magmas were channelled during deformation. A U–Pb zircon age of 425 ± 1.5 Ma for the outer component of the central pluton provides an upper limit on regional deformation and metamorphism within host Moine rocks. These findings are consistent with the view that a fundamental change in tectonic regime occurred in the Scottish Caledonides at *c.* 425 Ma, corresponding to the switch from regional thrusting that resulted from the collision of Baltica and Laurentia, to the development of the orogen-parallel Great Glen Fault system.

Keywords: granite, geochronology, tectonics, Caledonides.

1. Introduction

Orogenic belts typically include a range of contractional, strike-slip and extensional shear zones and faults that evolve during plate convergence (e.g. Dewey *et al*. 1986). Tectonic models for the mid-crustal parts of orogens are highly dependent upon the dating of deformation events that can be linked kinematically to displacements along regional-scale shear zones and faults. The structural analysis of igneous intrusions that were emplaced at a known time relative to a particular set of regionally developed fabrics and/or shear zones has proved particularly effective in constraining the timing of tectonic events in various orogens worldwide (e.g. Paterson & Tobisch, 1988; Ingram & Hutton, 1994; Jacques & Reavy, 1994; De Saint Blanquat & Tikoff, 1997; Schofield & D'Lemos, 1998; Strachan, Martin & Friderichsen, 2001; Grocott & Taylor, 2002; Rosenberg, 2004).

Integrated structural and geochronological studies of syn-kinematic igneous complexes are increasing steadily the number of reliable constraints on the timing of events within the Early Palaeozoic Caledonian orogen in Scotland (Fig. 1). The Caledonian orogeny resulted from the closure of the Iapetus Ocean: an Ordovician arc–continent collision known as the Grampian event (Lambert & McKerrow, 1976; Soper, Ryan & Dewey, 1999; Oliver *et al*. 2000) was followed during the Silurian by the oblique collision of three continental blocks, Avalonia, Laurentia and Baltica (Soper & Hutton, 1984; Pickering, Bassett & Siveter, 1988; Soper *et al*. 1992). Baltica collided with the segment of the Laurentian margin that incorporated northern Scotland, to result in the Scandian orogenic event (Coward, 1990; Dallmeyer *et al*. 2001; Dewey & Strachan, 2003; Kinny *et al.* 2003). Scandian crustal thickening was followed by displacements along orogen-parallel strike-slip faults, including the Great Glen Fault (Fig. 1). Slab break-off during the final phase of the orogeny resulted in the generation of a variety of granites and syenites (e.g. Atherton & Ghani, 2002; Fowler *et al.* 2008; Oliver, Wilde & Wan, 2008; Neilson, Kokelaar & Crowley, 2009). Early members of the suite were emplaced along Scandian thrusts (Kinny *et al*. 2003; Kocks, Strachan & Evans, 2006; Goodenough *et al.* 2011), whereas later members appear to have been emplaced along steeply dipping strike-slip or normal faults (Hutton, 1988*a,b*; Hutton & McErlean, 1991; Rogers & Dunning, 1991; Jacques & Reavy, 1994; Stewart *et al.* 2001; Hughes *et al.* 2013).

In common with most other orogens, studies of the emplacement of individual igneous complexes within the Caledonides have largely focused on *one* main tectonic control, which might be thrusting, strike-slip or extension. In this paper we summarize the structural

†Author for correspondence: rob.strachan@port.ac.uk

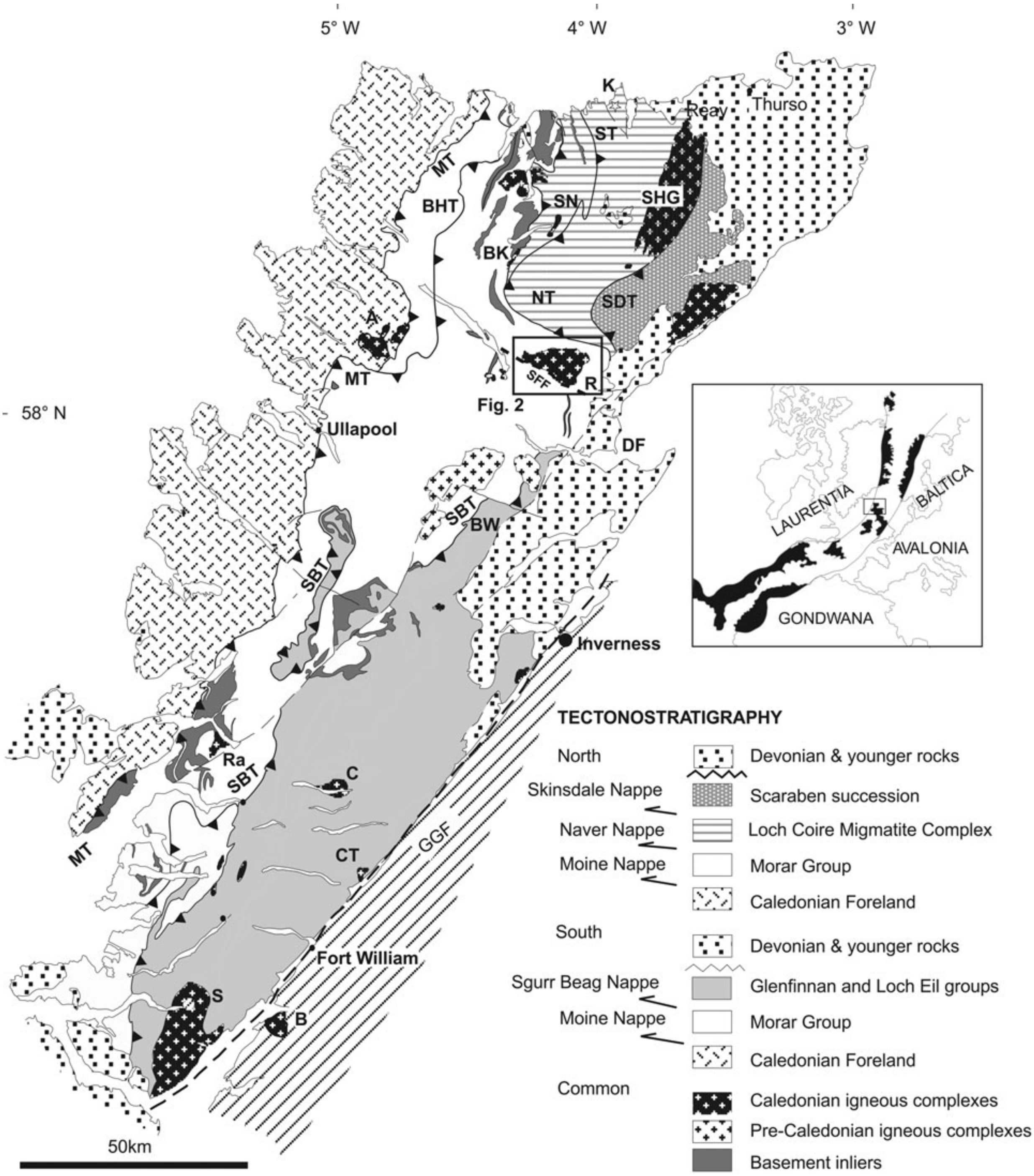

Figure 1. Regional geology map of the Scottish Highlands north of the Great Glen Fault. Inset map shows the relative positions of Laurentia, Baltica, Avalonia and Gondwana following the closure of the Iapetus Ocean (Caledonide–Appalachian belt in black). Abbreviations: A – Assynt; B – Ballachulish Granite; BHT – Ben Hope Thrust; BK – Ben Klibreck; BW – Ben Wyvis; C – Cluanie Granite; CT – Clunes Tonalite; DF – Dornoch Firth; GGF – Great Glen Fault; K – Kirtomy; MT – Moine Thrust; NT – Naver Thrust; R – Rogart igneous complex; Ra – Ratagain intrusion; S – Strontian Granite; SBT – Sgurr Beag Thrust; SDT – Skinsdale Thrust; SFF – Strath Fleet Fault; SHG – Strath Halladale Granite; SN – Strathnaver Granite; ST – Swordly Thrust.

setting, emplacement and U–Pb geochronology of the Rogart igneous complex, a member of the Newer Granite suite in NW Scotland (Fig. 1). This is of particular significance because, uniquely, its emplacement appears to have overlapped the switch from regional contraction to strike-slip within this sector of the Caledonides.

2. Geological setting

In northern Scotland, the Caledonian orogen is largely underlain by metasedimentary rocks of the lower Neoproterozoic Moine Supergroup (Holdsworth, Strachan & Harris, 1994; Strachan *et al*. 2010; Fig. 1). The western margin of the orogen is defined by the Moine Thrust, which is overlain by Moine rocks assigned to the Morar Group. In Sutherland, the Morar Group lies structurally beneath the Naver Thrust that carries the Loch Coire Migmatite Complex, and further east, the Skinsdale Thrust carries the unmigmatized Moine rocks of the Scaraben Succession (Fig. 1). U–Pb geochronology shows that the Loch Coire Migmatite Complex formed during the Ordovician Grampian orogenic event at ∼ 470–460 Ma (Kinny *et al.* 1999). This was followed by widespread Silurian (Scandian) ductile deformation and thrusting that propagated towards the foreland and culminated in development of the Moine Thrust Zone (Holdsworth, Strachan & Alsop, 2001; Holdsworth, Alsop & Strachan, 2007; Johnson & Strachan, 2006; Alsop *et al.* 2010; Leslie *et al*. 2010). U–Pb dating of syn-kinematic intrusions constrains thrusting to have occurred at ∼ 435–425 Ma (Kinny *et al.* 2003; Kocks, Strachan & Evans, 2006; Goodenough *et al.* 2011). A broad arcuate swing defined by the regional foliation and ductile thrusts has been attributed to the development of a major thrust culmination, both within the Moine rocks and the underlying Moine Thrust Zone of the Assynt area (Fig. 1; Elliott & Johnson, 1980; Butler & Coward, 1984; Leslie *et al*. 2010).

The Rogart igneous complex is mainly hosted by Moine metasediments of the Morar Group (Fig. 1; Soper, 1963; H. Kocks, unpub. Ph.D. thesis, Oxford Brookes Univ., 2002). Regionally, these are typically unmigmatized psammites with subordinate pelitic horizons; sedimentary structures such as cross-bedding are present in areas of low tectonic strain (e.g. Krabbendam, Prave & Cheer, 2008; Bonsor *et al*. 2012). Occasional concordant amphibolite sheets are interpreted as deformed and metamorphosed mafic intrusions. The dominant structures are tight-to-isoclinal D_2 folds that carry an axial-planar mica fabric (S_2) and deform an earlier bedding-parallel schistosity (S_1). The main foliation is therefore a composite $S_0/S_1/S_2$ fabric; it carries an ESE-plunging L_2 mineral and extension lineation that is interpreted to lie parallel to the direction of tectonic transport during Caledonian (Scandian) thrusting. D_2 axes commonly trend parallel to L_2 as a result of intense rotation during ductile thrusting. Regional metamorphic grade during D_2 was within the low- to mid-amphibolite facies (Strachan & Holdsworth, 1988).

The D_2 Naver Thrust crops out a few kilometres to the northeast of the Rogart igneous complex (Fig. 1). The Ordovician Loch Coire Migmatite Complex in the hangingwall is strongly reworked and blastomylonitic in the immediate vicinity of the Naver Thrust. At structurally higher levels, where the level of superimposed Scandian strain is less, the migmatites are dominated by regularly layered, stromatic metasedimentary gneisses. The degree of partial melting is variable and leucosomes may increase and coalesce to form bodies of schlieric diatexite that intrude and cross-cut migmatitic layering. Semi-pelitic migmatites comprise biotite + quartz + plagioclase + K-feldspar ± muscovite ± garnet. Melanosomes comprise coarse-grained brown biotite, whereas leucosomes show abundant igneous plagioclase, K-feldspar, recrystallized quartz and rare garnet. The mineral assemblage in the leucosomes is interpreted to have resulted from biotite dehydration melting at ∼ 8–10 kbar (H. Kocks, unpub. Ph.D. thesis, Oxford Brookes Univ., 2002).

The SE part of the Rogart igneous complex is thought to be overlain unconformably by Old Red Sandstone (Devonian) sedimentary rocks, although the contact is not exposed (Fig. 2; Read *et al.* 1925; Read, Phemister & Ross, 1926). Both are limited to the south by the Strath Fleet Fault (Fig. 2), which is likely to have a complex history of movement. The fault lies along and parallel to a NW-trending lineament termed the Loch Shin Line, which is defined by a concentration of late Caledonian minor intrusions with mantle parentage (Watson, 1984). The Strath Fleet Fault has been interpreted as an anti-Riedel shear to the late Caledonian sinistral Great Glen Fault system, and early dextral displacement inferred (Johnson & Frost, 1977; Watson, 1984). This was followed by a post-Devonian component of normal displacement with downthrow to the northeast (Fig. 2).

3. Geology of the Rogart igneous complex and related injection phenomena

The Rogart igneous complex *sensu stricto* is a zoned central pluton formed of an outermost quartz monzodiorite, a granodiorite and an innermost granite (Read *et al.* 1925; Read, Phemister & Ross, 1926; Soper, 1963; H. Kocks, unpub. Ph.D. thesis, Oxford Brookes Univ. 2002). However, the term 'Rogart igneous complex' is used in a wider sense here to include a separate body of quartz monzodiorite, the Creag Mhor sheet, and a range of slightly older leucogranites and associated injection migmatites developed within the country rocks to the north and the east (Fig. 2). Evidence presented below suggests that the leucogranites resulted from partial melting of Moine rocks at a deeper structural level, possibly as a consequence of the injection of mafic magma associated with the main pluton. Hence these are an integral part of the magmatic record in the Rogart area.

3.a. Leucogranites and injection migmatites

The Morar Group rocks to the north and east of the central pluton are anomalous because they are typically coarse grained and gneissic, and locally contain discrete melanosomes and leucosomes, thus conforming to commonly accepted definitions of metatexite (e.g. Brown, 1973). They also contain variable proportions of intrusive leucogranite (Fig. 2). There is every gradation from occasional centimetre–metre-scale sheets to areas of intensely sheeted 'injection migmatites', which in turn pass transitionally into coherent bodies of leucogranite up to 1–2 km^2 in extent that contain relict schlieren and rafts of psammite and semi-pelite. Notable areas of injection migmatite and

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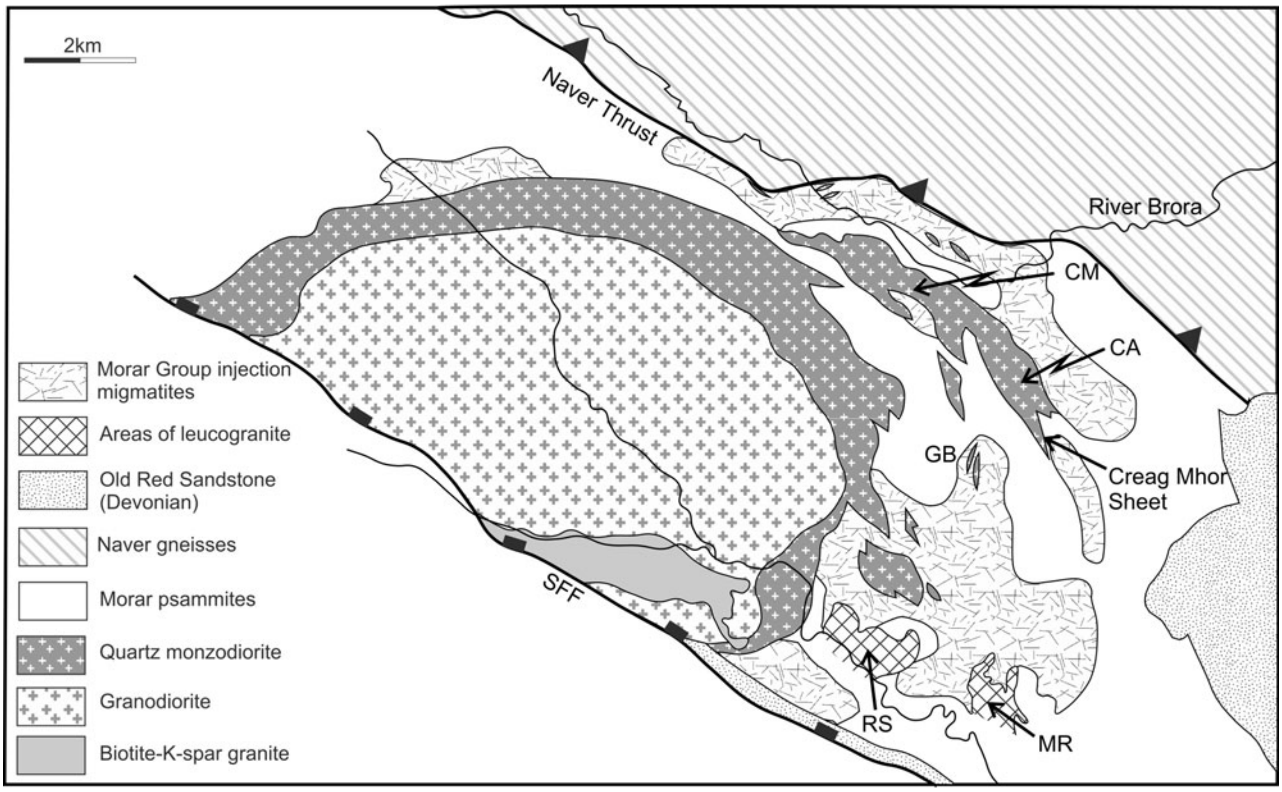

Figure 2. Simplified geological map of the Rogart igneous complex, also showing areas of injection migmatites within host psammites of the Morar Group. See Figure 1 for location. Abbreviations: CN – Cnoc Arthur; CM – Creag Mhor; GB – Garvoult Bridge; MR – Marian's Rock; RS – Rogart Station; SFF – Strath Fleet Fault. Marginal numbers are UK National Grid coordinates in area 'NC'.

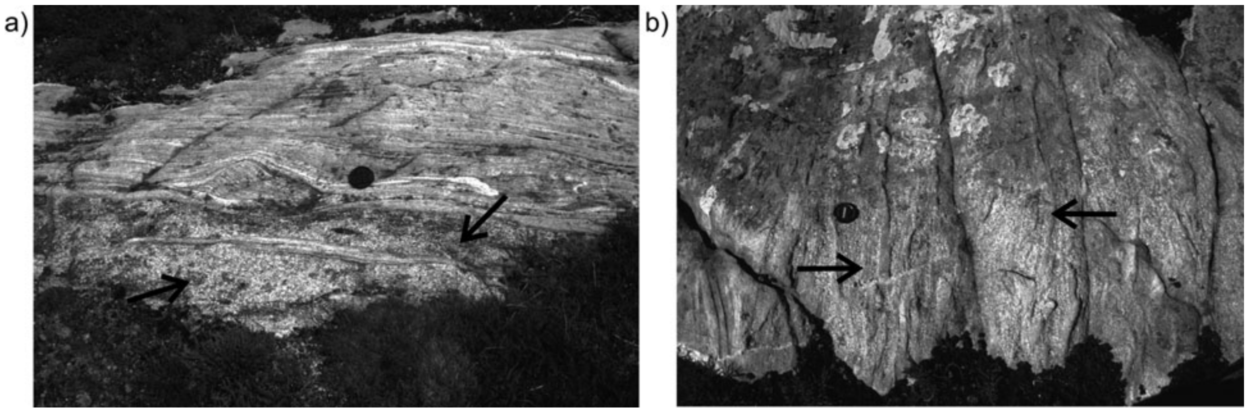

Figure 3. (a) Banded Morar Group psammites intruded by S2-parallel leucogranite sheets (arrowed); (b) injection migmatites within the Morar Group showing relict layers of psammite (arrowed) engulfed by S2-parallel leucogranite. Both outcrops in the vicinity of Marian's Rock [NC 748 013]. Camera lens cap for scale is 5 cm in diameter.

leucogranite occur near Rogart Station [NC 720 027] and at Marian's Rock [NC 748 013] (Fig. 3a, b). Leucogranite sheets are also focused in the vicinity of the Naver Thrust, both in its footwall and hangingwall. The leucogranites are fine-to-medium grained, and mainly comprise quartz + plagioclase + K-feldspar ± biotite ± muscovite. They are petrographically distinct from the leucosomes within the Loch Coire Migmatite Complex in two important respects: (1) although commonly deformed, magmatic-state fabrics are indicated by the straight grain boundaries of eu- to subhedral early crystallized phases, and (2) they lack garnet. Leucogranite sheets typically have sharp contacts with their host rocks; although some sheets are highly discordant to metasedimentary layering, most are concordant to subconcordant.

On the basis of dissimilar geochemistry (being relatively rich in Fe_2O_3, MgO, TiO_2 and related trace elements at comparable SiO_2) and rare earth element (REE) patterns (in particular a persistent negative Eu anomaly and relatively high heavy REEs), the leucogranites are regarded as petrogenetically distinct from the high Ba–Sr magmas of the central pluton (Fowler *et al.* 2001), and a crustal origin by the melting of Moine metasediments is most likely (H. Kocks, unpub. PhD thesis, Oxford Brookes Univ., 2002).

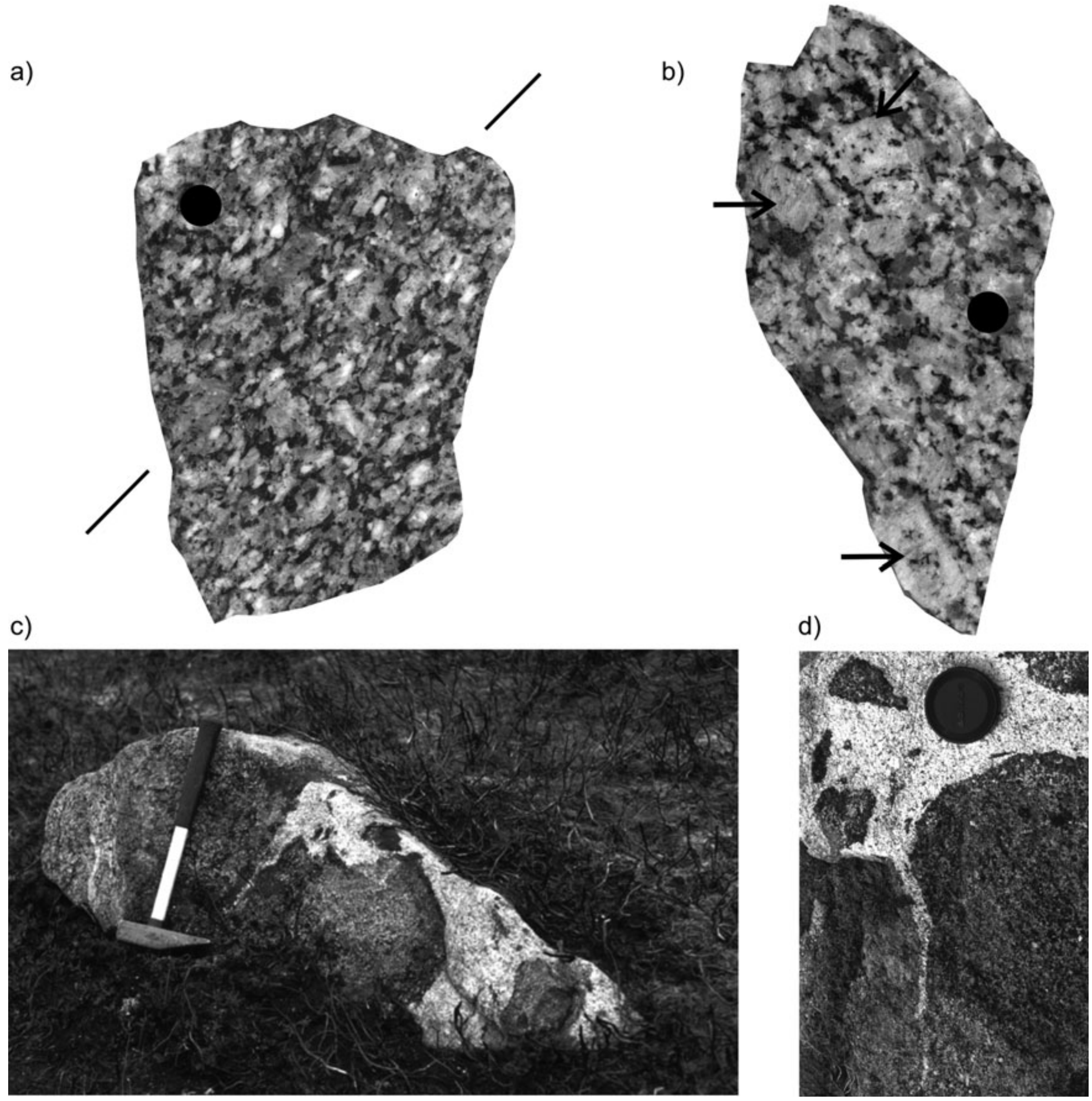

Figure 4. Field photographs and polished hand specimens from the Rogart igneous complex: (a) outer quartz monzodiorite; note the general alignment of magmatic hornblende and plagioclase parallel to black line; (b) porphyritic granodiorite; note euhedral K-feldspar megacrysts indicated by arrows; (c, d) appinitic enclaves cut by late leucocratic sheets within the innermost biotite granite [NC 703 026]. Black circle on hand specimens is 5 mm in diameter; hammer is 35 cm long; camera lens cap is 5 cm in diameter.

3.b. Central pluton and associated marginal sheets

The outer quartz monzodiorite of the central pluton is medium-to-coarse grained and comprises sodic plagioclase (An_{20-25}) + quartz + biotite + hornblende with minor K-feldspar (Fig. 4a). Quartz dioritic facies occur towards the margins of the pluton. The quartz monzodiorite grades into the granodiorite that makes up the bulk of the pluton over *c.* 50 m in the south-east of the body, but more gradually over *c.* 100–300 m in the north. The granodiorite is coarse grained and porphyritic and comprises sodic plagioclase + quartz + K-feldspar + biotite + hornblende. K-feldspar occurs as large (1–2 cm) mostly eu- to subhedral phenocrysts (Fig. 4b) that are commonly twinned and poikilitically enclose small, earlier crystallized plagioclase and occasional amphibole crystals. The innermost biotite granite cross-cuts the boundary between the granodiorite and the quartz monzodiorite. It comprises mainly subhedral K-feldspar megacrysts and quartz, with abundant small plagioclase feldspars. Biotite is present as large, often chloritized grains. Mafic to ultramafic appinitic enclaves are abundant throughout (Fowler *et al.* 2001) and comprise variable proportions of clinopyroxene + hornblende + biotite, set in a groundmass of K-feldspar and subordinate plagioclase (Fig. 4c, d). The pluton is flanked to the north and east by quartz monzodiorite stocks and sheets, notably at Creag Mhór [NC 730 086] and in the River Brora [e.g. NC 7180 0995]. These are mineralogically similar to the outermost facies of the central pluton.

The Rogart igneous complex has the distinctive high Ba–Sr chemistry that is typical of other members of the Newer Granite suite in northern Scotland (Tarney & Jones, 1994; Fowler *et al.* 2001, 2008). Various workers have shown that the high Ba–Sr characteristics can be traced back to associated appinitic rocks and that such

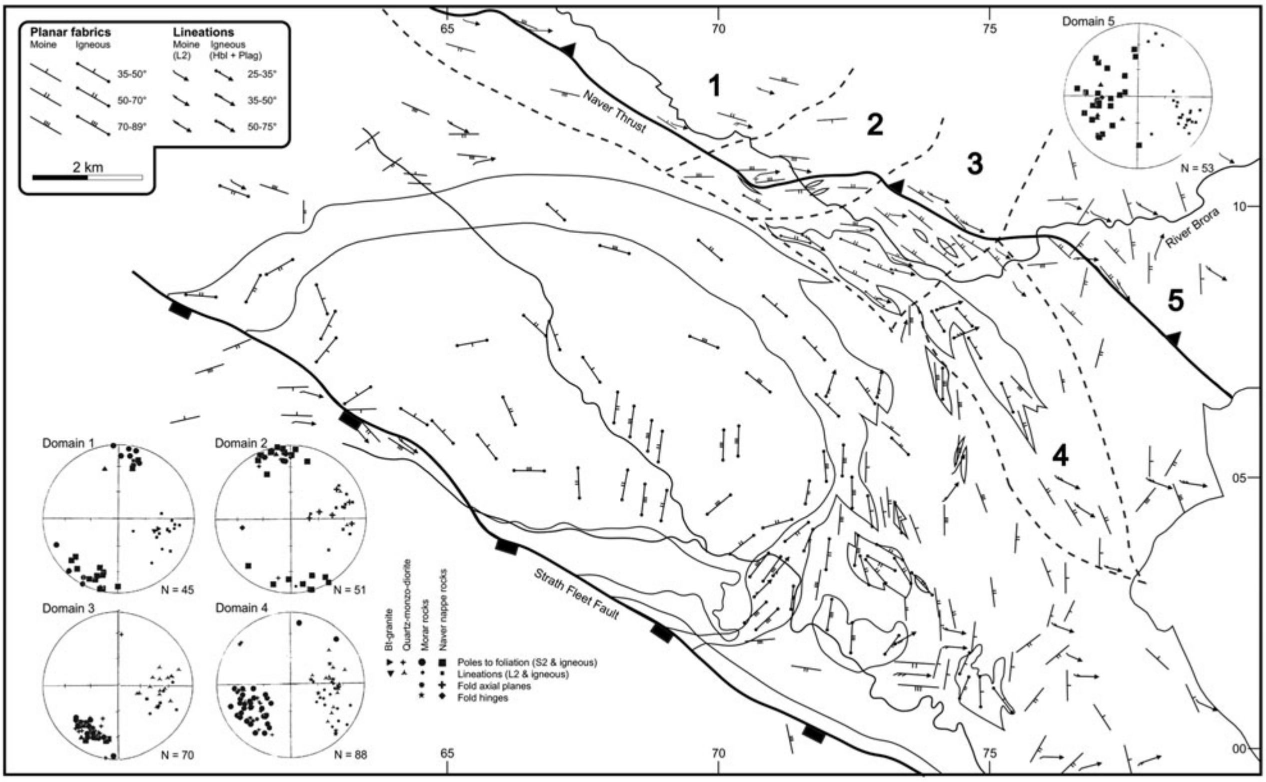

Figure 5. Detailed structural map of the Rogart igneous complex and its Moine country rocks; see text for discussion. Lower-hemisphere stereographic projections of data (see key) are linked to the domains indicated by dashed lines and numbers.

granitoids can be generated from these mantle-derived magmas by extended crystal fractionation coupled with crustal contamination (e.g. Thirlwall & Burnard, 1990; Fowler, 1992; Fowler & Henney, 1996; Fowler *et al.* 2001, 2008). The REE patterns of the various components of the pluton are characteristically steep with La/Yb > 50, lack prominent Eu anomalies and exhibit relatively low contents of Y and heavy REEs (Fowler *et al.* 2001).

3.c. Structure and contact relationships of the central pluton

On the map scale, the central pluton is concordant with the S2 foliation in its Moine country rocks (Figs 5, 6a). Both the quartz monzodiorite and the granodiorite contain a well-developed foliation (Figs 5, 6b; Soper, 1963; H. Kocks, unpub. Ph.D. thesis, Oxford Brookes Univ., 2002). Foliations in the northern part of the pluton dip at *c.* 60° outwards, away from the centre of the body whereas they are subvertical on its eastern side. The foliation within the quartz monzodiorite generally parallels the pluton margin and the foliation within the Morar Group country rocks. Locally, a subhorizontal to shallowly plunging lineation defined by aligned feldspars is also present (Figs 5, 6b). Within the central to western part of the granodiorite, foliations form an inward-dipping funnel structure (Figs 5, 6b; Soper, 1963). Deformed mafic enclaves are generally oblate in form (Soper, 1963; H. Kocks, unpub. Ph.D. thesis, Oxford Brookes Univ., 2002) and flattened parallel to the foliation. In the southeast, the trace of the foliation is at high angles to the Strath Fleet Fault whereas in the northwest this angle is shallow.

Contacts between the Moine rocks and the outer quartz monzodiorite of the pluton are invariably sharp and subconcordant. There is no evidence of contact metamorphism of the Moine rocks, but it is likely that growth of diagnostic minerals would have been inhibited by their dominantly quartzo-feldspathic mineralogy. When traced towards the pluton, the structures within the country rocks north of the Strath Fleet Fault undergo significant reorientation in several ways (Fig. 6a). North of the pluton, the dips of both the composite $S_0/S_1/S_2$ foliation and the Naver Thrust steepen to 50–70°, and are locally 80–90° (Figs 5, 6a). Notably, the foliation within the Moine rocks to the northwest of the pluton is overturned and dips to the south or southeast (Soper, 1963; Figs 5, 6a). On the northeastern and eastern side of the central pluton, the foliation within the Moine rocks strikes broadly parallel with the margins of the pluton (Figs 5, 6a). As the Strath Fleet Fault is approached from the north and south, steep foliations within the Moine rocks are progressively rotated in a clockwise sense (Fig. 6a), consistent with dextral displacement.

4. Deformation fabrics, microstructures and emplacement chronology

An emplacement chronology for the igneous rocks in the Rogart area can be deduced with reference to their

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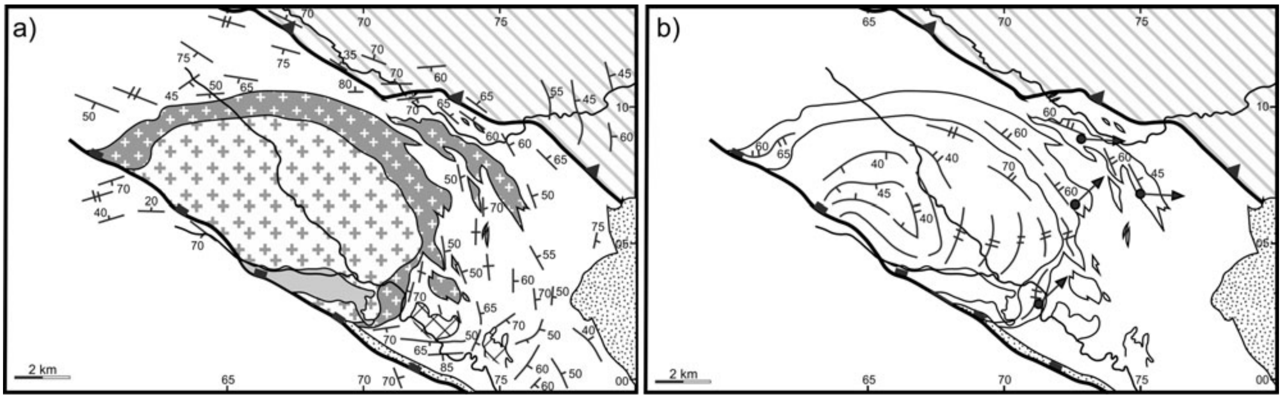

Figure 6. Simplified pluton and host rock fabric patterns: (a) S2 foliation within the host Moine rocks; note the clockwise swing of S2 towards the Strath Fleet Fault, consistent with dextral shear; (b) foliation and lineation within the Rogart igneous complex; note the elongate funnel structure in the central pluton, the subvertical foliations to its east and the outward-dipping foliations in the northeast. Ornament as for Figure 2.

deformation fabrics, microstructures and temporal relationships to ductile structures within their Moine country rocks.

4.a. Syn-D_2 generation of leucogranites and injection migmatites

Injection migmatites and leucogranites east of Cnoc Arthur [NC 730 086], near Marian's Rock [NC 748 013] and around Garvoult Bridge [NC 739 057] are characterized by alternation on all scales of bands of psammite and migmatitic semi-pelite with sheets and lenses of intrusive biotite leucogranite. The metasediments carry a strong $S_0/S_1/S_2$ foliation and a well-developed L_2 mineral and extension lineation defined by mica and quartz that plunges down-dip to the east (Fig. 5). The leucogranites are subconcordant to the $S_0/S_1/S_2$ gneissic foliation in host Moine rocks, and some examples are boudinaged and deformed by tight-to-isoclinal D_2 folds (Fig. 7a). At [NC 7418 0483], centimetre–decimetre-scale leucogranite sheets appear to have been channelled up D_2 thrust planes (Fig. 7b).

A well-developed foliation within the leucogranites is parallel to $S_0/S_1/S_2$ in host rocks, but is essentially magmatic in origin with variable amounts of solid-state overprinting at temperatures of 400–500 °C. Where least overprinted, it is defined by mainly euhedral plagioclase laths of 2–3 mm length that are wrapped by biotite and/or retrogressive chlorite. The grain contacts between these early crystallized phases are generally straight and well defined, consistent with magmatic-state mineral alignment (Fig. 7d). Plagioclase grains are rarely slightly bent or show weak undulose extinction and/or marginal recrystallization. They are aligned on foliation surfaces to define a lineation that is parallel to L_2. On surfaces parallel to L_2, asymmetric feldspar grains locally define a top-to-the-W sense of shear, parallel to the inferred direction of tectonic transport during D_2 (Fig. 7c). Quartz occurs either in pressure shadows around plagioclase grains, or as recrystallized thin ribbons between them that show prismatic and equant deformation bands as well as undulose extinction, and grain boundary migration that occasionally leads to subgrain formation. In other areas, the magmatic fabric is more strongly overprinted and feldspars show undulose extinction and evidence for grain boundary migration and marginal recrystallization.

To summarize, these field and microstructural observations are consistent with emplacement of the leucogranites during D_2, with variable amounts of solid-state overprinting during later stages of that deformation episode.

4.b. Late D_2 emplacement of marginal quartz monzodiorite sheets

Quartz monzodiorite sheets to the northeast of the central pluton at Creag Mhór (Fig. 2) and in the River Brora are neither cut by leucogranites nor deformed by D_2 folds, and it is therefore assumed that they are younger than these features. Nonetheless, they are broadly concordant to $S_0/S_1/S_2$ and show evidence for variable amounts of fabric development and overprinting during the late stages of D_2. Magmatic-state fabrics are best preserved in the northern part of the Creag Mhór sheet where aligned euhedral plagioclase and hornblende define a foliation that is co-planar with $S_0/S_1/S_2$ and a lineation that is parallel to L_2 (Fig. 8a, b, d). In sections parallel to the lineation, tiling of hornblende grains indicates that magmatic flow was directed to the west. Quartz occurs as interstitial pools between feldspar and hornblende and is only weakly deformed (Fig. 8c). Microcracks affecting early crystallized titanite and hornblende are healed with late magmatic feldspar.

Essentially similar magmatic fabrics are occasionally preserved in low strain areas in the southeastern part of the Creag Mhór sheet and in the River Brora examples, but here the influence of solid-state deformation is much greater. Within these areas (e.g. Cnoc Arthur, NC 730 086), planar and linear fabric elements are parallel to $S_0/S_1/S_2$ and L_2, respectively

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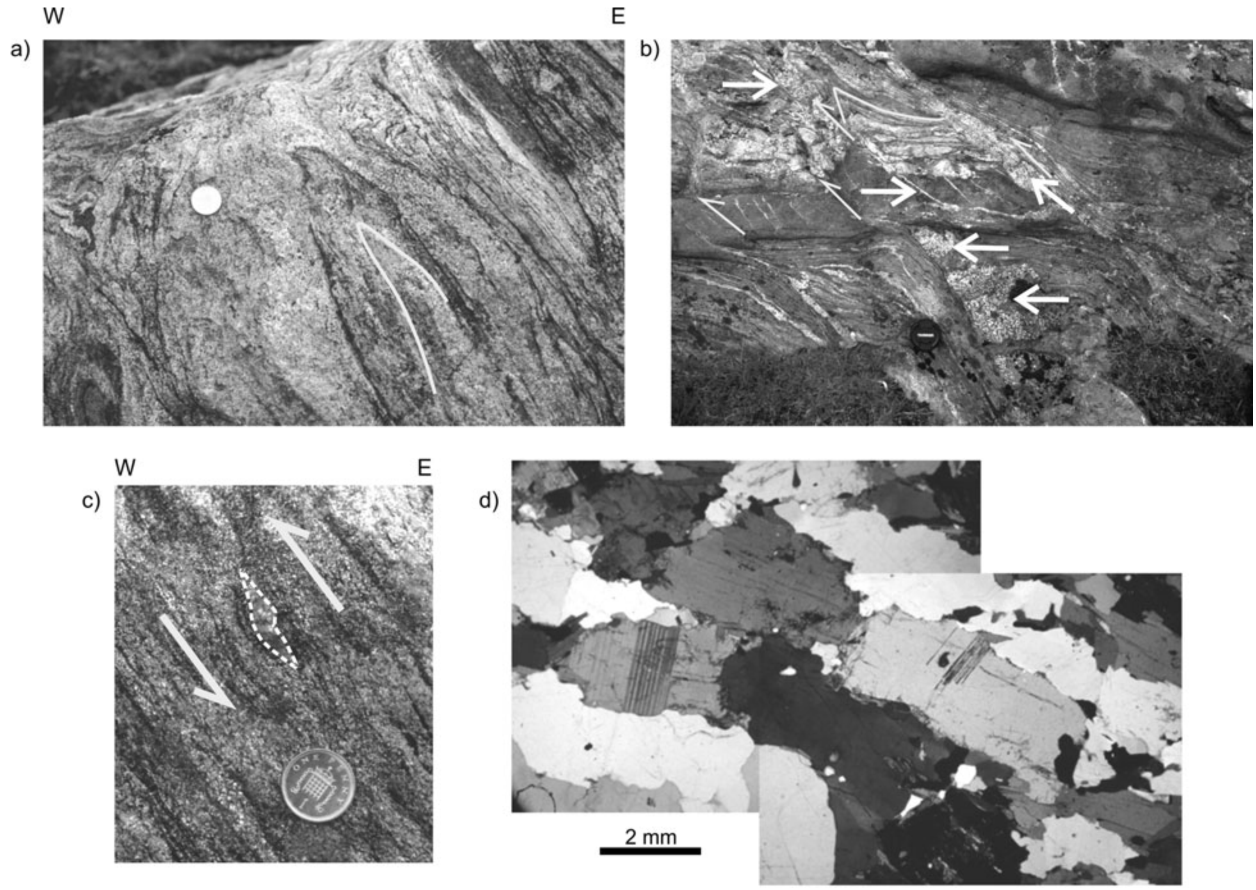

Figure 7. (a) isoclinal F2 fold of leucogranite veins (vicinity of Cnoc Arthur [NC 730 086]); (b) emplacement of biotite-leucogranite sheets (arrows) along thrust planes (half arrows) (east of Garvoult Bridge, [NC 0732 0945]); note granitic sheets along thrust planes and granite ponds in the hangingwall; (c) asymmetrically sheared feldspar within leucogranite, indicating top-to-the-W movement parallel to L2 (vicinity of Cnoc Arthur [NC 730 086]); (d) aligned plagioclase laths (*c.* 5 mm long) defining the magmatic-state fabric in leucogranite. Coin in (a) and (c) is 5 mm in diameter; camera lens cap in (b) is 5 cm in diameter; scale bar in (d) is 2 mm.

(Fig. 5), but record solid-state deformation. Plagioclase and hornblende grains are generally subhedral with embayed grain boundaries (Fig. 9a), and are often broken (Fig. 9b), but cracks are only rarely healed by late magmatic minerals. Feldspars show bent twins, marginal recrystallization (Fig. 9c) and undulose extinction. Quartz occurs as recrystallized tails in pressure shadows (Fig. 9d) and ribbons that show evidence for subgrain development and grain boundary migration (Fig. 9e). In areas of high solid-state strain, centimetre-scale C-S fabrics indicate a top-to-the-W sense of shear parallel to L_2 (Fig. 9f). The microstructures are consistent with deformation at temperatures of *c.* 550–400 °C (Boullier & Bouchez, 1978; Tribe & D'Lemos, 1996; Passchier & Trouw, 2005 and references therein).

4.c. Post-D_2 emplacement of the central pluton

Two field observations imply that the central pluton was emplaced post-D_2: firstly, the regional $S_0/S_1/S_2$ foliation within the country rocks is reoriented significantly in the vicinity of the pluton (Fig. 6a), and secondly, although outer components of the pluton carry a foliation, this is not accompanied by any lineation that might correlate with L_2 in the country rocks.

In a traverse towards the margin of the pluton, the outer quartz monzodiorite records systematic changes in fabric (Fig. 10). Away from the margin of the pluton, it carries a variably developed planar foliation defined by euhedral tabular plagioclase and prismatic hornblende with occasional eu- to subhedral alkali feldspar (Fig. 10a). Quartz occurs as approximately circular interstitial pools. Towards the pluton margin, high strain zones may develop where the fabric is progressively closer spaced, grain size may be reduced and the crystal habit is subhedral (Fig. 10b, c). The constituent phases show straight grain boundaries and together with interstitial ovoid to elongate quartz pools form an interlocking framework that we interpret as a pre-rheologically critical melt percentage fabric (pre-RCMP; e.g. Tribe & D'Lemos, 1996). Bent plagioclase and marginal recrystallization of feldspar are interpreted to result from solid-state deformation at *c.* 650 °C. Locally abundant micrographic and myrmekitic intergrowths are interpreted to result from strain-induced recrystallization at *c.* 600–550 °C (Simpson, 1985). Quartz grains within the low strain ovoid interstitial positions are generally undeformed whereas elongate quartz ribbons occur

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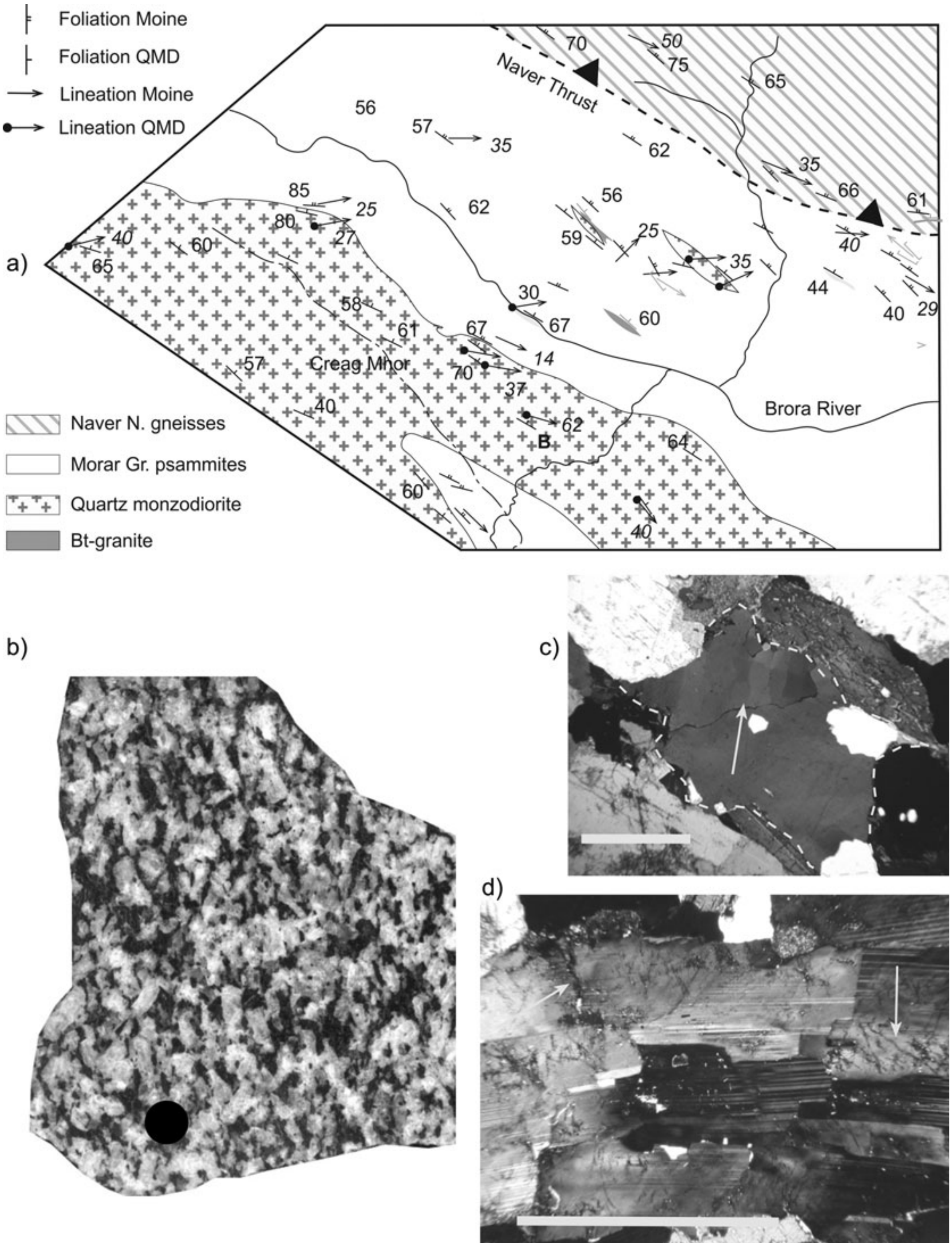

Figure 8. Geology and igneous fabrics in the northern part of the Creag Mhor sheet: (a) geological map; note parallelism of pluton and host rock fabrics; (b) polished slab of quartz monzodiorite showing alignment of magmatic, euhedral plagioclase and hornblende, with subordinate biotite and interstitial quartz (black circle is 5 mm diameter); (c) rectangular, multigrain quartz pool (arrowed), interstitial between early crystallizing and aligned feldspar and hornblende; (d) aligned, subhedral plagioclase with some evidence for bent twins and undulose extinction and local brittle cracking (arrowed) (scale bar in (c) and (d) is 1 mm long).

between tabular feldspar crystals. However, they show no microstructural evidence for high-temperature grain boundary migration recrystallization, but are characterized by undulose extinction and the development of internal prismatic deformation bands formed by subgrain rotation at moderate to lower temperatures of about 500–400 °C (Drury & Urai, 1990; Hirth & Tullis, 1992; Tribe & D'Lemos, 1996; Stipp *et al.* 2002). In summary, the formation of the pervasive foliation occurred in the magmatic state and was followed by coaxial flattening and minor high- to moderate-temperature solid-state recrystallization which did not significantly reorientate the primary fabric.

In outcrop, the porphyritic granodiorite is characterized by a coarse-grained, slightly anastomosing foliation defined by the alignment of eu- to subhedral, small tabular plagioclase, large, eu- to subhedral porphyritic alkali feldspar and hornblende (Fig. 4b).

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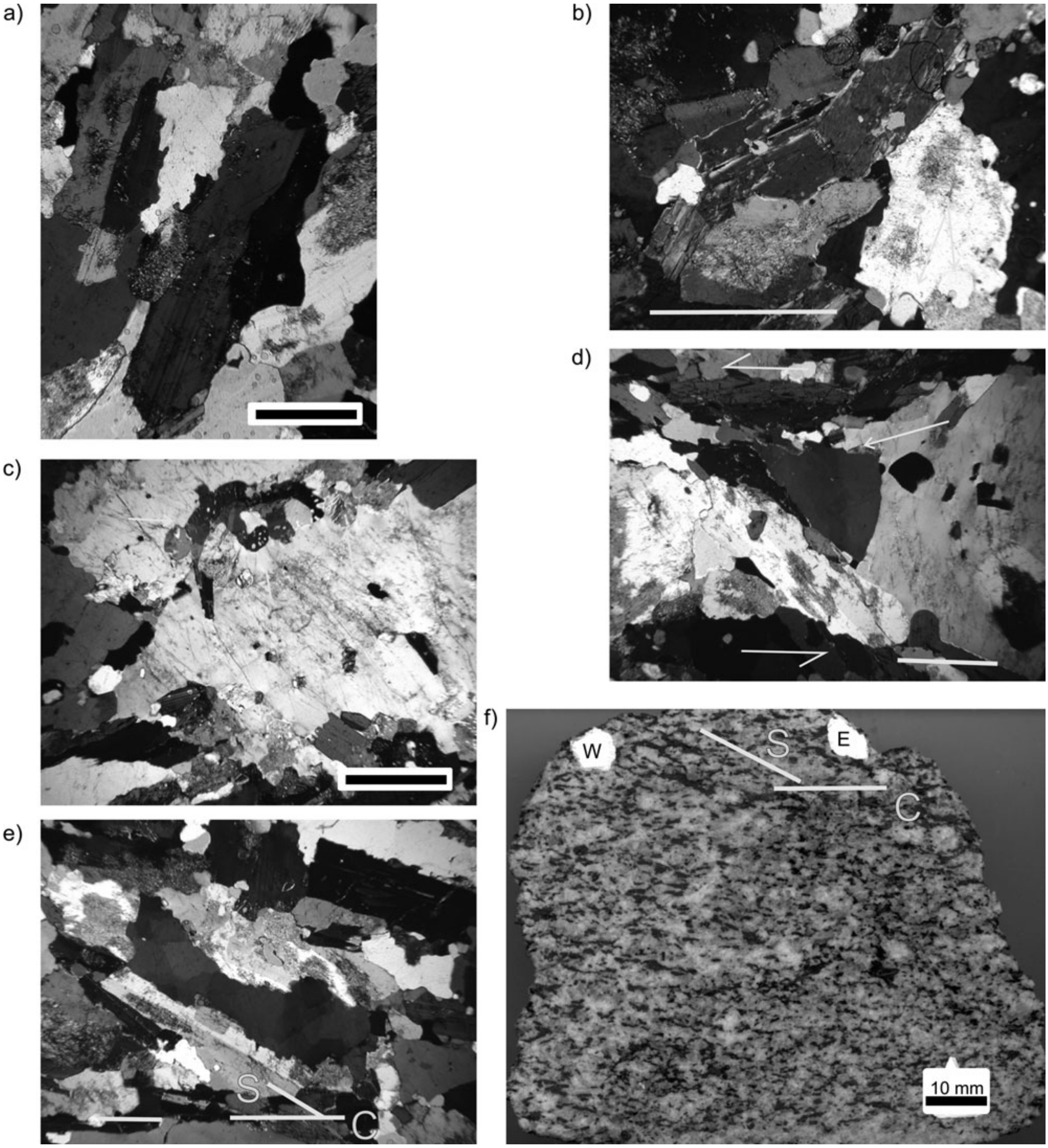

Figure 9. Evidence for solid-state deformation within the Creag Mhor quartz monzodiorite sheet at Cnoc Arthur [NC 730 086] (all samples cut parallel to mineral lineation): (a) subhedral plagioclase with irregular, embayed grain boundaries; (b) kinked and broken hornblende; also note irregular grain boundaries in feldspar; (c) subhedral K-feldspar showing marginal recrystallization and exsolution at intersecting K-feldspar grain boundaries; (d) recrystallized quartz in pressure shadow drawn out into foliation and giving top-to-the-W (left) sense of shear (half arrows); (e) recrystallized quartz aligned parallel to the S-fabric defined by earlier crystallized plagioclase; (f) polished slab with mafic minerals defining grain-scale S-C fabrics consistent with top-to-the-W shear during down-temperature deformation (W – west, E – east). Scale bar in (a–e) is 1 mm long.

Interstitial spaces are occupied by large, generally ovoid multigrain quartz pools. In thin-section, the minerals show similar magmatic-state features as described for the quartz monzodiorite, preserving prismatic grain shapes, shape-preferred orientations and igneous grain contacts. Evidence for a down-temperature solid-state overprint (e.g. marginal recrystallization of feldspars and myrmekite development) is similarly present. However, the interstitial multigrain quartz aggregates are largely undeformed. Recrystallization of hornblende to biotite is common and may have occurred at lower-greenschist-facies temperatures. Overall, the features are consistent with magmatic-state, pre-RCMP foliation development and subsequent largely undisturbed

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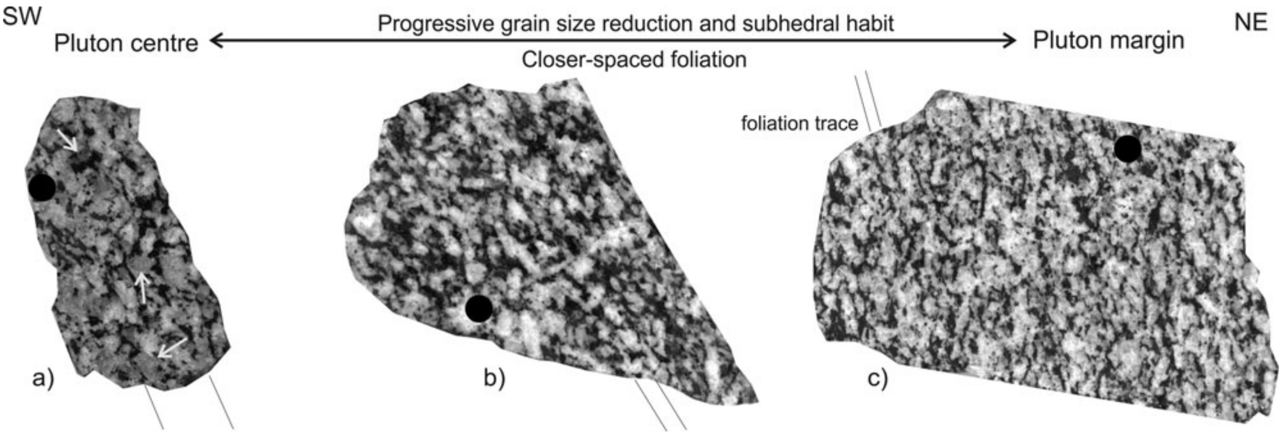

Figure 10. Polished slabs showing progressive pre-RCMP fabric development in the outer quartz monzodiorite in a traverse towards the NE margin of the central pluton: (a) weak alignment of K-feldspar, plagioclase and hornblende, note the circular interstitial quartz pools (arrows); (b) fabric is more prominent, defined by hornblende and euhedral to subhedral plagioclase; interstitial quartz pools are oval-shaped; (c) well-developed fabric defined by subhedral to oval aggregates of plagioclase and quartz that are aligned parallel to small but euhedral grains of hornblende. Black dot is 5 mm in diameter.

cooling. In contrast to the quartz monzodiorite and the granodiorite, the inner biotite granite does not carry any tectonic or magmatic foliations.

In summary, the quartz monzodiorite and granodiorite components of the central pluton are dominated by magmatic fabrics that were modified by weak down-temperature solid-state recrystallization and coaxial strain during cooling. The microstructural observations are therefore consistent with the field evidence that the central pluton was emplaced post-D_2 (see also Soper, 1963).

5. U–Pb geochronology

The only available geochronological data relating to the age of the Rogart igneous complex is a K–Ar whole-rock age of *c*. 420 Ma (Brown, Miller & Gresty, 1968). In order to constrain more precisely its age of emplacement, zircons were analysed from a sample of the outer quartz monzodiorite of the central pluton collected at [NC 7095 0295].

5.a. Sample preparation procedure and analytical techniques

The outer quartz monzodiorite of the central pluton was dated using the U–Pb technique. A sample of *c*. 30 kg was jaw crushed and disc milled and the < 400 micron fraction sieved out. Heavy mineral concentrates were obtained using a Gemini shaking table, followed by a superpanner. A > 3.3 g/ml density separate was recovered using Di-iodomethane and the minerals separated magnetically using a Frantz LB-1 magnetic separator. The recovered zircons were hand picked under alcohol and then air abraded. U and Pb separations followed the procedures of Krogh (1973) with minor modifications of Corfu & Ayres (1984). Fractions were spiked with a mixed $^{205}Pb/^{235}U$ isotopic tracer (Krogh & Davis, 1975) before digestion and chemical analysis. U and Pb were loaded onto outgassed single Re filaments with silica gel and were analysed on a VG 354 mass spectrometer using a Daly detector following Noble, Tucker & Pharaoh (1993). Chemistry blanks were *c*. 5 pg, and these were monitored in each batch of chemistry. Uranium blanks were < 0.1 pg U. All results and errors were calculated following Ludwig (1993, 1994) and the Pb isotope ratios were corrected for initial common Pb in excess of laboratory blank using the Stacey & Kramers model (1975). Ages were calculated using the decay constants of Jaffey *et al.* (1971). The 2σ errors (95 % confidence levels) given in Table 1 for ages and isotope ratios were obtained by propagating key sources of error through all calculations following the methods using Ludwig (1993, 1994).

5.b. Results

Three zircon fractions plot on or just below concordia and give a concordant $^{207}Pb/^{235}U$ – $^{206}Pb/^{238}U$ age of 425 ± 1.5 Ma (2σ) for crystallization of the intrusion (Fig. 11). Data are presented in Table 1.

6. Emplacement model for the Rogart igneous complex

The syn-D_2 leucogranites and late-D_2 quartz monzodiorites are strikingly similar in their structural setting to granitic sheets that further north in central Sutherland were emplaced during D_2 (Holdsworth & Strachan, 1988; Kinny *et al*. 2003). The location of these variably deformed intrusions in both central and SE Sutherland within the immediate footwall of the Naver Thrust suggests that this structure played an important role in channelling mantle- and crustal-derived melts during Scandian nappe stacking. Similarly, the D_2 Skinsdale Thrust in E Sutherland and Caithness appears to have acted as a fundamental structural control on emplacement of the Strath Halladale Granite (Kocks, Strachan

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Table 1. Analytical data for the U–Pb zircon analyses from the Rogart granite

Fraction code	Weight (µg)	U† (ppm)	Pb†c (ppm)	Total Pb c	^{206}Pb/^{204}Pb‡	^{208}Pb/^{206}Pb‡	^{206}Pb/^{238}U‡	± %	^{207}Pb/^{235}U‡	± %	^{207}Pb/^{206}Pb‡	± %	^{207}Pb/^{206}Pb§	± Ma	P**
rog-1	11.6	384	29.3	17	1627	0.2022	0.06803	0.22	0.5217	0.29	0.05562	0.17	437	4	0.79
rog-2	48.0	414	30.0	14	9106	0.1758	0.06803	0.22	0.5298	0.25	0.05548	0.12	432	3	0.88
rog-3	76.0	386	28.3	21	7637	0.1866	0.06807	0.22	0.5206	0.25	0.05547	0.12	431	3	0.88

† Sample weights and hence of U and Pb concentrations are approximate.
‡ Measured ratios are corrected for fractionation and common Pb spike.
§ Corrected for fractionation, spike, laboratory blank and initial common Pb using calculated at 425 Ma (Stacey & Kramers, 1975).
** Correlation coefficients of ^{207}Pb/^{235}Pb and ^{206}Pb/^{235}U are calculated using procedures and algorithms of Ludwig (1993). Errors for the measured ratios are propagated through data reduction and quoted at the 2σ level.

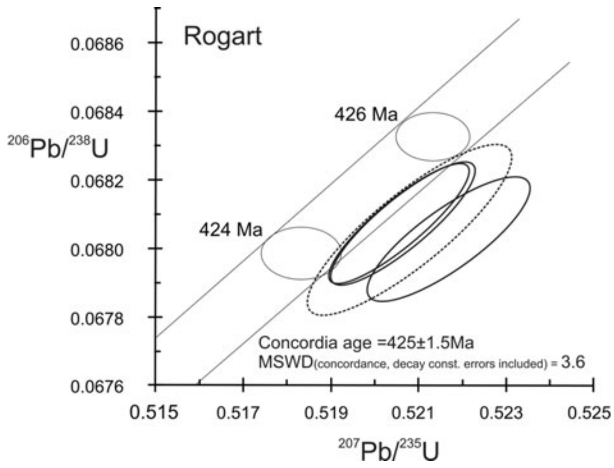

Figure 11. U–Pb concordant zircon age from the outer quartz monzodiorite of the central pluton. The MSWD is of concordance and equivalence at 2σ and takes into account errors on the decay constant. The dashed ellipses are the weighted mean error ellipse of the data points.

& Evans, 2006). Leucogranites and associated injection migmatites are, however, only found associated with the Rogart igneous complex, and their spatial coincidence suggests some form of genetic relationship. We suggest that leucogranite melts were generated during D_2 crustal thickening in response to heat and fluid influx from ascending mantle-derived magmas, which resulted in melting of Moine semi-pelitic rocks at lower structural levels. The field relations of the leucogranites are consistent with pervasive flow through actively deforming ductile crust, with injection of centimetre–metre-scale melt sheets along previously formed anisotropies and newly developed thrusts (e.g. Collins & Sawyer, 1996; Brown & Solar, 1999; Weinberg & Searle, 1998). In contrast, the slightly younger late-D_2 quartz monzodiorite sheets were emplaced as coherent bodies.

The post-D_2 Rogart central pluton is completely different in its structure and field relations. Two different scenarios are commonly invoked to explain the emplacement of such sub-circular to elliptical, compositionally zoned plutons that contain concentric fabric patterns and show a deformed wall rock envelope. The first is that the pluton represents a diapir that rose vertically through the crust as a pre-assembled pluton that deformed its wall rocks on the way to its final location (e.g. Paterson & Vernon, 1995; Miller & Paterson, 1999). Alternatively, it could represent a pluton that evolved more or less *in situ* by rapid additions of batches of magma at the site of emplacement leading to inflation and lateral expansion ('ballooning') of the intrusion (e.g. Petford, Kerr & Lister, 1993; Clemens, Petford & Mawer, 1997; Molyneux & Hutton, 2000). Various field criteria might distinguish between these two models, although they may not be unequivocal or exclusive (Miller & Paterson, 1999; Molyneux & Hutton, 2000). Nonetheless, structural features of the Rogart central pluton and its host rocks are inconsistent with the

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diapiric interpretation. Diagnostic features such as steep magmatic lineations, margin-parallel foliations with pluton-up kinematic indicators, steep high-temperature marginal shear zones and a well-developed rim syncline are absent. Instead, the development within the pluton of a pervasive magmatic-state foliation, local subhorizontal or shallowly plunging (non-radial) lineations, and oblate mafic enclaves suggest a subhorizontal flattening strain during emplacement, consistent with *in situ* inflation and lateral expansion.

We suggest that the Rogart central pluton was assembled by successive batches of magma that were channelled up an actively deforming fault zone that was later reactivated to form the Strath Fleet Fault. Pluton emplacement may have been facilitated by development of a localized dilational jog or pull-apart structure into which magma was injected forcefully to result in the observed pluton fabric patterns and reorientation of host rock foliations. The role of steep strike-slip faults in controlling the ascent and emplacement of magmas has been highlighted by numerous workers (e.g. Hutton, 1988*b*; D'Lemos, Brown & Strachan, 1992; Hutton & Reavy, 1992; Tikoff & Tessyier, 1992; Jacques & Reavy, 1994; Karlstrom & Williams, 1995). Although we have no geophysical data, we envisage that the pluton was originally tabular with a gently inclined roof and floor. The map-scale clockwise swing of Moine foliations in the vicinity of the Strath Fleet Fault (Fig. 5a), and the sense of obliquity between the fault and the long axis of the pluton are features consistent with emplacement during dextral shear. This is kinematically compatible with sinistral shear along the Great Glen Fault if displacements along the two structures were contemporaneous (Johnson & Frost, 1977; Watson, 1984). However, these dextral movements cannot have been substantial as further west there is no significant offset of regional foliation trends and structures either side of the Loch Shin Line.

7. Conclusions

The Rogart igneous complex is unique within the Scottish Caledonides because it comprises an apparent continuum of genetically related magma types that records a progressive change in emplacement mechanisms related to large-scale tectonic controls. Syn-D_2 leucogranites and slightly younger late-D_2 quartz monzodiorites were emplaced during crustal thickening and focused within the broad zone of ductile deformation associated with the Naver Thrust. In contrast, emplacement of the post-D_2 composite central pluton appears to have been controlled by development of a steeply dipping dextral shear zone along the Loch Shin Line. There is no evidence for any significant hiatus in magma emplacement. The mantle-derived nature of the late-to-post-D_2 melts implies that the Naver Thrust and the Loch Shin Line were both crustal-scale structures along which magmas were channelled during deformation.

The results of the geochronology study reported here place constraints on the timing of regional tectonic events. The new U–Pb zircon age of 425 ± 1.5 Ma for the post-D_2 Rogart central pluton represents an upper limit on the timing of D_2 ductile thrusting and associated deformation and amphibolite-facies metamorphism within this part of the Caledonides. The cessation of D_2 is now tightly bracketed between the age of the Rogart central pluton and that of the only slightly older syn-to-late-D_2 Strath Halladale Granite (426 ± 2 Ma; Kocks, Strachan & Evans, 2006). The new age for the Rogart central pluton also provides indirect constraints on the age of marginal thrusting, specifically within the 'Assynt bulge' in the Moine Thrust Zone further west. The broad arcuate swing of D_2 fabrics within the Moines that resulted from the formation of this structure is disrupted and reoriented in the envelope of the Rogart central pluton. It therefore seems clear that the main displacements along the Moine, Ben More and Glencoul thrusts in the Assynt area must have been essentially complete before the Rogart central pluton was emplaced. This is consistent with the view that the main displacements in the Moine Thrust Zone occurred at *c*. 435–430 Ma (Johnson *et al.* 1985; Kelley, 1988; Freeman *et al.* 1998; Goodenough *et al.* 2011). Any Early Devonian displacements (Freeman *et al.* 1998) must have been very limited.

The Rogart central pluton is essentially the same age as the Ratagain, Strontian and Clunes plutons that were emplaced during regional strike-slip faulting along the NE-trending Great Glen Fault system (Fig. 1; Hutton, 1988*b*; Hutton & McErlean, 1991; Stewart *et al.* 2001). In the Grampian Highlands to the east, emplacement of the similar-aged Etive–Glencoe–Rannoch Moor–Strath Ossian plutons has also been related to late Caledonian sinistral strike-slip faulting (Jacques & Reavy, 1994) as has the Etive Dyke Swarm (Morris & Hutton, 1993; Morris, Page & Martinez, 2005). All these plutons share a number of structural features, including steeply dipping margins and well-developed magmatic-state fabrics. The model proposed here for emplacement of the Rogart pluton, involving intrusion and progressive assembly by ballooning within a dilational jog developed during dextral shear along the NW-trending Loch Shin Line, supports the interpretation that this structure is an anti-Riedel shear to the Great Glen Fault system (Johnson & Frost, 1977; Watson, 1984). The Rogart and Ratagain plutons are of particular importance because in both cases they demonstrably post-date ductile, thrust-related fabrics in their host rocks, and were emplaced along brittle faults that are related to the Great Glen Fault system. The timing is similar to that envisaged in NW Ireland where a major splay of the Great Glen Fault (the Leannan Fault) has magma emplaced along it at 422 ± 2 Ma during sinistral strike-slip tectonics (Kirkland, Alsop & Prave, 2008). These findings are consistent with the view that a fundamental change in tectonic regime occurred in the Scottish Caledonides at around 425 Ma, corresponding to the switch from regional thrusting that resulted from the oblique

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collision of Baltica and Laurentia, to the development of the orogen-parallel, sinistral Great Glen Fault system. By analogy with the present-day Himalayas, such a change could correspond to the transition from collision to lateral 'escape tectonics', although in the case of the Caledonides it has been modelled in terms of progressively changing relative plate motions between Baltica–Avalonia and Laurentia (Dewey & Strachan, 2003).

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