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Structural setting and U–Pb zircon geochronology of the Glen Scaddle Metagabbro: evidence for polyphase Scandian ductile deformation in the Caledonides of northern Scotland

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Abstract – Within the Scottish Caledonides, the Glen Scaddle Metagabbro was intruded into the Moine Supergroup of the Northern Highland Terrane after Grampian D_2 folding and prior to regional D_3 and D_4 upright folding and amphibolite-facies metamorphism. A U–Pb zircon age of 426 ± 3 Ma obtained from the metagabbro is interpreted to date emplacement. D_3–D_4 folding is constrained to have occurred during the Scandian orogenic event. In contrast, polyphase folding and regional metamorphism of the Dalradian Supergroup southeast of the Great Glen Fault is entirely Grampian. These differences are consistent with published tectonic models that invoke a minimum of 700 km of post-Scandian sinistral displacements across the Great Glen Fault to juxtapose the Grampian and Northern Highland terranes.

Keywords: U–Pb zircon, Caledonides, Scandian, Scotland.

1. Introduction

The geological complexity of many Mesozoic–Cenozoic orogens often results from the progressive amalgamation of volcanic arcs and continental fragments during oceanic closure, as well as regionally significant strike-slip displacements that arise either from the oblique nature of a collision or lateral escape during orthogonal convergence (Dewey *et al.* 1986). Even in well-exposed recent orogens such as the Himalayas, the magnitude of such strike-slip displacements can be difficult to evaluate (e.g. Searle, Weinberg & Dunlap, 1998; Searle, 2006), and such difficulties are compounded in older, Palaeozoic and Precambrian orogens. The Lower Palaeozoic Caledonide orogen in Scotland and Ireland is an excellent ancient example of such complexity. It evolved as a result of the closure of the Iapetus Ocean and the convergence of three continental blocks, Laurentia, Baltica and Avalonia (Soper, 1988; Pickering, Bassett & Siveter, 1988; Soper *et al.* 1992; Dewey & Strachan, 2003). Early arc–continent collisions along the Laurentia and Baltica margins during the Ordovician were followed by final oblique continental collision during Silurian times. Orogen-parallel, sinistral displacements occurred during the final stages of collision along various structures, including the Great Glen Fault in Scotland (Fig. 1).

Estimates of displacements along the Great Glen Fault are controversial because of overprinting of the palaeomagnetic record and the lack of any unambiguous correlation across the fault of pre-Devonian markers. An alternative way of evaluating likely displacements across such structures is by comparison of the varying intensity of individual Caledonian events across the orogen as a means of reconstructing original collisional templates. The results of isotopic dating have, for example, already provided indications of a significant contrast in the intensity of Scandian (Silurian) deformational and metamorphic events across the Great Glen Fault (Kinny *et al.* 2003). In this paper we investigate this further and provide additional evidence that the Great Glen Fault separates crustal blocks with contrasting Caledonian tectonothermal histories.

The Scottish Highland Caledonides comprise a series of fault-bounded terranes derived from the margin of eastern Laurentia. The Great Glen Fault separates the Northern Highland and Grampian terranes (Fig. 1). The Northern Highland terrane is mainly underlain by the early Neoproterozoic Moine Supergroup (Holdsworth, Strachan & Harris, 1994). In contrast, the Grampian terrane is dominated by the late Neoproterozoic to early Palaeozoic Dalradian Supergroup (Harris *et al.* 1994). A possible equivalent of the Moine Supergroup, the Dava succession, occurs in the Grampian Terrane (Highton, Hyslop & Noble, 1999; Smith, Robertson & Rollin, 1999), but otherwise there are no obvious lithostratigraphic correlations across the Great Glen Fault.

Both the Moine and Dalradian supergroups were deformed and metamorphosed during an Ordovician

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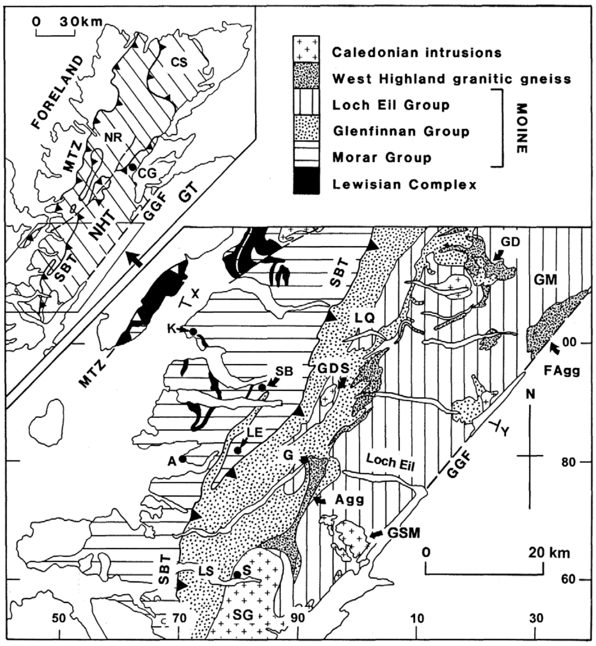

Figure 1. Sketch map of the southern outcrop of the Moine Supergroup (see inset for location) showing the main geological units, igneous bodies and structures mentioned in the text. Diagonal hatching in inset corresponds to the outcrop of the Moine Supergroup in northern Scotland. Numbers around edge of main map correspond to British National Grid. Abbreviations: A – Ardnish; Agg – Ardgour granite gneiss; CG – Carn Gorm; CS – Central Sutherland; FAgg – Fort Augustus granite gneiss; G – Glenfinnan; GD – Glen Doe; GDS – Glen Dessary syenite; GGF – Great Glen Fault; GM – Glen Moriston; GSM – Glen Scaddle metagabbro; GT – Grampian terrane; K – Knoydart; LE – Loch Eilt; LQ – Loch Quoich; LS – Loch Sunart; MTZ – Moine Thrust Zone; NHT – Northern Highland Terrane; NR – northern Ross-shire; S – Strontian; SB – Sgurr Breac; SBT – Sgurr Beag Thrust; SG – Strontian Granite.

(*c.* 480–465 Ma) Grampian orogenic event that resulted from the collision of the Laurentian margin with an intra-Iapetan volcanic arc (Dewey & Ryan, 1990; Dewey & Mange, 1999; Oliver *et al.* 2000; Strachan *et al.* 2002; Dewey, 2006). In addition, U–Pb zircon dating of syn-tectonic granites in east Sutherland (Fig. 1) has provided evidence for ductile reworking and associated amphibolite facies metamorphism of the Moine Supergroup during the Silurian (Kinny *et al.* 2003; Kocks, Strachan & Evans, 2006). This is attributed to the collision of the Northern Highland segment of Laurentia with Baltica and correlated with the Scandian event recognized in Norway (Dallmeyer *et al.* 2001). The lack of any evidence for a comparable Silurian tectonothermal event in the Grampian terrane has led to the suggestion that at that time it was situated further to the southwest along the Laurentian margin, remote from the Scandian collision (Dewey & Strachan, 2003; Kinny *et al.* 2003). It has been concluded that at least 700 km of subsequent sinistral displacement along the Great Glen Fault would have been necessary to bring the Grampian terrane to its present location relative to the Northern Highland terrane (Dewey & Strachan, 2003).

In this paper we review briefly the Caledonian evolution of the Moine rocks of West Inverness-shire (Fig. 1) and present the results of a geochronological study of the Glen Scaddle Metagabbro (Bailey & Maufe, 1916; Drever, 1940). The structural setting of this intrusion was established by Stoker (1983; M. Stoker, unpub. Ph.D. thesis, Univ. Liverpool, 1980) and confirmed during recent fieldwork by one of us (RAS).

2. Geological setting

The Moine rocks of West Inverness-shire comprise the Morar, Glenfinnan and Loch Eil groups (Fig. 1; Holdsworth, Strachan & Harris, 1994). The Morar Group lies within the Moine Nappe, and the Glenfinnan and Loch Eil groups within the Sgurr Beag Nappe (Powell *et al.* 1981; Barr, Holdsworth & Roberts, 1986). The upper part of the Sgurr Beag Nappe is dominated by mainly unmigmatized psammites and quartzites of the Loch Eil Group (Stoker, 1983; Strachan, 1985). The base of the Loch Eil Group passes transitionally into the underlying migmatitic pelites and thinly interbanded psammites and semi-pelites of the Glenfinnan Group. A lower limit for deposition of the Glenfinnan and Loch Eil groups is provided by the *c.* 1000–950 Ma ages of the youngest detrital zircons incorporated within the metasediments (Friend *et al.* 2003; Cawood *et al.* 2004). The West Highland Granitic Gneiss suite, prominent members of which crop out in Ardgour, at Fort Augustus and at Glen Doe (Fig. 1), was emplaced at *c.* 870 Ma (Friend *et al.* 1997; Rogers *et al.* 2001). The current consensus is that this probably represents an early rift-related igneous suite, broadly coeval with intrusion of amphibolites and meta-gabbros that record all the tectonothermal events present in their Moine host rocks (Millar, 1999; Dalziel & Soper, 2001).

The Moine rocks of the Loch Eil Group in West Inverness-shire record four main phases of deformation (Strachan, 1985; see also Dalziel, 1966 and Stoker, 1983). Early minor isoclinal folding (D_1) was associated with formation of an S_1 schistosity that developed under amphibolite facies conditions. Elsewhere in West Inverness-shire (E. K. Hyslop, unpub. Ph.D. thesis, Univ. Hull, 1992; Rogers *et al.* 1998; Vance, Strachan & Jones, 1998; Tanner & Evans, 2003), a mid-Neoproterozoic (820–730 Ma) age has been demonstrated for early folding, amphibolite-facies metamorphism and segregation of dated syn-metamorphic pegmatites at Ardnish, Sgurr Breac, Knoydart, Loch Eilt and Carn Gorm (Fig. 1). A similar age is assumed for D_1 in the Loch Eil Group. A subsequent phase of widespread minor tight to isoclinal folding (D_2) resulted in formation of a composite $S_0/S_1/S_2$ foliation (Strachan, 1985). The foliation carries a stretching and mineral lineation

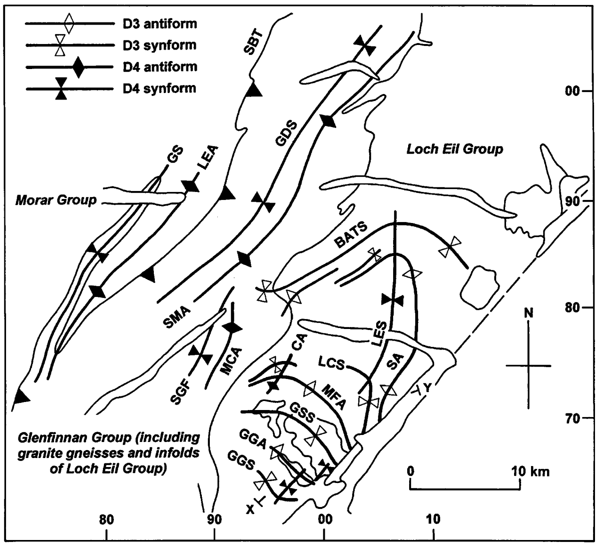

Figure 2. Simplified map of the main D_3 and D_4 folds within the SW Moine (using data from Powell *et al.* 1981; Roberts, Smith & Harris, 1984; Stoker, 1983; Strachan, 1985). Abbreviations: SBT – Sgurr Beag Thrust; GS – Glenshian Synform; LEA – Loch Eilt Antiform; GDS – Glen Dessary Synform; SMA – Spidean Mialach Antiform; SGF – Sgurr Ghiubhsachain Fold; MCA – Meall na Cuartaige Antiform; BATS – Beinn an Tuim Synform; LES – Loch Eil Synform; SA – Stronchreggan Antiform; CA – Corrlarach Antiform; LCS – Lochan na Cruaich Synform; MFA – Meall an Feidh Antiform; GSS – Glen Scaddle Synform; GGA – Glen Gour Antiform; GGS – Glen Gour Synform.

(L_2) that trends north–south where unaffected by later deformation. These structures are correlated with the D_2 folds and associated fabrics recognized in the northern outcrop of the Loch Eil Group east of Loch Quoich (Fig. 1; Holdsworth & Roberts, 1984). Titanites aligned within the composite S_1/S_2 foliation within the Fort Augustus Granite Gneiss (Fig. 1) have yielded a U–Pb age of 470 ± 1 Ma, suggesting that D_2 occurred during the Ordovician Grampian orogenic event (Rogers *et al.* 2001).

The large-scale structural geology of the southern Loch Eil Group is dominated by major upright D_3 and D_4 folds (Fig. 2; Strachan, 1985). D_3 folds are all upward-facing and plunge towards the Great Glen, with the result that younger rocks come on to the east. Folds are open to close in style, and an S_3 mica schistosity (locally with fibrolite) is locally developed axial-planar to D_3 folds. The refolding of D_3 folds during D_4 generated a regional-scale interference pattern (Fig. 2). D_4 folds are gentle to open, and vary in trend from north–south in the area north of Loch Eil to NNE–SSW in Ardgour; an axial-planar crenulation fabric (S_4) is widespread. Fibrolite, hornblende and biotite all recrystallize around S_4 crenulations, and it is therefore concluded that D_4 was characterized by amphibolite-faces conditions. D_4 folding increases in intensity westwards to form the Northern Highland Steep Belt (Figs 2, 3; Roberts & Harris, 1983).

The prevailing view has been that the upright folds and associated metamorphic assemblages formed at a late stage of the Ordovician Grampian orogenic event (e.g. Kelley & Powell, 1985; Powell & Phillips, 1985; Harris, 1995). A lower limit for the formation of the steep belt is provided by the intrusion of the pre-D_4 Glen Dessary Syenite (Fig. 1) at 456 ± 5 Ma (U–Pb

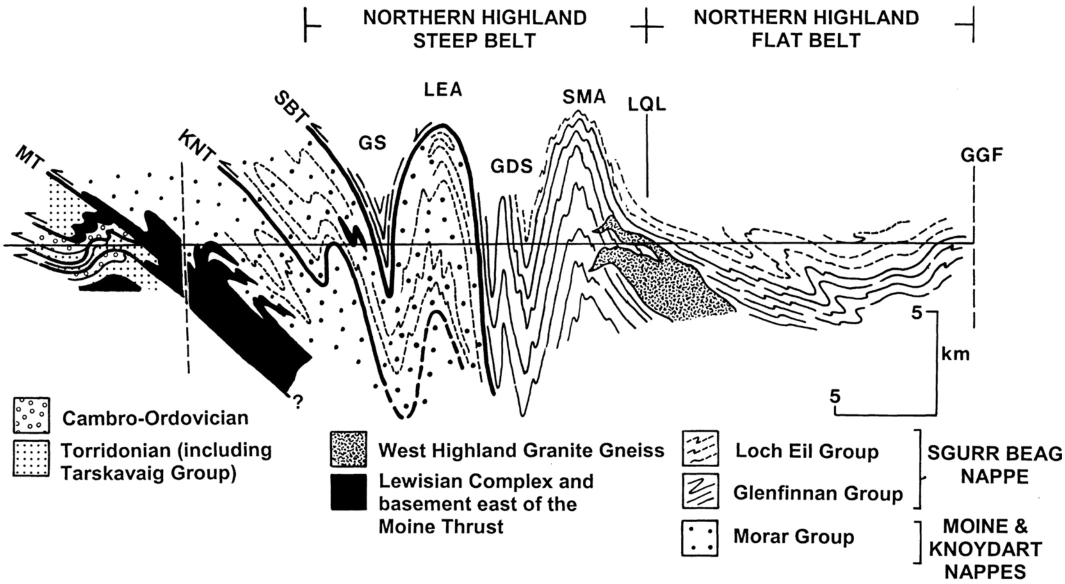

Figure 3. Generalized geological cross-section across the SW Moine drawn approximately along line XY in Figure 1, showing the westerly increase in the intensity of D_4 upright folding to form the Northern Highland Steep Belt (modified from Powell & Glendinning, 1988). Abbreviations: MT – Moine Thrust; KNT – Knoydart Thrust; SBT – Sgurr Beag Thrust; GS – Glenshian Synform; LEA – Loch Eilt Antiform; GDS – Glen Dessary Synform; SMA – Spidean Mialach Antiform; LQL – Loch Quoich Line; GGF – Great Glen Fault. Note (a) the infold of Loch Eil Group in the core of the Glen Dessary Synform; (b) the local emergence of Glenfinnan Group rocks adjacent to the Great Glen Fault (see Fig. 1).

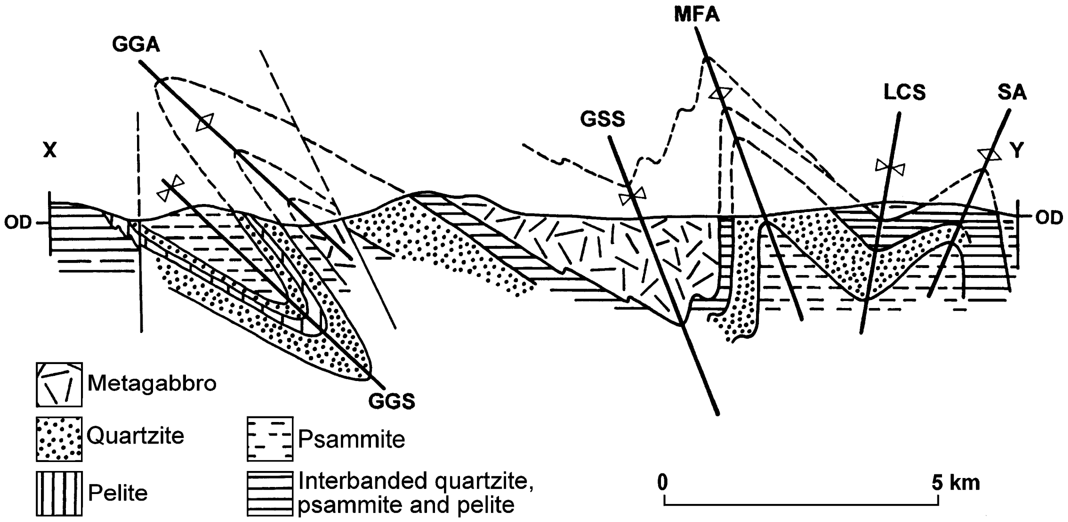

Figure 4. Composite cross-section across the Glen Scaddle Metagabbro and its Moine country rocks to illustrate the nature of the major D_3 folds and the structural setting of the intrusion in the core of the Glen Scaddle Synform (modified from Stoker, 1983). The intrusion carries a moderately to steeply dipping foliation that is axial-planar to the Glen Scaddle Synfom. Note that the Glen Gour Metagabbro to the southwest occupies a lower structural level, in the core of the D_3 Glen Gour Antiform. The Moine succession is right-way-up. See Figure 2 for line of section; abbreviations for folds as in Figure 2.

zircon: van Breemen *et al.* 1979; Roberts, Smith & Harris, 1984). An upper limit is apparently provided by a U–Pb monazite age of 450 ± 10 Ma obtained from a pegmatite sampled within the steep belt west of Glenfinnan and thought to pre-date upright folding (van Breemen, Pidgeon & Johnson, 1974). According to Powell & Phillips (1985), formation of the steep belt was followed by a prolonged period of post-tectonic cooling from *c.* 453 Ma to *c.* 405 Ma. The southern part of the steep belt is cut by the Strontian Granite that was intruded at 425 ± 3 Ma (Fig. 1; Rogers & Dunning, 1991). Most of the intrusion is unmetamorphosed and dominated by pre-full-crystallization magmatic fabrics (Hutton, 1988).

Reappraisal of this interpretation is appropriate because the Grampian event is now thought to have been short-lived (*c.* 480–465 Ma) and followed by very rapid exhumation (Oliver *et al.* 2000). Furthermore, Kinny *et al.* (2003) have demonstrated widespread Silurian ductile deformation and amphibolite-facies metamorphism in the Moines of central and west Sutherland. Upright folds of the steep belt in northern Ross-shire (Fig. 1) deform lineations within the Morar Group that have been correlated with the Silurian fabrics identified in central Sutherland (Kinny *et al.* 2003). Either regional correlations of structures are in error or the published upper limit on the age of the steep belt (van Breemen, Pidgeon & Johnson, 1974) is less robust than thought previously. In an effort to place further constraints on the age of upright folding, we now focus on the geology of eastern Ardgour, with particular reference to the structural setting and U–Pb geochronology of the Glen Scaddle Metagabbro (Fig. 1).

3. Geology of the Glen Scaddle Metagabbro

3.a. Structural setting and contact relationships

The Glen Scaddle Metagabbro intrudes the Moine rocks of the Loch Eil Group (Stoker, 1983; Strachan, 1985). In eastern Ardgour these comprise a varied succession of psammites and quartzites which are mostly right-way-up where sedimentary structures are present. The structure of eastern Ardgour is dominated by upright to moderately inclined, tight to close D_3 folds (Figs 2, 4). The Glen Scaddle Metagabbro occupies the core of a major D_3 fold, the Glen Scaddle Synform, flanked to the northeast by the D_3 Meall an Feidh Antiform and to the southwest by the D_3 Glen Gour Antiform (Figs 2, 4). A smaller intrusion, the Glen Gour Metagabbro, occupies the core of the Glen Gour Antiform (Fig. 4) and is apparently at a lower structural level than the Glen Scaddle Metagabbro.

The margins of the Glen Scaddle Metagabbro are broadly parallel to the regional composite $S_0/S_1/S_2$ foliation within host Moine psammites. Contacts with Moine rocks are generally concordant and sharp [e.g. NN 0050 6920]. Small xenoliths (10–50 cm) of Moine lithologies are locally common within the marginal facies of the intrusion [e.g. NM 9662 7004]. Within a narrow (0.75–1 km) aureole developed within the Moine rocks, regional metamorphic assemblages are overprinted by contact metamorphic minerals (Drever, 1940; Ashworth & Chinner, 1978). Quartz–feldspar–biotite rocks that are interpreted as nebulitic migmatites formed from the partial melting and mobilization of Moine lithologies are locally developed on the decametre scale along the northeast contact of the Glen Scaddle body [e.g. NM 9656 7012]. These are characterized by disoriented xenoliths of Moine psammites that apparently resisted melting, as well as zones of complex disharmonic folding.

3.b. Meta-igneous lithologies

The most common rock type is a medium- to coarse-grained, foliated metagabbro. Subordinate meta-igneous rock types range from ultrabasic to acidic in composition. Foliated hornblende peridotite and serpentinite were recorded by Drever (1940) from the margins of the Glen Gour and Glen Scaddle intrusions. Also present within the metagabbro are concordant metre-scale sheets of fine-grained hornblende schist and at least two phases of fine- to medium-grained granitic veins that are mainly developed on the centimetre–decimetre scale but can range up to 2–3 m in thickness. The earliest (meta)granitic veins are foliated and locally associated with hornblende schist; complex textures indicative of mingling between the two parent magmas are sometimes preserved [e.g. NM 9965 6856]. The later granitic veins are generally unfoliated and discordant, locally forming ramifying networks that cross-cut host meta-igneous lithologies.

3.c. Petrology and microfabrics

Relic igneous mineralogies and textures are best preserved in rare areas of low tectonic strain up to several hundred metres wide [e.g. River Scaddle, NM 9814 6818] and it is appropriate to describe these first before outlining the effects of superimposed deformation and metamorphism. In low strain zones, the metagabbro is essentially undeformed and typically consists of hypersthene, clinopyroxene, plagioclase ($An_{35–40}$) and amphibole with minor quartz, biotite and accessory ilmenite, titanite and apatite. Feldspars are rectangular and randomly oriented. Pyroxene is mostly replaced partially to completely by uralitic amphibole, and this is interpreted to be the result of late stage deuteric alteration within the igneous protolith (Stoker, 1983). Feldspar is commonly highly altered and sericitized. Sub-ophitic textures are common, as are symplectic intergrowths between pyroxene and plagioclase. The effects of apparently static metamorphism are represented by the recrystallization of amphibole into granoblastic aggregates of hornblende, and the growth of radiating mats of biotite. M. Stoker (unpub. Ph.D. thesis, Univ. Liverpool, 1980) recorded a local crude rhythmic layering in metagabbro [e.g. NM 9945 6850] shown by gradation of melanocratic to leucocratic gabbroic types on scales of up to several metres. Low strain areas of metagabbro locally contain metre-scale mafic enclaves [e.g. NM 9852 6827] and are intruded by undeformed granitic sheets.

Areas of low tectonic strain pass transitionally into the foliated metagabbro that forms the bulk of the intrusion. The relic igneous features described above are progressively replaced by a penetrative amphibolite-facies deformation fabric defined by aligned layers of intergrown hornblende and biotite that wrap augen of recrystallized plagioclase (Fig. 5). The mafic enclaves and the undeformed granites present in the low strain zones are interpreted as the protoliths of, respectively, the hornblende schists and the early foliated granitic veins within the foliated metagabbro. Within the hornblende schists, the foliation is defined by a penetrative alignment of fine-grained hornblende and recrystallized feldspar. The early granitic veins are characterized by an intense mylonitic fabric: classic mortar texture is displayed by ribbons of dynamically recrystallized quartz that wrap feldspar augen (Fig. 6). Feldspar porphyroclasts are sometimes fringed by myrmekite which is probably strain-induced (Fig. 6).

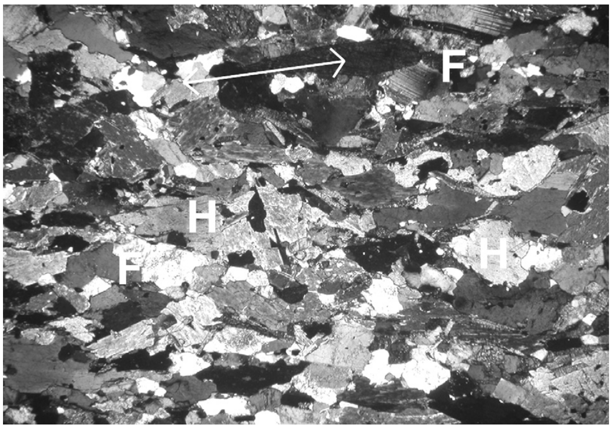

Figure 5. Photomicrograph of typical foliated metagabbro (horizontal field of view, 4 mm). F – feldspar, H – hornblende; double-headed arrow indicates orientation of foliation.

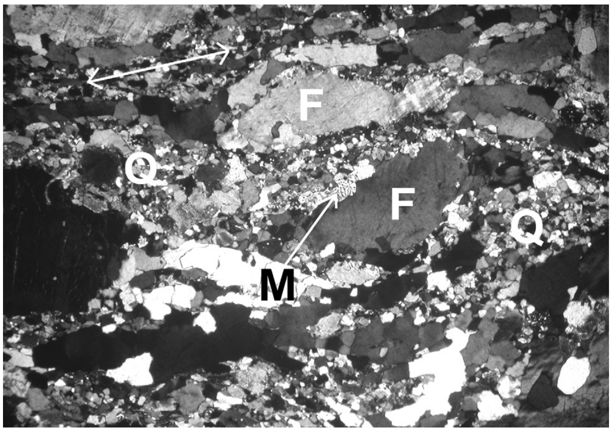

Figure 6. Photomicrograph of mylonitic granite sheet within the Glen Scaddle Metagabbro (field of view, 4 mm). Q – aggregates of dynamically recrystallized quartz, F – feldspar porphyroclasts, M – myrmekite; double-headed arrow indicates orientation of foliation.

3.d. Structure and age of emplacement

Along the margins of the Glen Scaddle Metagabbro, the foliation described above is broadly parallel to the contact with host Moine rocks. However, within the intrusion the foliation is more uniform in orientation, trending approximately NW–SE and dipping moderately to steeply to the northeast. A moderately plunging mineral and extension lineation is defined locally by alignment of hornblende–biotite aggregates and plagioclase augen [e.g. NM 9965 6856].

The following two observations establish that intrusion post-dated the early fabric-forming events D_1 and D_2. Firstly, within the aureole around the Glen Scaddle Metagabbro, syn-D_1 peak regional metamorphic assemblages are overprinted by contact metamorphic minerals, including sillimanite, biotite, plagioclase, quartz, K-feldspar, cordierite and andalusite which have been reported from various samples of pelite (Ashworth & Chinner, 1978; Stoker, 1983). Secondly, the intrusion locally incorporates xenoliths that contain isoclinal folds that are most probably D_2 in age [e.g. NM 9680 6835].

A pre-D_3 age of emplacement is consistent with the broad parallelism of the metamorphic foliation in the intrusion to the axial plane of the D_3 Glen Scaddle Synform, and the observation that contact metamorphic sillimanite is wrapped by the S_3 fabric (Stoker, 1983). Furthermore, the Glen Scaddle Synform is defined within the intrusion by the orientation of primary layering which is folded by NW-trending upright folds that are equated with the D_3 folds developed within the host Moine rocks (Stoker, 1983). Local structural complexity within the core of the synform is indicated by the observation that the foliation in the metagabbro and the mylonitic fabric within early granite veins are also locally deformed by tight, steeply plunging D_3 folds [e.g. NM 9965 6856]. M. Stoker (unpub. Ph.D. thesis, Univ. Liverpool, 1980) interpreted this complexity as indicating that D_3 was locally polyphase.

A pre-D_4 age of intrusion is certain because the foliation is deformed and crenulated by NE–SW-trending open folds that are correlated with regional folds of this age within the Moine country rocks. A mesoscopic D_4 fold pair deforms the Glen Gour body and the southeasternmost part of the Glen Scaddle Metagabbro (Fig. 2; Stoker, 1983).

3.e. Summary

It is therefore concluded, following Stoker (1983), that the Glen Scaddle Metagabbro was emplaced after D_2, probably as a series of sills that were concordant with the regional $S_0/S_1/S_2$ foliation within host Moine rocks. This foliation was probably flat-lying after D_2. The generalized gradation from ultrabasic rocks at the margins of the Glen Scaddle and Glen Gour intrusions to basic and acidic rocks centrally suggests that they may represent differentiated layered sheet intrusions. The intrusion was then deformed and metamorphosed during D_3 and D_4. The structural evidence therefore indicates that the Glen Scaddle Metagabbro is an important marker within the regional tectonometamorphic sequence; its age places a lower limit on the timing of regional upright folding and associated amphibolite-facies metamorphism.

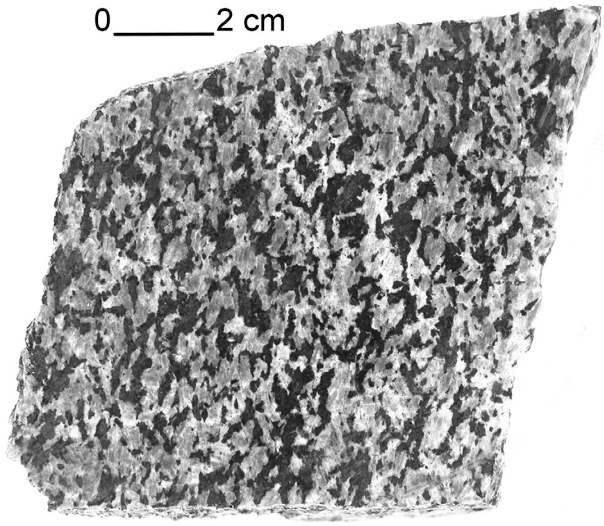

Figure 7. Hand specimen of foliated metagabbro sampled for isotopic dating in this study.

4. U–Pb geochronology

4.a. Sample preparation procedure and analytical techniques

The sample analysed was a medium-grained, foliated metagabbro (Fig. 7) collected from the River Scaddle [NN 0004 6869]. A sample of 30 kg was crushed and milled, and the less than 400 μ fraction sieved out. Heavy mineral concentrations were obtained using a Gemini shaking table, followed by a superpanner. A separate, with specific gravity greater than 3.3 gm ml^{-1}, was recovered using Di-iodomethane. The minerals were then separated magnetically using a Frantz LB-1 magnetic separator. The recovered zircons from the non-magnetic $\sim$ 1.8 Amp fraction were hand-picked under alcohol and abraded. The majority of the zircons in the sample were fragments of quite large grains (about 150 μ length). The fragments were predominantly clear with sharp terminations and edges where visible. A few showed elongate melt inclusions and these were avoided during picking.

U and Pb separations followed the procedures of Krogh (1973) with minor modifications of Corfu & Ayres (1984). Zircon grains were analysed on a VG 354 mass spectrometer at the NERC Isotope Geosciences Laboratory following the procedures of Noble, Tucker & Pharaoh (1993). Chemistry blanks were $\sim$ 5 pg, and these were monitored in each batch of chemistry.

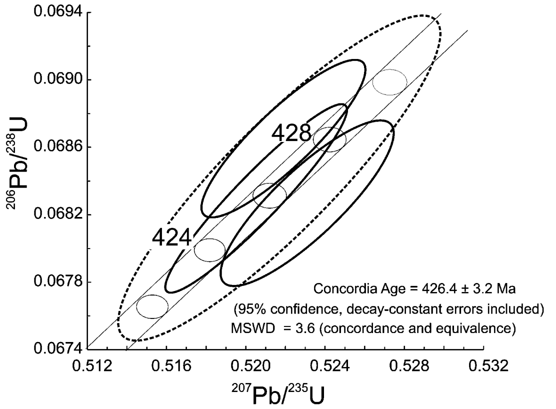

Figure 8. U–Pb concordant ages from the Glen Scaddle metagabbro. The MSWD is of concordance and equivalence at 2σ and takes into account errors on the decay constant. The labelled ellipse is the weighted mean error ellipse of the three data points.

Uranium blanks contained < 0.1 pg U. All results and errors were calculated following the methods of Ludwig (1993, 1994), and the Pb isotope ratios were corrected for initial common Pb in excess of laboratory blank using the model of Stacey & Kramers (1975). Ages were calculated using the decay constants of Jaffey *et al*. (1971).

4.b. Results

Three zircon fractions plot either on or close to concordia and give an age of 426 ± 3 Ma (Fig. 8; Table 1). This age is interpreted to date closely igneous crystallization of the Glen Scaddle Metagabbro.

5. Discussion

5.a. Age of polyphase upright folding in the SW Moine

The U–Pb zircon age of 426 ± 3 Ma reported here for the emplacement of the Glen Scaddle Metagabbro suggests that this intrusion is a basic member of the late Caledonian ‘Newer Granite’ suite (Read, 1961; Stephenson *et al*. 1999, and references therein). More importantly, in combination with the structural history outlined here, as well as the 425 ± 3 Ma age for the Strontian Granite located only a few kilometres to the south, it implies a very different regional tectonometamorphic history for the Moine Supergroup in West Inverness-shire and Ross-shire to that currently published. Regional-scale D_3–D_4 upright folding, including the formation of the Northern Highland Steep Belt, must have occurred during a relatively short (Scandian) orogenic event. Western parts of the Strontian Granite are overprinted by locally developed steep, N–S-trending solid-state deformation fabrics (Hutton, 1988), and it is therefore possible that granite emplacement overlapped final stages of D_4 folding.

Table 1. U–Pb data for zircon from the Glen Scaddle Metagabbro

Fraction code	[1]Weight (μg)	[2]U (ppm)	[2]Pb (ppm)	Total Pb (pg)	^{206}Pb/^{204}Pb[3]	^{208}Pb/^{206}Pb[3]	^{206}Pb/^{238}U[3]	± %	^{207}Pb/^{235}U[3]	± %	^{207}Pb/^{206}Pb[3]	± %	^{207}Pb/^{206}Pb[4]	± Ma	Rho[5]
GSM-03-a	5.0	408	29.34	15	49225	0.1669	0.0683	0.69	0.52046	0.74	0.05528	0.26	423	6	0.94
GSM-03-b	8.0	307	24.02	17	5073	0.2543	0.0686	0.57	0.52189	0.64	0.05514	0.28	418	6	0.90
GSM-03-c	10.0	659	51.58	12	3800	0.2570	0.0683	0.59	0.52307	0.69	0.05557	0.35	435	8	0.86

(1) All analyses picked from non magnetic at 1.8 Amp fraction of zircons. (2) Sample weights and hence U and Pb concentrations are approximate. (3) Measured ratios are corrected for fractionation and common Pb spike. (4) Corrected for fractionation, spike, laboratory blank and initial common Pb calculated at 427 Ma (Stacey & Kramers, 1975). (5) Correlation coefficients of ^{207}Pb/^{235}Pb and ^{206}Pb/ ^{238}U are calculated using procedures and algorithms of (Ludwig, 1993). Errors for the measured ratios are propagated through data reduction and quoted at the 2 sigma level.

A younger age for regional upright folding than the Ordovician age proposed previously resolves the apparently contradictory structural relationships in Ross-shire, where steep belt folds deform structures assigned to the Scandian event (Kinny *et al.* 2003). However, a Silurian age for the formation of the Northern Highland Steep Belt is in contradiction to the U–Pb monazite age of 450 ± 10 Ma obtained from a pegmatite west of Glenfinnan that was interpreted to post-date upright folding (van Breemen, Pidgeon & Johnson, 1974). The exact significance of this age is difficult to evaluate, partly due to the lack of a detailed field description of the dated pegmatite and its structural setting, but also because of the possibility that the dated monazites included an unrecognized inherited component. We consider the new age constraints reported here on the age of regional upright folding more reliable, although the structural setting and age of pegmatites within the steep belt clearly deserves reinvestigation.

5.b. Implications for late-orogenic displacements along the Great Glen Fault

A Silurian age for regional, polyphase upright folding and associated amphibolite-facies metamorphism of the Moine Supergroup is consistent with the current model for Caledonian orogenic activity in the Northern Highland terrane, involving Grampian (470–460 Ma) and Scandian (435–425 Ma) events (Kinny *et al.* 1999, 2003; Friend, Jones & Burns, 2000; Dallmeyer *et al.* 2001). The new evidence reported here, in combination with the findings of Kinny *et al.* (2003), demonstrates widespread reworking of Grampian structures and metamorphic assemblages during the Scandian event. This culminated in development of the Moine Thrust Zone and emplacement of the Moine rocks onto the Laurentian foreland. The Northern Highland Steep Belt is thought to have formed at the same time and presumably detaches at depth on a ductile thrust zone, probably the Moine Thrust (Barr, Holdsworth & Roberts, 1986).

The tectonothermal history detailed above is in marked contrast to that recorded by the Dalradian Supergroup southeast of the Great Glen Fault, where the main phases of folding and associated regional metamorphism are assigned entirely to the Ordovician Grampian orogenic event. The present consensus is that the peak of Grampian metamorphism in the Dalradian rocks occurred at *c.* 470 Ma and was followed by cooling and uplift relatively soon thereafter at *c.* 460 Ma (Dempster, 1985; Dempster, Hudson & Rogers, 1995; Dempster *et al.* 2002; Soper, Ryan & Dewey, 1999; Oliver *et al.* 2000; Oliver 2001; Baxter, Ague & DePaulo, 2002). As yet, there is no evidence that the Dalradian Supergroup was affected by regionally significant Silurian deformation or metamorphism. The conclusions reported here therefore reinforce tectonic models that invoke a minimum of 700 km of late Caledonian (425–390 Ma?) sinistral movement along the Great Glen Fault in order to juxtapose the Grampian and Northern Highland terranes following the Scandian collision between Baltica and the Northern Highland segment of eastern Laurentia (Dewey & Strachan, 2003; Kinny *et al.* 2003).

6. Conclusions

(1) The Glen Scaddle Metagabbro forms a valuable time marker within the Northern Highland Terrane of the Scottish Caledonides because its age places a lower limit on the timing of regional upright folding and associated amphibolite-facies metamorphism.

(2) The intrusion has yielded a U–Pb zircon age of 426 ± 3 Ma that is interpreted to date its igneous crystallization.

(3) Regional-scale D_3 and D_4 upright folding of the intrusion and its Moine host rocks, including formation of the Northern Highland Steep Belt, occurred during a relatively short Silurian (= Scandian) orogenic event. Final stages of D_4 deformation may have overlapped emplacement of the Strontian Granite, dated previously at 425 ± 3 Ma.

(4) The data reported here provide further evidence for widespread Silurian ductile deformation and amphibolite-facies metamorphism northwest of the Great Glen Fault; the apparent absence of this orogenic event within the adjacent Grampian Terrane reinforces arguments that this structure separates crustal blocks with contrasting Caledonian tectonothermal histories.

(5) These differences support tectonic models that invoke a minimum of 700 km late Caledonian sinistral movement along the Great Glen Fault in order to juxtapose the Grampian and Northern Highland terranes following the Scandian collision.

(6) This study therefore shows how comparison of the varying intensities of deformational events across an orogen can be used to reconstruct original collisional templates and constrain likely displacements along late-orogenic transcurrent faults.

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