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Geochemistry, petrogenesis and structural setting of the meta-igneous Strathy Complex: a unique basement block within the Scottish Caledonides?

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Abstract – The Strathy Complex of the Scottish Caledonides is a bimodal association of amphibolites and siliceous grey gneisses that structurally underlies adjacent metasediments of the Moine Supergroup. Both rock units record a common polyphase Caledonian tectonometamorphic history. New elemental and radiogenic isotope data indicate that both end-members of the Strathy suite were derived from a depleted mantle source, that they are cogenetic and that they may have been related by crystal fractionation. $\delta^{18}O$ values and their correlations with major and trace elements suggest that the protoliths were hydrothermally altered at temperatures below 200 °C. Tectonomagmatic discrimination based on relatively immobile elements and isotope systems, plus comparison with geochemically similar bimodal supracrustal associations elsewhere, strongly support the conclusion that the igneous protoliths of the Strathy Complex formed in an oceanic destructive margin setting. If T_{DM} model ages of *c.* 1000 Ma approximate protolith crystallization, the Strathy Complex may have formed as juvenile crust in the peri-Rodinian ocean broadly contemporaneous with the Grenville orogenic cycle.

Keywords: bimodal, volcanic, hydrothermal, Moine, Grenville.

1. Introduction

Definition of past tectonic settings is a major goal of petrological investigation, usually based on analogy with similar rocks currently observed in the present tectonic regime. Interpretations become increasingly speculative as the degree of geological reworking increases, such that in many polymetamorphic terrains there is ample room for protracted debate. Geochemical investigations have much to contribute, and there is a well-established framework of diagnostic elemental criteria for the recognition of past geodynamic settings. Stable and radiogenic isotopes are often used to refine conclusions based on elemental work, to provide age constraints and to elucidate petrogenetic processes. Such techniques are applied here to the enigmatic meta-igneous rocks of the Strathy Complex in the Ordovician–Silurian Caledonian orogenic belt of the Scottish Highlands.

The Caledonian orogenic belt of the Scottish Highlands is dominated by two thick Neoproterozoic metasedimentary successions. The Moine Supergroup crops out in the Northern Highland Terrane to the northwest of the Great Glen Fault and was deposited between *c.* 1000 Ma and *c.* 870 Ma (Friend *et al.* 1997, 2003). To the southeast of the Great Glen Fault, in the Grampian Terrane, the younger Dalradian Supergroup was deposited between the mid-Neoproterozoic (*c.* 750 Ma?) and the Lower Ordovician (Soper, Ryan & Dewey, 1999, and references therein). The basement rocks on which these metasedimentary successions were deposited are only infrequently exposed but provide important insights into the pre-Neoproterozoic crustal evolution of this part of Laurentia. The meta-igneous Strathy Complex is located within the Caledonian thrust sheets of north Sutherland (Fig. 1). A probable basement origin for the complex was first proposed by Harrison & Moorhouse (1976) and Moorhouse (V. E. Moorhouse, unpub. Ph.D. thesis, Univ. Hull, 1979), who highlighted the characteristic incompatible element depletion. Moorhouse & Moorhouse (1983) suggested that the complex originated as a dacitic supracrustal sequence whose unusual geochemistry was the result of pervasive melt extraction during amphibolite facies metamorphism. This paper revisits the complex, first summarizing new information relating to its structural and metamorphic history. The available geochemistry is extended to include REEs (rare earth elements), and radiogenic and stable isotopes, and these data are interpreted in

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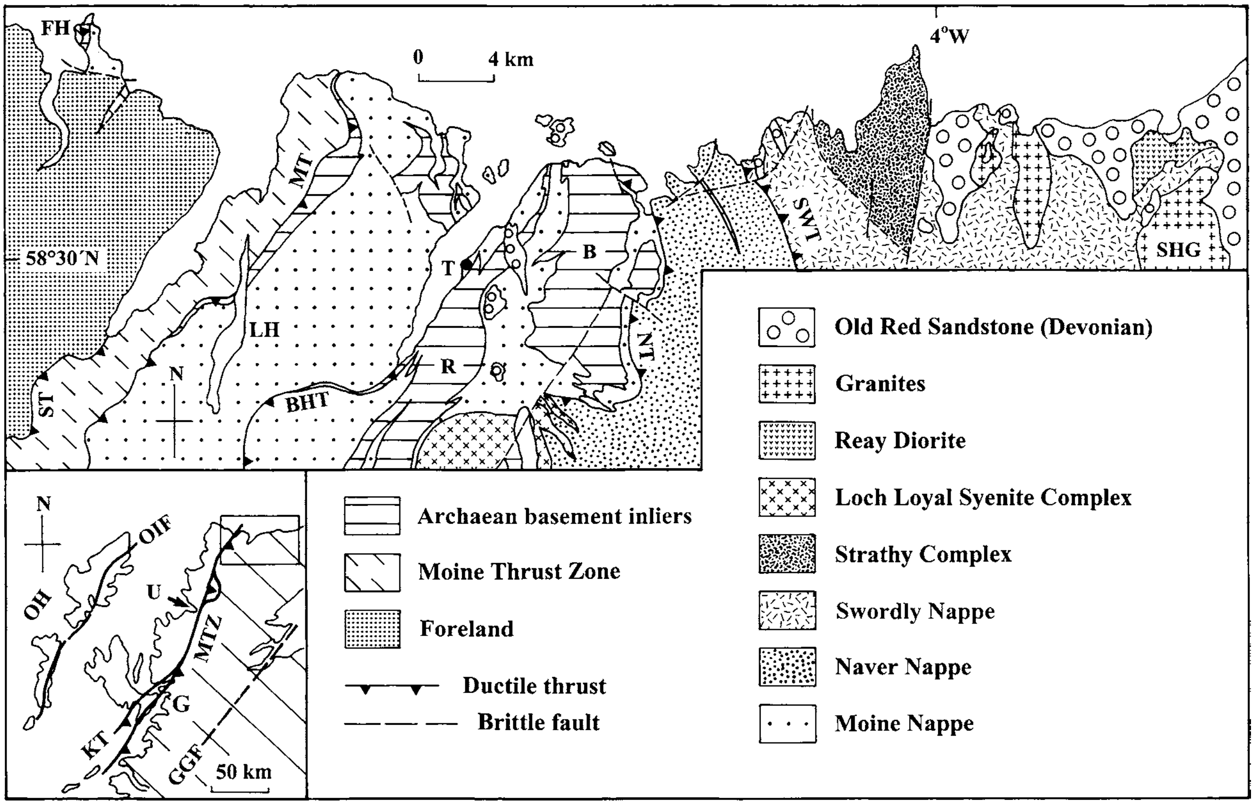

Figure 1. Geological map of north Sutherland. Inset shows position of north Sutherland (outlined) relative to other sectors of the Caledonian belt in Scotland. FH, Faraid Head; LH, Loch Hope; T, Tongue; U, Ullapool; G, Glenelg; OH, Outer Hebrides; R, Ribigill basement inlier; B, Borgie basement inlier; ST, Sole Thrust; MT, Moine Thrust; MTZ, Moine Thrust Zone; BHT, Ben Hope Thrust; NT, Naver Thrust; SWT, Swordly Thrust; OIF, Outer Isles Fault Zone; KT, Kishorn Thrust; GGF, Great Glen Fault; SHG, Strath Halladale Granite.

the context of current geodynamic discriminators (e.g. Pin & Paquette, 1997).

2. Regional geology

The Moine Supergroup of northern Scotland comprises a thick sequence of metasedimentary rocks that is tectonically bounded to the west and southeast by the Moine Thrust and the Great Glen Fault, respectively (Fig. 1; Holdsworth, Strachan & Harris, 1994). It is divided into the Morar, Glenfinnan and Loch Eil groups, and sedimentological analysis indicates deposition under shallow-marine conditions (Strachan, 1986; Glendinning, 1988). Deposition is thought to have occurred in two half-graben that formed during a period of extensional rifting of the Neoproterozoic Rodinian supercontinent (Soper, Harris & Strachan, 1998; Dalziel & Soper, 2001). Infolds and tectonic slices of orthogneisses are generally believed to represent fragments of the Laurentian basement on which the Moine rocks were deposited (Holdsworth, Strachan & Harris, 1994). Three basement inliers in north Sutherland have yielded Archaean protolith ages (U–Pb zircon: Friend, Kinny & Strachan, unpub. data). The Moine rocks were intruded by numerous minor (meta)basic igneous sheets that display a MORB-like tholeiitic chemistry (Moorhouse & Moorhouse, 1979; Winchester, 1984; Winchester & Floyd, 1983; Rock *et al.* 1985; Millar, 1999). Although it is clear that the basic sheets were not emplaced within an oceanic setting *sensu stricto* (the host Moine rocks were apparently deposited on Archaean basement), the chemistry is thought to reflect intrusion into thinned continental crust during extension and rifting.

Detrital zircons that have yielded U–Pb SHRIMP ages of *c.* 1000 Ma define a maximum age of deposition for the Moine Supergroup (Friend *et al.* 1997, 2003). A minimum depositional age is provided by the *c.* 870 Ma age of the intrusive West Highland Granite Gneiss, although whether this body was emplaced during orogenesis (Friend *et al.* 1997; Rogers *et al.* 2001) or continental rifting (Soper & Harris, 1997; Dalziel & Soper, 2001) is controversial. The Moine rocks were subsequently affected by Knoydartian orogenic activity at *c.* 800 Ma (Rogers *et al.* 1998; Vance, Strachan & Jones, 1998). Caledonian orogenesis (*s.l.*) in the North Atlantic region was associated with the closure of the Iapetus Ocean during the Ordovician–Silurian and the convergence of three crustal blocks: Laurentia, Baltica and Avalonia (e.g. Soper & Hutton, 1984; Pickering, Bassett & Siveter, 1988; Soper *et al.* 1992; Dewey & Strachan, 2003). Early orogenic activity

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along the Iapetan margins of both Laurentia and Baltica resulted from arc–continent collisions that occurred during initial oceanic closure in the early to middle Ordovician, followed by final amalgamation of crustal blocks in the late Silurian. In the Scottish Highlands, the Ordovician arc–continent collision is referred to as the Grampian event (Lambert & McKerrow, 1976; McKerrow, MacNiocaill & Dewey, 2000), and the Silurian continent–continent collision as the Scandian event (e.g. Strachan *et al.* 2002; Kinny *et al.* 2003).

The Moine rocks of north Sutherland comprise three main thrust sheets, the Moine, Naver and Swordly nappes (Fig. 1; S. J. Moorhouse, unpub. Ph.D. thesis, Univ. Hull, 1977; Moorhouse & Moorhouse, 1983; Strachan & Holdsworth, 1988; Moorhouse & Moorhouse, 1988; Moorhouse, Moorhouse & Holdsworth, 1988). Moine rocks within the structurally lowest Moine Nappe are mainly unmigmatized psammites which locally preserve sedimentary structures. The Naver and Swordly nappes are dominated by strongly deformed, migmatized psammitic and semipelitic gneisses. Tectonic interleaving of Moine metasediments and Archaean basement gneisses occurred during Caledonian thrusting and folding (Holdsworth, 1989; Strachan & Holdsworth, 1988; Holdsworth, Strachan & Alsop, 2001). There is evidence for two main Caledonian events in north Sutherland. The earliest corresponds to the Grampian event and was associated with deformation and regional migmatization of the Moine rocks of the Naver and Swordly nappes at *c.* 470–460 Ma (Kinny *et al.* 1999). Regional nappe stacking, widespread folding and accompanying amphibolite facies metamorphism occurred later in the Scandian event at *c.* 435–425 Ma (Dallmeyer *et al.* 2001; Kinny *et al.* 2003).

The Strathy Complex crops out within the Swordly Nappe (Fig. 1). The outcrop of the complex corresponds to a prominent magnetic anomaly that is terminated 9 km offshore, possibly by an ENE-trending fault. The meta-igneous rocks of the complex are very different, both lithologically and chemically, from the undoubted Moine and associated basement inliers elsewhere in north Sutherland (Harrison & Moorhouse, 1976; V. E. Moorhouse, unpub. Ph.D. thesis, Univ. Hull, 1979; Moorhouse & Moorhouse, 1983). The complex has been described as being bounded by late, brittle faults and to have been 'faulted into' the Moine rocks (Moorhouse & Moorhouse, 1983), although subsequent interpretations depicted the west margin of the complex as corresponding to a major ductile thrust (Moorhouse & Moorhouse, 1988; Moorhouse, Moorhouse & Holdsworth, 1988).

3. The Strathy Complex: lithologies, petrology and field relations

The Strathy Complex is dominated by mainly K-feldspar-free, siliceous grey gneisses with subordinate hornblende gneiss, rare ultramafic units, garnet/staurolite/sillimanite gneiss and marble (Fig. 2). The complex was intruded at a late stage by numerous cross-cutting trondhjemitic pegmatites and a subordinate suite of slightly discordant foliated amphibolites, most likely during the Caledonian orogenic cycle. Brief descriptions of the main lithologies follow and supplement those provided by Moorhouse & Moorhouse (1983).

3.a. Siliceous gneiss

Siliceous gneisses comprise $> 70\,\%$ of the complex (Fig. 2). They vary from centimetre-scale layers interbanded with concordant amphibolite through to metre-wide, homogeneous, regularly foliated layers. No sedimentary structures have been observed. They are medium-grained, pink/grey, sub-granoblastic to foliated and the rare banding (millimetre- to centimetre-scale) in the massive layers is usually poorly defined. Quartz-feldspar ribbons and aggregates define a mineral stretching lineation. Small compositional differences and gneissic banding are defined by modal variations in the assemblage (average values in parentheses) quartz (47 %), plagioclase (oligoclase/low-labradorite, 40 %) and biotite (10 %) $\pm$ garnet. The only regional variation is a slight eastward increase in biotite content (up to *c.* 17 %). Aligned biotite ($\pm$ amphibole) defines the foliation within a granoblastic groundmass of sub-grained quartz, and plagioclase. In many gneisses, late idioblastic biotite randomly overprints the early fabric. Garnet is usually very fine-grained (*c.* 0.2 mm) and fresh, although larger porphyroblasts (up to 1 cm) occur rarely, and these exhibit variable states of retrogression. Within centimetres, siliceous gneiss may grade into a more mafic variety containing up to 10 % medium-grained, green hornblende or cummingtonite, aligned parallel to the biotite foliation. In thin-section, sub-xenoblastic cummingtonite appears as colourless/light brown and simply twinned laths or as alteration from hornblende at margins and along cleavage planes. Any garnet in these more mafic gneisses is generally larger and often slightly retrogressed. Accessory phases are common and well developed in siliceous gneiss with titanite often overgrowing allanite, and magnetite, ilmenite and pyrite all common.

The siliceous gneisses differ from local Moine rocks because of their high quartz and plagioclase content in the absence of K-feldspar. The presence of cummingtonite is also distinctive as is a high (up to 4 %) ore content which is thought to contribute to the marked aeromagnetic anomaly characteristic of the complex.

3.b. Concordant amphibolite

An integral part of the Strathy Complex is a suite of concordant amphibolites (Fig. 2) that also grade into

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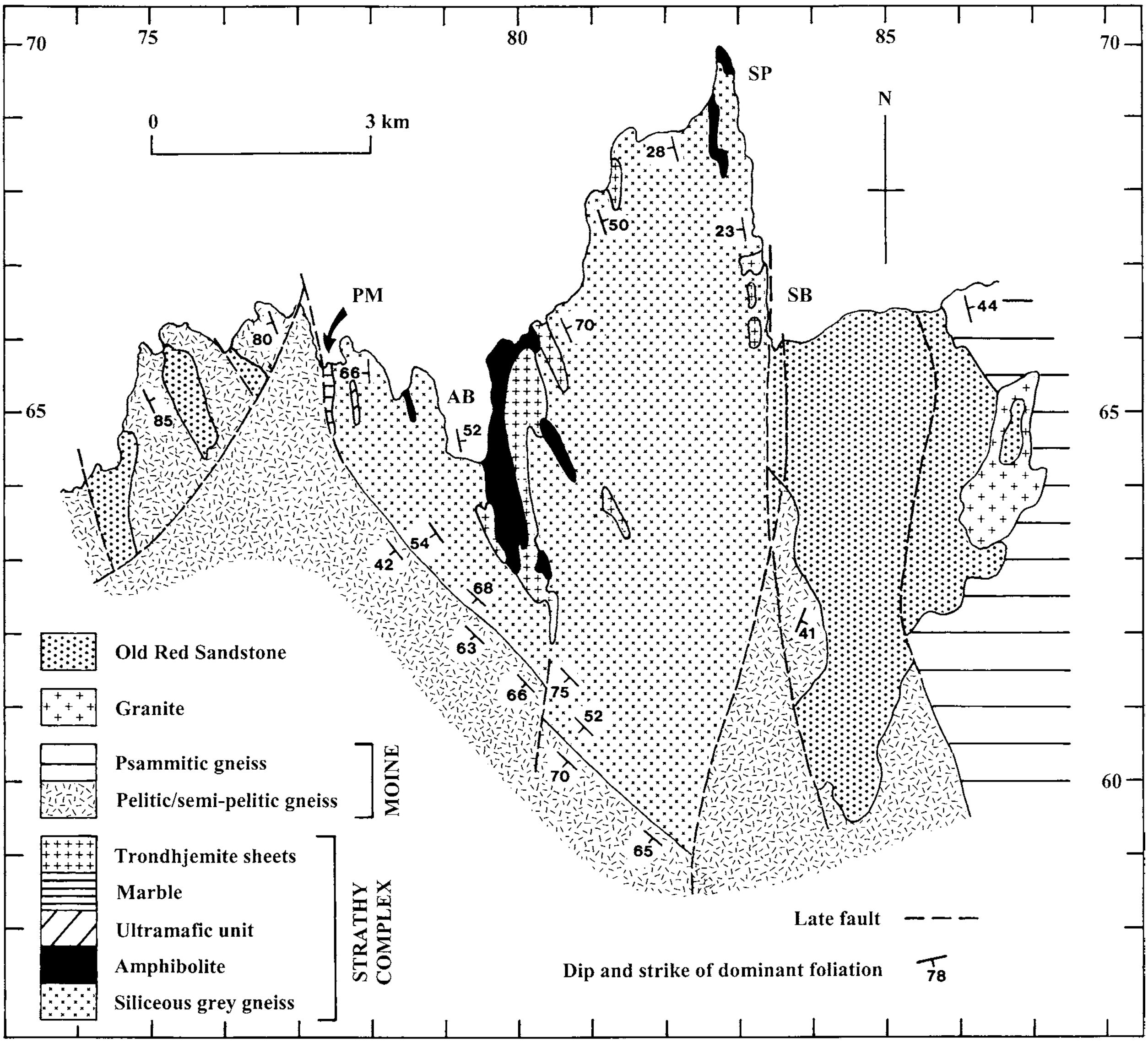

Figure 2. Simplified geological map of the Strathy Complex and adjacent Moine rocks of the Swordly Nappe (modified from British Geological Survey, 1996, and also using unpublished data from RAS). PM, Port Mor; AB, Armadale Bay; SB, Strathy Bay; SP, Strathy Point.

hornblende- and cummingtonite-bearing gneiss. These generally have sharp contacts with the siliceous gneiss, although gradational relationships (over centimetres) have been recognized. The dominant variety is dark green/black, medium-grained and strongly foliated (rarely banded) and occurs as sheets throughout the complex. These vary from a few centimetres to 1–2 m thick, usually exhibit lateral thickness continuity and can occur individually, as swarms or in such a density that siliceous gneiss becomes subordinate (e.g. east side of Armadale Bay, Fig. 2). Any compositional differences are defined by variations in the modal assemblage (average values in parentheses) quartz (3 %), plagioclase (43 %), green hornblende (46 %), brown biotite (5 %), + titanite, zircon, ore ± cummingtonite, rutile, garnet, epidote, apatite, chlorite + calcite. Plagioclase is oligoclase/andesine and aligned biotite and hornblende define the strong foliation. Cummingtonite, commonly coexisting with green hornblende, is common in the more leucocratic amphibolites (up to *c.* 50 % quartz and feldspar). Subidioblastic titanite (commonly overgrowing allanite or ore) and ore phases are small (< 1 mm) yet numerous. Virtually unaltered amphibolites may have subordinate, late, randomly oriented biotite laths overgrowing the main foliation. A stable mineral assemblage of plagioclase, hornblende and biotite (± quartz and garnet) is only rarely recorded because of extensive alteration; many amphibolites are partly altered to chlorite schists (e.g. east side of Armadale Bay). In these rocks, hornblende is replaced by biotite (itself often altered to chlorite/Fe opaque phases) and plagioclase and

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hornblende are pseudomorphed or replaced at rims and along cleavage planes by calcite. Abundant epidote veins and clots are also common.

Very coarse-grained garnetiferous amphibolites (restricted to the east side of Armadale Bay) occur as discrete bodies (up to 3 m thick) and are only weakly foliated or banded. Any compositional differences are defined by variations in the modal assemblage of plagioclase, quartz, garnet, gedrite ± biotite, ore and chlorite. These amphibolites differ from any described previously in that gedrite (often replaced and pseudomorphed by chlorite) is the amphibole present. In the largest body of this type (Ard a' Mhinn Ghlais), very large (up to 7 cm long) garnet porphyroblasts have grown syn-kinematically during folding and large scale S-C fabric development. They are not retrogressed and commonly contain parallel ribbons of quartz (up to 2 mm wide), which occur along the length of the porphyroblasts but do not extend into, and only rarely occur in, the coarse-grained, gedrite-rich groundmass.

3.c. Marble

Bands of marble crop out along the eastern side of Port Mor (Fig. 2, [NC 7750 6497]). The marble is a white/grey, medium-grained, foliated and granular-weathered lithology with compositional differences defined by variations in the modal assemblage calcite, diopside, scapolite, quartz, epidote, titanite, biotite, apatite and ore. Concordant green calc-silicate bands contain abundant diopside, scapolite and altered plagioclase.

3.d. Ultramafic rock

This rock type crops out approximately 500 m east of Port Mor [NC 7784 6532], as an isolated vivid green body that is dominated by coarse-grained anthophyllite with small amounts of plagioclase and subordinate retrogressed clinopyroxene. Contacts with adjacent siliceous gneiss are unexposed, but its geometry is inferred to be lensoid (*c.* 225 × 40 m). A weak foliation is parallel to the inferred margins that are sub-parallel to the structural grain in the host grey gneisses.

3.e. Garnet–staurolite–sillimanite gneiss

The only occurrence of this rock type is as a boudin (*c.* 6 m × 2 m) situated in the eastern foundations of Strathy Lighthouse [NC 8282 6964], and it is the only lithology that contains a thermobarometrically useful mineral assemblage. It is a medium- to coarse-grained, semi-leucocratic, foliated, porphyroblastic rock with compositional differences defined by variations in the assemblage quartz, plagioclase (An_{47-63}), garnet, staurolite, sillimanite, anthophyllite, brown and green biotite, spinel (gahnite), apatite, zircon, rutile, ilmenite and chlorite.

4. Metamorphic and deformation history

The complex records three distinct phases of deformation and amphibolite facies metamorphism (I. M. Burns, unpub. Ph.D. thesis, Oxford Brookes Univ. 1994). The oldest fabrics and mineral assemblages are preserved within the garnet–staurolite–sillimanite gneiss boudin exposed beneath Strathy Lighthouse. A steep S1 gneissic fabric is oriented at *c.* 90° to the subhorizontal enveloping gneissosity in host siliceous grey gneisses. Peak metamorphic conditions within the boudin have been estimated (I. M. Burns, unpub. Ph.D. thesis, Oxford Brookes Univ. 1994) at *c.* 700 °C and 6 kbar, by a combination of garnet–biotite Mg/Fe exchange thermometry (Ferry & Spear, 1978) and the garnet–Al silicate–quartz–plagioclase barometer (Newton & Haselton, 1981). D2 deformation created the dominant composite S1/S2 gneissic fabric within the complex. F2 folds are tight to isoclinal in style, and their axes are commonly parallel to a N- to NNW-trending L2 mineral and extension lineation. This linear fabric is inferred to lie parallel to the direction of tectonic transport, although kinematic indicators are developed only rarely and are inconsistent. Upright to inclined, N- to NNW-trending, tight to open F3 folds deform all pre-existing structures and developed under lower amphibolite facies conditions (I. M. Burns, unpub. Ph.D. thesis, Oxford Brookes Univ. 1994).

5. Structural setting

Previous descriptions and published maps have depicted the Strathy Complex as being bounded entirely by steep, brittle faults. To the east, a steep, normal fault indisputably separates the Strathy Complex from post-Caledonian Old Red Sandstone (Devonian) sedimentary rocks (Fig. 2). To the west, at Port Mor, a steep, normal fault separates the complex from the Moine migmatites of the Swordly Nappe [NC 7750 6497] and this fault was extrapolated southwards along the largely unexposed western margin of the complex (V. E. Moorhouse, unpub. Ph.D. thesis, Univ. Hull, 1979; Moorhouse & Moorhouse, 1983; British Geological Survey, 1996). However, this contact was later reinterpreted by Moorhouse & Moorhouse (1988) as a steep, west-directed ductile thrust that they correlated with the regionally significant Sgurr Beag Thrust within the Moine rocks of Inverness-shire and Ross-shire (Fig. 1).

Recent mapping (by RAS) has shed further light on the nature of the critical western boundary of the Strathy Complex. Although this boundary is certainly defined by a brittle, normal fault on the coast at Port Mor, there is no compelling reason to extrapolate this fault inland for more than a few hundred metres. Along the entire length of the western boundary, siliceous grey gneisses of the Strathy Complex dip moderately to steeply (45–75°) to the southwest, beneath the Moine migmatites (Fig. 2). The actual contact between the two rock units is nowhere exposed, although it can be narrowed down to within a few metres in the Allt Beag stream [NC 7850 6305], just south of the A836 road. Here, the contact does not appear to be associated with any significant increase in ductile strain. Although both Strathy Complex and Moine lithologies are locally strongly foliated, they do not contain any of the structural features that might be expected if the contact represented a regionally significant ductile shear zone (e.g. well-developed lineations, kinematic indicators, extensive blastomylonites). The ductile strain shown by the lithologies adjacent to the contact is no more intense than might be expected from regional metamorphism, given the probable rheological contrast between the siliceous gneisses and the semi-pelitic Moine migmatites. For these reasons, the original interpretation of Harrison & Moorhouse (1976), that the Strathy Complex is essentially autochthonous relative to the structurally overlying Moine rocks of the Swordly Nappe, is preferred.

An autochthonous setting for the Strathy Complex implies that it should share a common deformational and metamorphic history with the adjacent Moine gneisses. In both rock units, the earliest structures are represented by S1 gneissic fabrics that in the Moine are accompanied by rare isoclinal minor folds. Correlation of these D1 structures is problematic in the absence of, for example, comparable lineation trends and/or similar syn-D1 metamorphic assemblages in both rock units. However, there are good reasons for correlating the D2 and D3 structures within the two units. D2 deformation in the Moine rocks of the Swordly Nappe is represented by widespread tight-to-isoclinal minor folding and development of a N-trending L2 mineral and extension lineation (I. M. Burns, unpub. Ph.D. thesis, Oxford Brookes Univ. 1994; British Geological Survey, in press; Strachan, unpub. data). These structures developed during regional migmatization that has been dated as middle Ordovician (U–Pb zircon: Kinny *et al.* 1999), and compare closely in their geometry and orientation with the D2 structures in the Strathy Complex. The absence of textural evidence for widespread syn-D2 melting within the Strathy Complex is attributed to the highly siliceous, K-feldspar-free composition of the grey gneisses (I. M. Burns, unpub. Ph.D. thesis, Oxford Brookes Univ. 1994). The Moine rocks were subsequently deformed by tight, upright, NNW-trending D3 folds which are co-planar with the D3 folds in the Strathy Complex. The age of D3 deformation is not constrained by isotopic evidence in this part of the nappe pile, but on regional grounds it seems likely to have occurred during Silurian ductile thrusting and nappe stacking (Kinny *et al.* 2003). Therefore, the Strathy Complex and the Moine rocks probably share a common, polyphase Ordovician–Silurian (Caledonian) tectono-metamorphic evolution, although correlation of the earliest deformational and metamorphic events is equivocal.

6. Geochemistry

Given the polyphase deformation and high-grade metamorphism recorded by the complex, geochemistry offers the only route to understanding its petrogenesis. Moorhouse & Moorhouse (1983) discussed an extensive X-ray fluorescence whole-rock database, demonstrating the elemental differences from the surrounding Moine metasediments. They also noted some similarities with the Lewisian Complex of the Caledonian foreland, especially in low abundances of K_2O and Rb, but recognized equally important elemental differences such as low CaO and high Y. The characteristic elemental signature of the siliceous gneisses was attributed to two phases of anatexis, removing K, Rb and Ba in the first and further Ba plus Sr during the second (Moorhouse & Moorhouse, 1983). Additionally, the calc-alkaline trend of the Strathy Complex rocks was demonstrated, in contrast with tholeiitic or mildly alkaline trends for other amphibolite groups in the Sutherland Moine (Moorhouse & Moorhouse, 1979). In this study, representative samples of siliceous gneisses and concordant amphibolites have been analysed for a wider range of elemental and isotopic parameters, to include comprehensive REE coverage, Nd and O isotopes.

6.a. Analytical techniques

Large and fresh samples were split, jaw-crushed and reduced to powder in a tungsten carbide shatterbox. Major elements were determined by ICPAES at Oxford Brookes University by fusion dissolution followed by analysis against calibrations defined with international standard rock materials (SRMs). Accuracy and precision are estimated to be better than 2–3 % RSD. Rare earth elements and Be were also analysed by ICPAES at Oxford Brookes University using natural rock standards, the former following cation-exchange preconcentration. Rb, Sr, Ba, Y, Zr, Nb, Cr, Co, Ni, Cu, Zn and Pb were analysed by XRF at the British Geological Survey (BGS), again calibrated and assessed with international SRMs. Accuracy and precision of all the trace element analyses are better than 5 % RSD. Oxygen isotope ($^{18}O/^{16}O$) analysis was conducted at the NERC Isotope Geosciences Laboratory (NIGL) using fluorination techniques based on those of Clayton & Mayeda (1963). Six to ten milligrams of whole-rock powder were reacted with ClF_3 at 625 °C for 16 hours, following outgassing at 250 °C *in vacuo* and prefluorination for two hours at room temperature. Oxygen thus liberated was converted to CO_2 by Pt-catalysed reaction with heated graphite, and the CO_2 samples analysed on a CMS systems triple collector mass spectrometer, at the NERC Isotope

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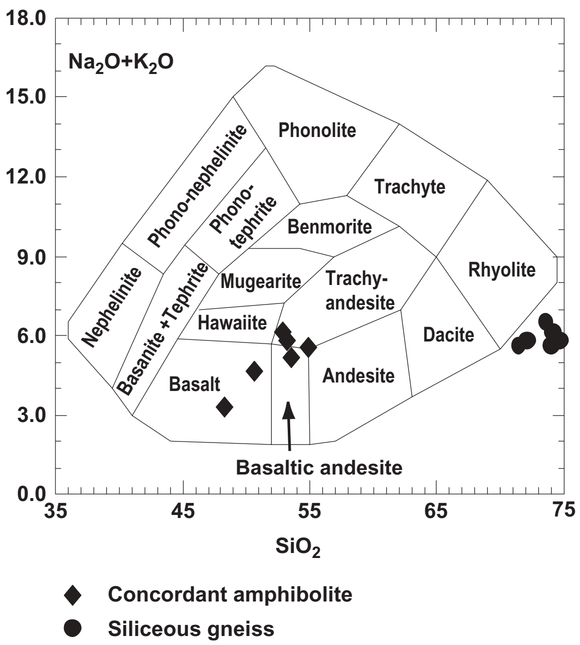

Figure 3. Total alkalis vs. silica volcanic rock classification diagram, showing the basalt–basaltic andesite amphibolites and the siliceous gneisses that have enhanced silica beyond dacitic and rhyolitic compositions.

Geosciences Laboratory (NIGL). Measured $^{18}O/^{16}O$ ratios are reported in standard delta notation relative to V-SMOW, and are estimated to be within 0.2 ‰ of the true value, on the basis of international and in-house standard analyses, and replicate determinations. International quartz standard NBS 28 gave $\delta^{18}O$ of + 9.6 ‰ throughout the period of analysis. The results are reported in Table 1 and discussed below. Sm–Nd isotopic data were acquired at the University of Oxford (M. J. Whitehouse, pers. comm.). Sm and Nd were separated from whole-rock powders using ion-exchange chromatography following dissolution with HF/HNO_3. Isotope ratios were determined using a VG54E single-collector thermal ionization mass spectrometer.

6.b. Elements and radiogenic isotopes

The amphibolites have bulk major element compositions comparable with mafic igneous rocks, representing mainly subalkaline basalts and basaltic andesites to trachyandesites (Fig. 3). MgO and transition metal abundances are sufficiently high (MgO up to 8.74 wt %, Cr up to 635 ppm and Ni up to 174 ppm) to signal mantle derivation. The siliceous gneisses, in contrast, have bulk major element chemistry akin to dacites and rhyolites (Fig. 3), but in many cases have SiO_2 abundances in excess of normal igneous compositions.

Figure 4a–i displays the major element data as a series of Harker diagrams. All plots exhibit a strong bimodal distribution, with well-defined clusters for the siliceous gneisses and concordant amphibolites but with no intermediate compositions. Concordant amphibolite SiO_2 values are low and form a narrow range (48.27–54.87 %), but those for the siliceous gneisses, which also define a narrow range, are extremely high (71.5–79.08 %). Some systematic trends are recognizable within the data clusters for the concordant amphibolites, with well-defined steep positive gradients displayed by Al_2O_3 and Na_2O and moderate to steep negative gradients displayed by Fe_2O_3, MgO and CaO. However, few recognizable trends are apparent within the data clusters for the siliceous gneisses.

Trace element data are presented as chondrite-normalized incompatible element diagrams and conventional REE plots (Fig. 5). Strathy Complex siliceous gneisses (Fig. 5a) show consistent patterns which are flat (*c.* 10–20 times chondrites) from Yb to La except for large negative Ti and to a lesser extent Sr anomalies, and variable small positive or negative P anomalies. There is a marked negative anomaly at Nb, a peak at K and lower values for Rb and Ba. Concordant amphibolite trace element patterns (Fig. 5b) are substantially similar, being flat between Yb and La (*c.* 6–15 times chondrites), with small positive Sr anomalies, variable P and small negative Zr and Ti anomalies. They also have marked negative Nb anomalies, peaks at K and lower values for Rb and Ba. Differences from the siliceous gneisses are therefore the magnitude and direction of the Sr anomalies, and the depth of the Ti anomaly. Figure 5c displays REE trends normalized to chondrites for the siliceous gneisses. Patterns are consistent and remarkably flat ($La/Yb_{(N)}$ average = 1.66) at *c.* 10–20 times chondrites with an overall slight concave-upwards curvature. The other marked feature is a consistent small negative Eu anomaly (Eu* average = 0.81). These are unlike any trends for either Moine metasediments (Fowler, 1988 and unpub. data), or quartzofeldspathic Lewisian material (e.g. Weaver & Tarney, 1980; Rollinson & Fowler, 1987; Fowler & Plant, 1987), or indeed more exotic potential protoliths such as deep sea chert. Figure 5d displays REE trends for the concordant amphibolites which are again consistently flat ($La/Yb_{(N)}$ average = 1.1) at *c.* 5–10 times chondrites with small positive Eu anomalies (Eu* average = 1.19). $La/Ce_{(N)}$ ratios are less than 1.

Two samples have been analysed for Nd isotope composition. Both the amphibolite (sample A1c: present day $^{143}Nd/^{144}Nd = 0.51297$, $^{147}Sm/^{144}Nd = 0.1949$) and the siliceous gneiss (sample PM10: present day $^{143}Nd/^{144}Nd = 0.512775$, $^{147}Sm/^{144}Nd = 0.1681$) give positive εNd calculated at the depleted mantle model age for the siliceous gneiss (*c.* 1000 Ma), of + 6.7 and + 6.9, respectively.

There are several possibilities for such bimodal igneous associations. Melting of different sources (commonly upper mantle and lower crust), different

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Table 1. Whole-rock major element, trace element and oxygen isotope analyses for Strathy Complex rocks

	Siliceous gneisses									Concordant amphibolites						
	153B	179B	199	63	PM10	PM7B	SB1	SP3	SP5	29J	46	74A	A1C	S7A	SP1	SP4
SiO_2	79.08	78.19	75.01	71.50	74.68	75.68	72.07	76.76	74.10	52.88	53.18	54.87	50.66	53.50	48.27	47.88
TiO_2	0.18	0.20	0.20	0.41	0.02	0.02	0.28	0.20	0.22	1.18	0.65	0.56	0.35	0.74	0.47	1.99
Al_2O_3	12.14	11.57	13.05	13.64	11.93	12.43	12.56	10.96	11.61	15.78	16.58	16.29	16.06	17.40	14.83	13.52
Fe_2O_3	2.82	2.90	3.29	5.16	3.35	3.18	3.54	2.04	3.51	10.15	10.63	8.64	10.76	10.38	10.07	13.15
MnO	0.06	0.11	0.04	0.16	0.09	0.03	0.06	0.04	0.06	0.31	0.30	0.22	0.16	0.10	0.55	0.89
MgO	0.62	1.15	2.11	1.32	0.84	0.80	1.49	0.69	0.92	5.32	4.83	6.98	8.31	4.61	8.74	6.32
CaO	1.09	1.29	2.76	2.13	1.33	1.23	1.97	0.80	1.18	5.87	5.17	4.92	9.23	7.42	11.29	9.36
Na_2O	4.34	3.48	2.52	4.99	4.64	5.65	3.80	4.71	4.91	5.14	5.01	5.16	4.15	4.64	2.81	3.00
K_2O	0.61	0.86	0.52	0.55	1.11	0.42	1.94	0.72	1.18	1.00	0.79	0.37	0.53	0.56	0.48	0.93
P_2O_5	0.08	0.18	0.32	0.13	0.06	0.06	0.09	0.05	0.05	0.13	0.17	0.12	0.05	0.19	0.09	0.24
LOI	0.17	0.28	0.26	1.07	0.44	0.61	0.81	1.16	0.65	0.91	1.36	0.98	1.00	0.11	1.39	1.29
Total	101.19	100.21	100.08	101.05	98.48	100.11	98.61	98.12	98.39	98.67	98.67	99.11	101.26	99.65	98.98	98.56
Be	0.78	0.72	0.87	0.96	0.97	0.87	na	0.56	0.69	0.96	1.13	0.94	0.57	0.72	0.74	1.36
Rb	13	17	5	10	17	4	29	14	28	12	19	5	8	2	5	17
Sr	178	68	196	165	99	135	178	339	339	266	306	82	218	226	227	290
Ba	173	89	26	46	74	72	175	207	487	117	146	33	37	16	52	190
Cr	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	91	35	62	196	bdl	635	143
Co	218	219	168	119	126	72	108	160	160	64	62	71	53	76	55	65
Ni	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	40	16	36	93	8	174	53
Cu	5	25	2	62	5	2	17	34	7	29	261	4	12	9	5	51
Zn	37	68	60	23	33	6	73	33	52	100	104	106	105	76	85	92
Y	30	19	28	21	26	23	22	3	7	21	13	11	17	12	12	33
Zr	102	72	86	70	81	83	98	79	111	63	45	58	45	37	39	129
Nb	2	1	1	1	2	1	2	1	2	1	2	1	1	1	1	3
Pb	6	5	2	3	3	2	8	10	8	3	7	3	4	8	5	2
La	6.41	4.71	5.09	4.47	6.20	3.71	5.72	1.83	6.68	4.11	na	na	2.34	2.28	na	na
Ce	16.7	12.6	11.0	9.75	16.0	11.5	15.4	4.77	13.6	11.7	na	na	7.45	6.26	na	na
Pr	2.38	1.68	2.60	na	2.22	2.61	2.11	2.58	na	1.79	na	na	1.17	0.90	na	na
Nd	10.6	7.35	6.68	5.65	9.60	7.20	10.2	3.30	6.75	8.83	na	na	6.07	4.61	na	na
Sm	3.19	2.25	2.00	1.85	2.86	1.32	3.09	0.89	1.55	2.78	na	na	1.91	1.46	na	na
Eu	0.82	0.57	0.45	0.64	0.62	0.67	0.81	0.32	0.50	1.11	na	na	0.77	0.65	na	na
Gd	3.55	2.33	3.23	2.53	3.81	2.64	na	0.50	1.25	na	na	na	na	na	na	na
Tb	0.79	0.49	na	na	0.64	na	0.64	na	na	0.57	na	na	0.43	0.32	na	na
Dy	5.31	3.35	3.92	4.18	4.39	3.60	4.13	0.98	1.50	3.73	na	na	2.85	2.16	na	na
Er	3.72	2.38	2.53	2.12	3.02	1.96	2.32	0.45	0.76	2.40	na	na	1.80	1.30	na	na
Yb	3.90	2.75	3.16	2.64	3.38	2.89	2.33	na	0.69	2.23	na	na	1.81	1.31	na	na
Lu	0.63	na	na	na	0.53	na	0.36	na	na	0.34	na	na	0.29	0.19	na	na
$\delta^{18}O_r$	8.7	9.4	na	na	8.3	6.5	na	na	na	8.2	na	na	6.8	10.2	6.3	7.3
$\delta^{18}O_q$	9.5	10.3	na	na	9.7	7.6	na	na	na	na	na	na	na	na	na	na
$\delta^{18}O_b$	5.3	4.7	na	na	5.3	3.9	na	na	na	na	na	na	na	na	na	na
$\delta^{18}O_p$	8.0	8.7	na	na	7.2	5.8	na	na	na	na	na	na	na	na	na	na

na = not analysed, bdl = below detection limit. For O isotope analyses, r = whole-rock, q = quartz, b = biotite, p = plagioclase.

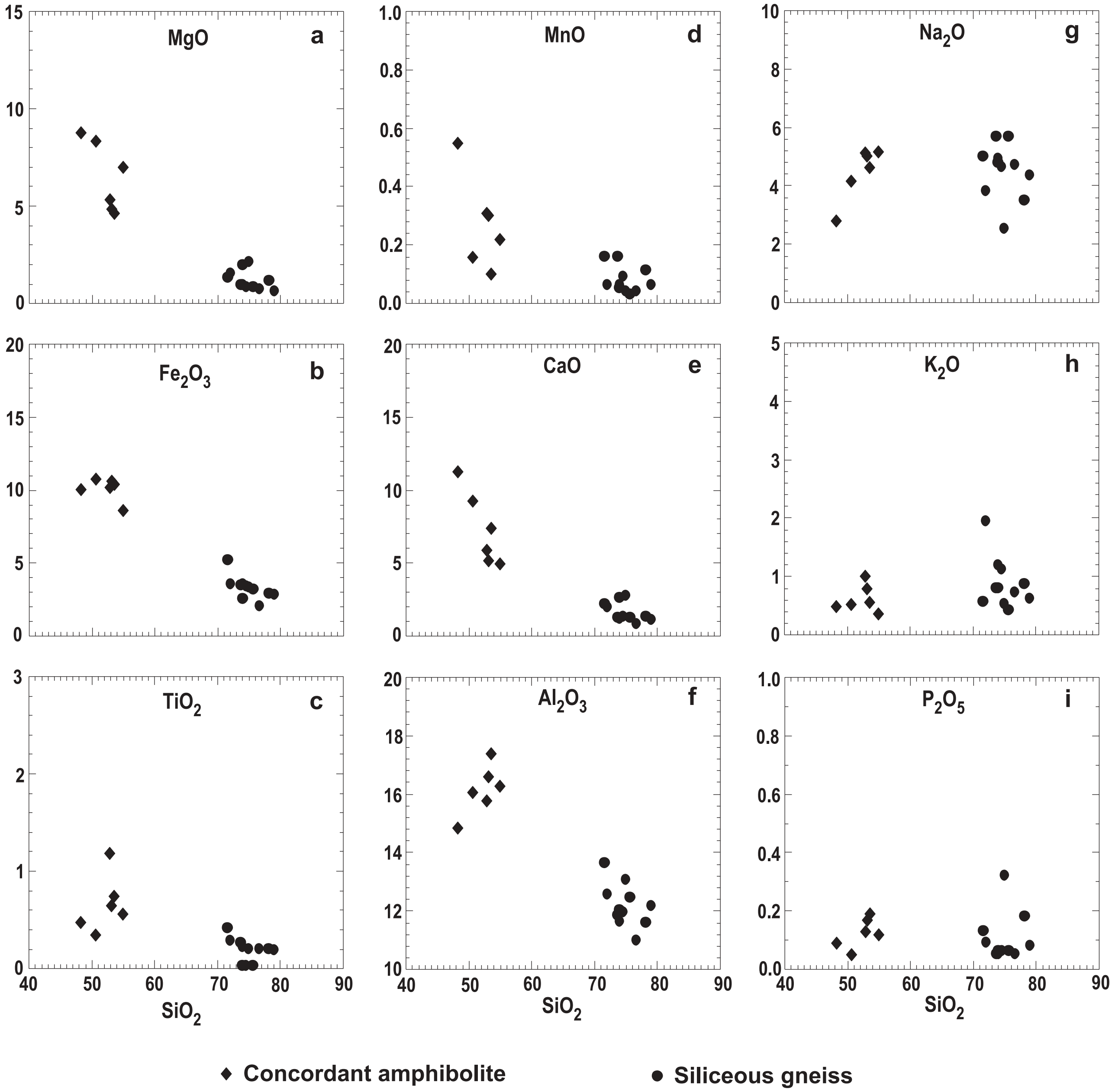

Figure 4. Harker diagrams for siliceous gneisses and concordant amphibolites of the Strathy Complex, highlighting the bimodal nature of the suite.

degrees of partial melting of the same source, and fractional crystallization have all been invoked (Barker & Arth, 1976; Bence & Taylor, 1985) and need not be mutually exclusive. A depleted mantle derivation for the amphibolites seems reasonable, but a completely separate crustal source for the siliceous gneisses is unlikely because of the strong similarity in initial εNd and many trace element ratios, in particular, the comparable REE patterns with complementary Eu anomalies. However, very low degrees of mantle melting would be required to generate magma with the required and typical 75 % SiO_2 ($\ll$5 %: Heltz, 1976; Green, 1982; Rapp, Watson & Miller, 1991) so that given the chemical similarities, fractional crystallization from amphibolite precursor to siliceous gneiss precursor may be more likely, despite the lack of intermediate compositions (Grove & Donnelly-Nolan, 1986). The pervasive metamorphic overprint renders unequivocal identification of the crystallizing minerals impossible, but obvious liquidus candidates would be pyxroxene and plagioclase ± olivine and Fe–Ti oxide. Likely elemental consequences of extensive basalt fractionation include falling MgO, Fe_2O_3 and CaO, early increasing but subsequently decreasing Na_2O, Al_2O_3 and TiO_2, and continuously increasing K_2O and SiO_2. All these are observed in the Strathy Complex data (Fig. 4), though the correlations are incomplete and often weak, and the extreme fractionates are probably

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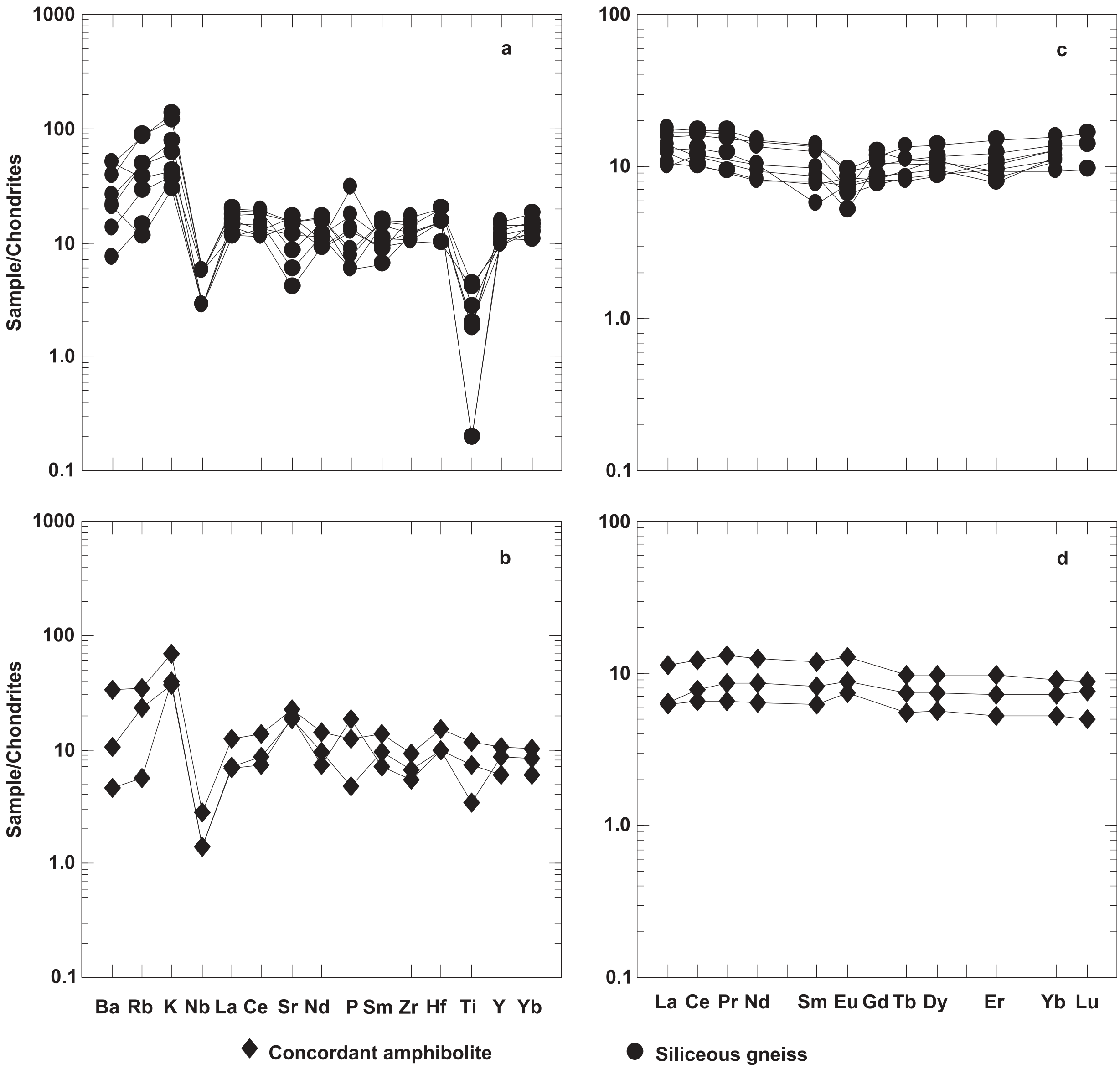

Figure 5. Chondrite-normalized, multi-element and REE diagrams for the siliceous gneisses and concordant amphibolites of the Strathy Complex. Note the close comparability of the plots, save for an enhanced Ti trough in the siliceous gneisses, and complementary Eu anomalies.

too silicic to be the products of this process alone. However, decreasing transition metals, little REE fractionation save the development of positive Eu anomalies in the (cumulus-rich?) mafic magmas with complementary negative anomalies in the acid differentiates and rapidly falling TiO_2 are all consistent with pyroxene- and plagioclase-dominated crystal fractionation with minor Fe–Ti oxide, as is the significant increase in total REE. Although the overall dominance of siliceous gneiss (70 %) over concordant amphibolite (30 %) introduces a significant volume problem for this crystal fractionation mechanism, the ratio now exposed is a direct result of tectonic repetition. In the structurally lowest parts of the complex around the eastern side of Armadale Bay (Fig. 1) concordant amphibolite is far more abundant (80 %).

Many elemental characteristics of the Strathy Complex are matched by bimodal volcanic suites elsewhere, from Archaean to Recent in age. The majority of these are rhyolitic/dacitic/trondhjemitic and basaltic, commonly hosting massive sulphide deposits of economic importance. Amongst the most directly comparable are the following: Cape Breton Island (Dostal, Keppie & Zhai, 1992), Ammonoosuc volcanics, New England (Robinson *et al.* 1986), West Shasta metavolcanic suite (Bence & Taylor, 1985), Fijian dacites and trondhjemites (Gill & Stork, 1984) and Galapagos andesites (Ridley *et al.* 1994). Detailed descriptions of several of these allude to hydrothermal alteration processes including silicification, and the mobility of Ca, Mg and light REEs being responsible for many of the elemental peculiarities (e.g. Bence & Taylor, 1985;

Ridley *et al.* 1994). Accordingly, the possibility of hydrothermal alteration of the Strathy Complex rocks is considered next, using stable isotope studies.

6.c. Oxygen isotopes

Oxygen isotopes are powerful monitors of fluid movement in the crust, and have been used extensively in studies of hydrothermal alteration. Although the high-grade metamorphism that affected the Strathy Complex will undoubtedly have reset mineral values, the whole-rock (WR) system may remain undisturbed during such processes (e.g. Wilson & Baksi, 1983). If the amphibolites represent unaltered mantle-derived basic magmas they should retain $\delta^{18}O$ of *c.* + 6 ‰, but this will be displaced by hydrothermal alteration, in either direction depending on fluid composition and temperature. $\delta^{18}O$ values for the siliceous gneisses may also reveal alteration processes, though uncertainty over their original values makes interpretation more difficult.

Five siliceous gneisses and five concordant amphibolites have been analysed, both for whole-rock values and mineral separates where appropriate (Table 1). Whole-rock values for the siliceous gneisses are in the range + 6.4 to + 10.4 ‰, and for the concordant amphibolites in the range + 6.3 to + 10.2 ‰. Some of the latter are clearly inconsistent with pristine, mantle-derived mafic magmas. The magnitude and direction of $\delta^{18}O$ variation in spilites is dependent on reaction temperature and water/rock ratio. Increase is confined to temperatures below 200–300 °C where the feldspar-water oxygen isotope fractionation curves exceed + 6 ‰ (Friedman & O'Neil, 1977). High temperature (> 400 °C) alteration results in ^{18}O depletion and therefore in values less than *c.* + 6 ‰ (Kempton, Hawkesworth & Fowler, 1991). There are strong correlations in both the amphibolites and the siliceous gneisses between $\delta^{18}O$ and MgO, Na_2O, Al_2O_3 and CaO, intriguingly in opposite directions (Fig. 6a–d). For the amphibolites, the highest $\delta^{18}O$ values are associated with lowest MgO and CaO and highest Na_2O and Al_2O_3, consistent with preferential feldspar alteration over the mafic silicates, as is usually the case (Kempton, Hawkesworth & Fowler, 1991), but with limited associated element mobility thus preserving original bulk elemental compositions. Limited mobility is also consistent with the correlation of highest Cr and Ni abundances in those rocks with lowest $\delta^{18}O$, approximating to sensible mantle values. If correct, the processes of hydrothermal alteration have caused a substantial increase in $\delta^{18}O$, which requires relatively low temperature (< 200 °C, discussed above). The siliceous gneisses, on the other hand have high $\delta^{18}O$ in the most MgO-rich but Na_2O- and Al_2O_3-poor examples, and an array of correlations with trace elements known for their ready mobility in hydrothermal solutions: positive with Rb and Zn, negative with Be and Sr. Unfortunately, uncertainty over the original values severely hampers interpretation. Pristine rhyolites may have $\delta^{18}O$ varying from + 6 to in excess of + 10 ‰, depending on the precise petrogenetic mechanism (e.g. the amount of crystal fractionation relative to crustal derivation, and the early involvement of fluids from various sources). However, assuming the presence of quartz in the original mineralogy, that the temperature was similar to the basalt alteration and recognizing that quartz–water equilibration below 200 °C produces $\delta^{18}O$ in excess of + 15 ‰ (Friedman & O'Neil, 1977), it seems probable that the highest $\delta^{18}O$ values in the siliceous gneisses represent the most altered rocks. If so, the low $\delta^{18}O$ rocks (*c.* + 6 ‰) are relict, and alteration has resulted in the leaching of Na_2O and Sr, Al_2O_3 and Be, and the introduction of MgO, Rb and Zn, much of which is consistent with previous observational and experimental studies of hydrothermal systems (e.g. Humphris & Thompson, 1978; Hajash & Chandler, 1981; Baker & Groot, 1983).

7. Tectonic setting of the igneous protoliths of the Strathy Complex

Bimodal magmatism is not in itself diagnostic of tectonic setting, especially in a fragment of the size of the Strathy Complex. Pin & Paquette (1997) reviewed the common geodynamic environments, citing familiar examples of within-plate extensional settings and continental rifts, but also ocean island and supra-subduction zone associations. Major element data for the amphibolites plotted on an AFM diagram (Fig. 7a) indicate a calc-alkaline affinity (see also Moorhouse & Moorhouse, 1983), and MORB-normalized trace element data (Fig. 7b) show typical subduction-related characteristics of high LILEs, negative Nb anomaly and flat high field strength elements. However, some caution should be exercised given the ready mobilization of LILEs during metamorphism. Recognizing such problems, Pin & Paquette (1997) used criteria involving a combination of petrological, Nd isotope and relatively immobile incompatible element data to distinguish between the following possibilities: I – within-plate continental and oceanic rifts, II – continental break-up, III – intra-oceanic arc, IV – mature continental arc and V – incipient back-arc spreading. Given the generally accepted extensional basin setting for Moine sedimentation (Strachan, 1986; Glendenning, 1988; Soper, Harris & Strachan, 1998), the most appealing hypothesis is that the Strathy Complex represents continental rift-related magmatism. Unfortunately, the data available do not support this. In particular, the amphibolites were not alkali basalts nor are they light REE-rich, and they combine strong positive εNd with negative Nb anomalies. The silicic rocks are neither strongly alkaline residua from alkali basalt fractionation, nor can they represent the products of crustal fusion ($\varepsilon Nd_i = +6.9$). The combination of flat

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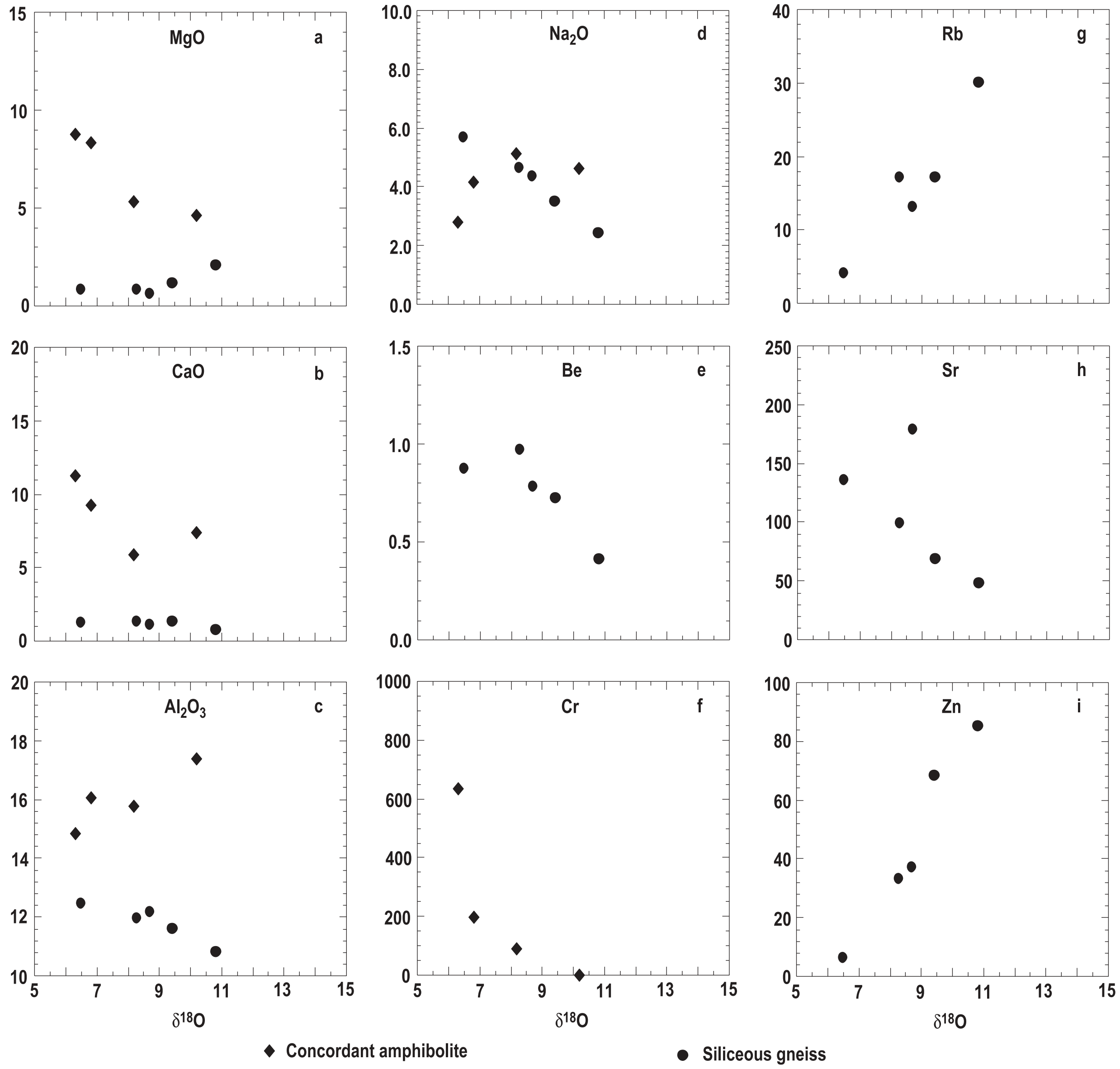

Figure 6. $\delta^{18}O$ vs. a variety of major and trace elements for the siliceous gneisses and concordant amphibolites of the Strathy Complex. Note the considerable $\delta^{18}O$ spread and its divergent behaviour in the two main rock types of the Complex.

LREE, negative Nb anomalies and strongly positive εNd in basalt–basaltic andesite compositions strongly suggests a destructive plate margin environment, either a juvenile intra-oceanic arc (category III) or an incipient back-arc (category V), in keeping with similar elemental and isotopic characteristics in the rhyolitic extreme.

8. Discussion and conclusions

The geochemical results presented here are in agreement with the conclusion of Moorhouse & Moorhouse (1983) that the Strathy Complex formed in an arc-related environment. A marine setting is consistent with the presence of marble and calc-silicate paragneisses. The new elemental and radiogenic isotope data indicate additionally that both end-members of the Strathy bimodal suite were derived from a depleted mantle source, that they are cogenetic and that they may have been related by a crystal fractionation mechanism. The new $\delta^{18}O$ values and their correlations with major and trace elements suggest that the protoliths were hydrothermally altered at temperatures below 200 °C. There is no need to consider anatexis as an additional mechanism for generating the peculiar geochemistry (cf. Moorehouse & Moorhouse, 1983).

New structural data indicate an autochthonous setting for the Strathy Complex, which possibly represents a piece of the sub-Moine basement. However, it is lithologically distinct from the Archaean basement inliers within the Moine, which are dominated by hornblendic orthogneisses with local evidence for

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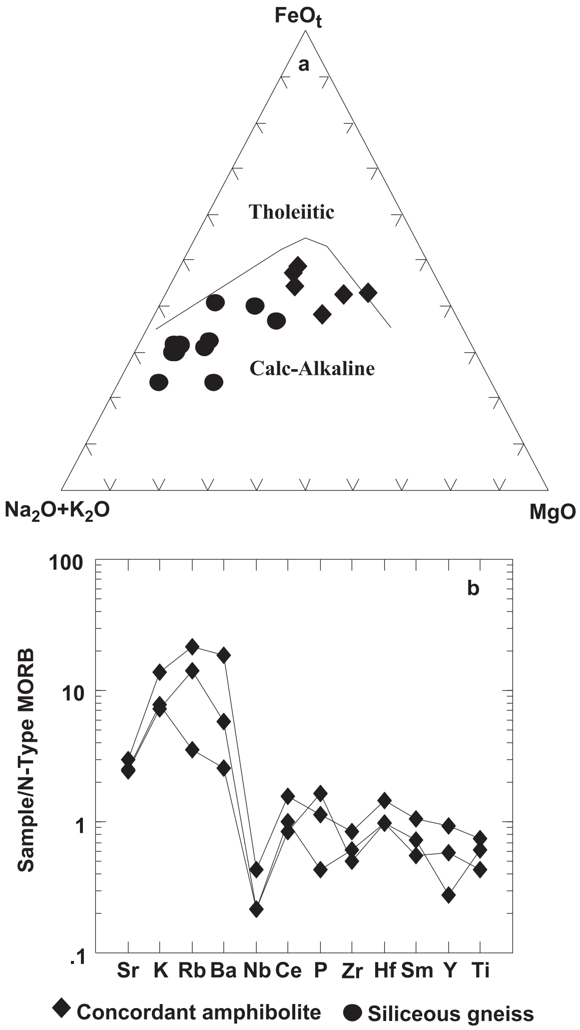

Figure 7. AFM (a) and MORB-normalized incompatible element (b) diagrams for the siliceous gneisses and concordant amphibolites of the Strathy Complex. Note the calc-alkaline trend on the AFM diagram, and the enhanced large-ion lithophile elements in the amphibolites.

granulite facies metamorphism (Holdsworth, Strachan & Alsop, 2001). Moorhouse & Moorhouse (1983) suggested a Proterozoic affinity for the Complex on the basis of La, Ce and Y data. Palaeoproterozoic calc-alkaline igneous rocks have been described from the Loch Maree area on the Caledonian foreland (Park, Tarney & Connelly, 2001) and from the Rhinns of Islay in the Inner Hebrides (Muir *et al.* 1994). However, the *c.* 1000 Ma model age of the Complex argues against direct correlation with either of these. Although model ages are notoriously unreliable indicators of protolith crystallization, there are several reasons for optimism in this particular case. There is good evidence that the magmas were direct products of mantle fusion, that the end-members were related by a mechanism that does not affect radiogenic isotope ratios (closed-system crystal fractionation), and the fractionating system produced little variation in Sm/Nd ratio. If so, comparison with the *c.* 1100–1000 Ma Grenville orogenic event, widespread in eastern North America and Scandinavia and now recognized in parts of Northern Scotland and Ireland, might be constructive. This resulted in high-grade, ductile reworking of basement within the Caledonian belt in the eastern Glenelg basement inlier in northwest Scotland (Sanders, Van Calsteren & Hawkesworth, 1984) and the Annagh Gneiss Complex of northwest Ireland (Menuge & Daly, 1994). However, rocks of the Grenville orogen are usually dominated by recycled crust with model ages > 1.5 Ga, rather than juvenile material such as that of the Strathy Complex. Since the deduced tectonic setting is also oceanic rather than continental, a coeval subduction-related site within the peri-Rodinian ocean (Murphy *et al.* 2000) might be more appropriate than one within the Grenville orogenic belt itself. In any case, the meta-igneous rocks of the Strathy Complex may represent the only occurrence of juvenile Grenvillian crust within the pre-Neoproterozoic basement of the Scottish Caledonides.

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