A fluvial origin for the Neoproterozoic Morar Group, NW Scotland; implications for Torridon - Morar group correlation and the Grenville Orogen Foreland Basin

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Running title: Correlation of Torridon and Morar groups

Abstract

Precambrian sedimentary successions are difficult to date and correlate. In the Scottish Highlands, potential correlations between the thick, undeformed siliciclastic 'Torridonian' successions in the foreland of the Caledonian Orogen and the highly deformed and metamorphosed siliciclastic Moine succession within the Caledonian Orogen have long intrigued geologists. New and detailed mapping of the Neoproterozoic A 'Mhoine Formation (Morar Group, lowest Moine Supergroup) in Sutherland has discovered low strain zones exhibiting well-preserved sedimentary features. The formation comprises 3-5 kilometres of coarse, thick-bedded psammite with abundant nested trough and planar cross-bedding bedforms, defining metre-scale channels. Palaeocurrent directions are broadly unimodal to the NNE-ENE. We interpret the A 'Mhoine Formation as high-energy, braided fluvial deposits. The A 'Mhoine Formation and the unmetamorphosed, Neoproterozoic Applecross-Aultbea formations (Torridon Group), are similar in terms of lithology, stratigraphical thickness, sedimentology, geochemistry, detrital zircon ages and stratigraphical position on Archaean basement. Depositional age constraints for both successions overlap and are coeval with late-Grenvillean orogenic activity. Detrital zircons imply similar source regions from the Grenville Orogen. The Morar and Torridon groups can thus be correlated across the Caledonian Moine Thrust and are best explained as parts of a single, large-scale, orogen-parallel foreland basin to the Grenville Orogen.

(end of Abstract)

The interpretation, correlation and age-control of Precambrian clastic sequences are hampered by a lack of biostratigraphical control. Post-depositional tectono-metamorphic events may have obscured or destroyed sedimentological evidence and subsequent plate motions may have transported formerly adjacent source and sink regions over long distances. In addition, some controlling geomorphical factors such as rates of weathering and erosion were different in the Precambrian compared to more modern-day processes (e.g. Eriksson *et al*. 2001). Over the last decades, the application of detrital zircon dating has provided a means to constrain the maximum age of deposition and the provenance of the detritus of such sequences (Froude *et al*. 1983; Nelson 2001; Cawood *et al*. 2004) and the database of such dates is growing fast (e.g. Cawood *et al*. 2007). However, correlations based solely on detrital zircon ages may be equivocal and in this study we use lithostratigraphy, sedimentology, geochemistry and published detrital zircon geochronology to interpret and correlate Neoproterozoic siliclastic sequences in Northern Scotland.

The metamorphosed Morar Group in the Northern Scottish Highlands occurs east of the Caledonian (Silurian) Moine Thrust and is the structurally lowest part of the Moine Supergroup. It comprises several kilometres of siliciclastic rocks (mainly psammite), has a large (>2000 km^2) outcrop area and is generally regarded as shallow marine in origin (e.g. Glendinning 1988; Holdsworth *et al.* 1994, Strachan *et al.* 2002).

West of the Moine Thrust, the unmetamorphosed Torridon Group represents a similarly widespread, thick and monotonous siliciclastic sequence. It is interpreted to be of mostly fluvial origin (Nicholson 1993; Stewart 2002). A number of workers have suggested that the 'Torridonian' (the informal stratigraphical parent of the Torridon Group) and the Moine Supergroup may be equivalent (Peach *et al.* 1907; 1913; Peach & Horne 1930; Kennedy 1951; Sutton & Watson 1964; Johnstone *et al.* 1969; Nicholson 1993; Prave *et al*. 2001). However, such a correlation has generally not been accepted and the two sequences are formally regarded as distinct (Clough in Peach *et al.* 1910, p.46; Gibbons & Harris 1994; Stewart 2002; Trewin 2002; Friend *et al.* 2003; Cawood *et al.* 2004). No thorough discussion or review of a potential correlation has been published since Kennedy (1951).

Here, we present new sedimentological and geochemical data for the Morar Group in the Northern Highlands of Scotland. These and other published data are used to compare and contrast the Morar and Torridon groups and to discuss possible basin interpretations. It is concluded that they represent a single foreland basin to the Grenville Orogen.

Geological Setting

Moine Supergroup - Morar Group

The Moine Supergroup occurs east of, and structurally above, the Caledonian Moine Thrust and north of the Great Glen Fault (Figure 1). After deposition, it was subjected to a number of tectonometamorphic events that have been the subject of some debate (Tanner & Bluck 1999 and references therein). The most common model involves an extensional event at *c.* 870 Ma, followed by Knoydartian (820-740 Ma) and Caledonian (470 - 460 Ma and 430 – 400 Ma) orogenic events (Strachan *et al.* 2002). Sedimentary structures, especially in pelitic and semipelitic lithologies, are generally deformed, obscured or obliterated by greenschist- to amphibolite-facies metamorphism and deformation. A number of ductile thrust faults disrupt the stratigraphy (Johnstone *et al.* 1969; Barr *et al.* 1986; Holdsworth *et al.* 1994). Within the outcrop of the Moine Supergroup are several Lewisianoid basement gneiss inliers with late Archaean protolith ages that are broadly similar to Lewisian gneisses west of the Moine Thrust (Friend *et al.* 2007).

The Moine Supergroup has been divided into three groups: the Morar, Glenfinnan and Loch Eil (Johnstone *et al.* 1969; Holdsworth *et al.* 1994; Soper *et al.* 1998).

<u>The Morar Group</u>, the lowest and westernmost group (Figure 1, 2), is dominated by psammite with minor pelitic, semipelitic and pebbly layers. Estimates of stratigraphical thickness in the literature (e.g. Holdsworth *et al*. 1994) are poorly constrained because of structural complexities. In Morar in the Western Highlands, the Group comprises four formations; these are in ascending order the Basal Pelite, Lower Morar Psammite, Morar Striped and Pelite and Upper Morar Psammite formations (Johnstone *et al.* 1969; Holdsworth *et al.* 1994). Locally, the base of the Basal Pelite Formation is marked by a thin, highly deformed basal meta-conglomerate, showing an unconformity with the Lewisianoid basement and it is now generally accepted that the Morar Group was deposited uncomformably upon

Lewisianoid basement (Peach *et al.* 1910; Ramsay 1957b; Holdsworth *et al.* 1994; 2001). Previously, sedimentary structures have only been studied in detail in the Upper Morar Psammite Formation (Glendinning 1988) and include tabular and trough cross-bedding in co-sets up to 0.5 m thick. Coarse-grained to gravely psammite locally displays cross-beds > 0.5 m thick. Most palaeocurrents are unidirectional to the north or north-east, but bipolar ‘herring-bone’ cross stratification and dunes and ripples with mudstone drapes are present locally. Glendinning (1988) interpreted the Upper Morar Psammite as a tidal, shallow-marine deposit but noted that the unit is unusually immature (arkosic) compared to other shallow-marine shelf deposits, and that a fluvial origin of these sediments could not be discounted.

In contrast, in the Northern Highlands north of Glen Oykel (Figure 1, 2), the Morar Group stratigraphy is rather simple. It is dominated by the psammitic A ‘Mhoine Formation (Figure 2), outcropping over *c.* 1500 km^2 (Figure 1, 3). The A ‘Mhoine Formation comprises several kilometres of psammite. A highly deformed pelitic / conglomeratic unit is intermittently present on or slightly above Lewisianoid Gneiss inliers (Mendum 1976; Holdsworth *et al.* 2001). The relationship between the A’Mhoine Formation and the Altnaharra and Glascarnoch Formation above the Achness Thrust (Figure 3) remains unclear.

The Morar Group is structurally overlain by the semipelite-dominated <u>Glenfinnan Group</u>, but the contact is generally marked by the ductile Sgurr Beag Thrust (Figure 1) and the original relationship between the two groups is unclear. The close association of Glenfinnan Group rocks and basement inliers suggests an original unconformable relationship (Holdsworth *et al.* 1994; Soper *et al.* 1998), and the group may represent a distal, lateral equivalent to the Morar Group. However, Morar Group rocks on the Ross of Mull appear to pass stratigraphically upward into Glenfinnan Group rocks; the section is, however, locally highly deformed and the field relationships are not unequivocal (Holdsworth *et al*. 1987). The Glenfinnan Group preserves few sedimentary structures and its depositional environment is unclear. The stratigraphically overlying psammite-dominated <u>Loch Eil Group</u> (Roberts *et al.* 1987) contains locally abundant sedimentary structures including unidirectional and bipolar ‘herring-bone’ cross-bedding and wave ripples and has been interpreted as a shallow marine shelf deposit (Strachan 1986).

Torridon Group

The Torridon Group occurs west of the Caledonian Moine Thrust and in thrust sheets within the Moine Thrust Zone (Figure 1, 3). The Torridon Group is generally unmetamorphosed and undeformed, except for gentle tilting. The Torridon Group was mostly deposited upon an exhumed land surface of Archaean Lewisian Gneiss with palaeo-relief up to 600 m (Peach *et al.* 1907; Stewart 1972). Locally, the group unconformably overlies the Mesoproterozoic Stoer and Sleat Groups, described elsewhere (Stewart 2002; Rainbird *et al*. 2001; Kinnaird *et al.* 2007). Including its inferred offshore extent, the Torridon Group currently occupies an area of *c.* 80 by 200 km (Stewart 2002). However, Torridon Group rocks also occur in the highest thrust sheets in the Moine Thrust Zone (e.g. Ben More Thrust Sheet and Kinlochewe Thrust Sheet; Peach *et al*. 1907; Butler 1997; Krabbendam & Leslie 2004; see also Figure 3), so that prior to Caledonian thrusting the Torridon Group must have extended some 50 – 100 km farther east (Elliot & Johnson, 1980, Butler & Coward 1984). The succession is *c.* 5-6 km thick but the top of the sequence is not exposed (Stewart 2002) because the group is unconformably overlain by Cambro-Ordovician sandstone.

The Torridon Group has been divided (base to top) into the Diabaig, Applecross, Aultbea and Cailleach Head formations (Stewart 2002). <u>The Diabaig Formation</u> comprises breccia, conglomerate, siltstone and sandstone. Cobble breccia or conglomerate infill palaeo valleys and are rich in vein-quartz clasts. The siltstones have been interpreted as lacustrine (Stewart 1988). The Diabaig Formation is absent in the Cape Wrath area in the north, occurs intermittently in Assynt and thickens to *c.* 200 m on Skye. <u>The Applecross and Aultbea formations,</u> two very similar sandstone formations, form the bulk of the Torridon Group, totalling *c.* 4-5 km in thickness. The contact with the underlying Diabaig Formation is sharp, locally erosional and may represent a disconformity (Kinnaird *et al*. 2007). The Applecross Formation consists predominantly of coarse to very coarse red sandstone in beds 0.1 - 5 metres thick. Pebble conglomerate and siltstone/mudstone beds occur locally. The Aultbea Formation comprises mainly fine to medium-grained sandstone and minor mudstone. Flat bedding, planar cross-bedding and trough cross-bedding are common in both formations (Stewart 2002; Nicholson 1993). Soft-sediment deformation structures are locally abundant (Selley *et al*. 1963; Owen 1995) and affect beds up to 5 m thick. Palaeocurrents are broadly eastward, but vary between NE and SE (Williams, 1969a; Nicholson 1993; Williams 2001). The pebble fraction of the Applecross Formation consists mostly of vein quartz or gneiss but also contains up to 30% of ‘exotic’ clasts (quartz-fuchsite schist, orthoquartzite, metaquartzite, microgranite, rhyolite, chert and red jasper) that cannot be linked to underlying rock units (Peach *et al*. 1907; Gracie & Stewart 1967; Williams 1969b). The formations are interpreted as alluvial braid plain deposits (Nicholson 1993; Stewart 2002), although Williams (2001) suggested an alluvial ‘mega fan’ environment.

SEDIMENTOLOGY OF THE MORAR GROUP IN THE NORTHERN HIGHLANDS

Well-preserved sedimentary structures are only rarely present in Moine rocks but are observed in several low strain zones within the A ‘Mhoine Formation in the Ben Hee area (Cheer 2006) and Glen Cassley (BGS, unpublished data) (Figure 3). The structure of the Ben Hee – Glen Cassley area is dominated by kilometre-scale, west-facing and west-verging folds, alternating with regional-scale ductile thrusts, all developed under greenschist- to lower amphibolite-facies metamorphism, presumed to be of Scandian (Silurian) age (Cheer 2006). The folds (Figure 3) trend roughly north-south, have shallow plunging axes and are near-cylindrical over many kilometres. The folds have highly-sheared gently east-dipping long limbs, some of which are ductile thrusts (e.g. Ben Hope and Achness thrusts; Figure 3). Inbetween these thrusts are low-strain zones, commonly in the steep to vertical short limbs of the large-scale folds. Such limbs are up to 500 m thick and many kilometres wide across strike (cross-sections on Figure 3). In these zones, strata have been rotated *c.* 80 - 100° to sub-vertical attitudes, but nevertheless show undeformed sedimentary structures (Figure 4). A modest fabric is locally present in rare semipelite or gritty units (Figure 4a), but most exposures of psammite show a complete lack of any tectonic fabric. Low strain zones with well-preserved sedimentary structures were found in two thrust sheets, above and below the Ben Hope Thrust (Figure 3) commonly on large, glacially polished outcrops.

Constraints on stratigraphical thickness

The stratigraphical thickness of the A ‘Mhoine Formation is well constrained between River Cassley and Carn nam Bò Maola [NC 462 095] (Figure 3). Here, a 3 km long section exposes subvertical strata that strike NNW-ESE and consistently young to the west; this equates to 3 km of stratigraphical thickness (Figure 3, cross-section B-B'). To the west in the Allt na Faile [NC 432 080], the strata are folded over *c.* 500 m section distance. West from this, another 3 km long section of steep to moderate dipping strata stretches west as far as Beinn an Eòin Bheag [NC 375 055], possibly adding another 2-3 km to the total stratigraphical thickness (cross-section B-B' on Figure 3). Neither the stratigraphical top nor base of the A 'Mhoine Formation occurs in this section but it is clear the formation has a stratigraphical thickness of at least 3 km, and possibly more than 5 km.

Lithology

The dominant lithology of the A 'Mhoine Formation is a fine to coarse quartzo-feldspathic psammite (grain size varies between 0.5 – 3 mm) with rare layers of pelite and semipelite. The psammites contain 80 – 90 % quartz, 3 – 8% alkali-feldspar and <4% plagioclase and biotite, with accessory opaques (derived from thin section study). Gritty beds (Figure 4a) are common, particularly in the lower parts of the sequence (e.g. east of Carn nam Bò Maola), with clasts up to 30 mm. Pebbles are mainly well-rounded (vein?) quartz with subordinate clasts of feldspar and rarer quartzofeldspathic gneiss and/or granitoid. Semipelite layers become more common (*c.* 5% of section) at higher levels in the west near Beinn an Eòin Bheag, defining an overall fining upward trend. Overall, the formation is exceptionally uniform and no distinct marker beds have been found.

Sedimentary structures

Observed sedimentary structures include isolated channels, nested channels, planar and trough cross-bedding, planar stratification and abundant soft-sediment deformation structures (Figures 4 and 5). Trough cross-bed sets, typically 0.1 – 1 m deep, infill channels up to several metres deep and 3 – 15 m wide. The sets occur as nested stacked units (co-sets) up to 8 m thick (Figure 4b-d). Gravel/pebble lags occur in the bases of larger channels whilst heavy mineral bands (up to 10 mm thick) are locally preserved along the bases of smaller channels. Planar cross-stratification (Figure 4c) makes up as much as one third of exposures and occurs as sets and co-sets that are laterally truncated by overlying channels or display migration toward channel thalwegs away from channel margins. Planar cross-bedded co-sets range in thickness from 0.1 m to 1 m. Both planar and trough cross-bedding locally display a fining upward trend along foresets; coarser grain sizes (in places pebbly) define bottomsets whereas topsets are characterised by finer grain sizes (fine sand to semi pelite). Soft-sediment deformation affected *c.* 20-30 % of the well-preserved outcrops (Figure 4e, f). Features include dewatering 'pipes' 0.2 – 2.5 m in height, typically confined to single beds, and oversteepened to overturned cross-bedding that can affect cross-stratified strata up to 5 m thick; in almost all cases, overturning is towards the east or NE, i.e. in the sediment transport direction. Slumping is developed locally and typically on decimetre scales but can incorporate up to 10 m of stratigraphy, involving single beds or groups of beds.

Most bed contacts are erosional and vertical trends are difficult to ascertain. However, it is apparent that the channelised, trough cross-bedded units tend to display a decrease in grain size (at least as coarse-tail fining) and scale of co-sets upward from an erosive base (Figure 4d). Large outcrop surfaces reveal that the planar cross-bed sets display lateral migration directions that are typically at high angles to the scooped-shaped bounding surfaces of the channels. Planar stratification and/or finer-grained facies occupy a stratigraphical position either in the topmost portions of the flared margins of the channels or along the tops of planar cross-bed co-sets.

Channel orientations typically trend approximately east-west and the infilling trough cross-strata indicate overall sediment transport was generally to the east to NNE (Figures 4b-d). Only few channels are exposed in 3D; however, planar-cross bedded strata at Carn Mor (Glencassley area) consistently indicate unidirectional palaeo-currents to the east or NE (Figure 4c).

Sedimentological interpretation

The A 'Mhoine Formation consists of metamorphosed sandstones and pebbly sandstones exhibiting a wide range of structures formed by bedload traction. The grain size distribution combined with the decimetre- to metre-scale trough and planar cross-bed sets imply high flow velocities in channels deep enough to permit development of metre-scale bedforms (i.e. dunes). High flow velocities are also indicated by (i) sigmoidal shaped foresets and the asymptotic toes of metre-scale trough cross-bed sets, (ii) the presence of flat stratification in coarse to pebbly grain sizes (upper flow regime plane beds), (iii) the syn-depositional shearing that steepened or overturned metre-scale foresets and (iv) the overall coarse grain size of the psammites. The channel-fills commonly display a sequence of sedimentary structures that decrease in scale, and fine upwards, indicating progressive channel abandonment. The arrangement of channelised beds in nested and stacked units several metres thick, which display fining upwards in both grain size and bedform scale, is a characteristic facies of braided fluvial environments (Collinson 1996; Miall 1985, 1992). A fluvial setting is also supported by the unidirectional palaeocurrents displayed by the planar and trough cross-beds which consistently show NNE-ENE directed sediment transport.

Planar and trough cross-bedding orientated at high angles to the channel margins are interpreted as laterally accreting bars. By contrast, bedforms showing migration parallel to the trough and channel axes are interpreted as downstream-migrating bars (e.g. Cant & Walker 1978; Miall 1992; Smith 1970). These facies are arranged in 20 – 50 m thick packages in which coarser-grained, channelised and trough cross-bedded units dominate the lower portions, with planar stratified and relatively finer grained units (including thin semipelitic intervals) characterising the upper parts. We interpret these decametre-scale patterns as recording lateral variation between channelised braided fluves and bars, interfluve areas and intermittent more widespread sheetfloods.

The A 'Mhoine Formation lacks well-developed vertical grain size and bedding thickness trends. This absence is typical for pre-land-plant braid plain settings (Schumm 1968; Cotter 1978). In contrast, metre to decametre-scale 'cyclicity' is what characterises parasequence development of shoreline and marine shelf settings whether tide, storm or fluvial dominated (e.g. Johnson & Baldwin 1996; Reading & Collinson 1996; Walker & Plint 1992). In summary, the evidence indicates that the A 'Mhoine Formation records fluvial deposition in a high-energy braided fluvial setting.

Geochemistry

Whole-rock and stream sediment geochemical data have been used to argue for and against a correlation between the Moine and 'Torridonian' rocks (Kennedy 1951; Stone *et al*. 1999; Stewart 2002). However, no modern whole-rock analyses are available for the A 'Mhoine Formation in the study area. A series of samples from the A 'Mhoine Formation were collected for whole-rock geochemical analysis as part of this project The samples come from a section from Glen Cassley to Carn nam Bò Maola and represent *c.* 2 km of the stratigraphical succession (Figure 3, cross-section

B-B'); the data are presented in Table 1 and Figure 6 and discussed in more detail below. The samples plot as arkosic to sub-arkosic, with an overall trend to more sub-arkosic (mature) compositions higher up in the stratigraphy (Figure 6). The samples indicate a mineralogical immaturity in accordance with the textural immaturity and the suggested fluvial depositional setting. Overall there is remarkably little geochemical variation between the samples, attesting to the lithological monotony of the A 'Mhoine Formation.

DISCUSSION

Correlating the A 'Mhoine and Applecross-Aultbea formations

The Torridon Group was deposited in a fluvial environment characterised by braided rivers flowing from the west (Stewart 2002). Since the Moine Thrust has an overall WNW-directed transport direction, restoration of the thrust would place the Morar Group 'downstream' from the Torridon Group, so that a correlation between the two groups is a distinct possibility. We suggest a correlation between the Applecross/Aultbea Formation (Torridon Group) and the A 'Mhoine Formation (Morar Group) as represented in the area north of Glen Oykel (Figures 1, 3).

General position, lithology and sedimentology

The Morar and Torridon groups both unconformably overlie Archaean – Palaeoproterozoic basement of comparable age (Stewart 2002; Holdsworth *et al.* 1994; Kinny *et al.* 2005; Friend *et al.* in press). Both sequences have a basal conglomeratic facies, together with siltstone/pelite and sandstone/psammite, which occurs intermittently above the unconformity. Both sequences are several (>3 to 5 km) kilometres thick and are typified by monotonous, coarse to very coarse (meta)sandstone with local pebble lags and some finer grained sandstone and minor muddy/pelitic layers becoming more frequent at higher stratigraphical levels. The two sequences lack marker horizons of different lithologies.

Sedimentary structures in both the Applecross-Aultbea and A 'Mhoine formations are comparable in style, scale and frequency: metre-thick cross-stratified beds, unidirectional trough cross-bedding and nested channels 1-5 m deep. Soft-sediment deformation structures are common and include metre-scale contorted bedding, oversteepened to overturned cross-beds, small-scale sag-structures involving heavy mineral bands, and these structures are typically confined to single beds (this study;

Selley *et al.* 1963; Selley 1969; Owen 1995; Nicholson, 1993; Williams, 1970, 2001; Stewart, 2002 for the Torridon Group). Both deposits are fluviatile, and were rapidly deposited in a high-energy, braid plain environment (this study; Williams 1969a; Nicholson 1993, Williams 2001; Stewart 2002).

Age of deposition

The youngest U-Pb age on detrital zircons from the A 'Mhoine Formation, dated at 1032 ± 32 Ma (Friend *et al.* 2003), is within error of the youngest detrital zircon ages of 1060 ± 18 Ma and 1046 ± 26 in the Applecross and Aultbea formations respectively (Rainbird *et al.* 2001). Rb/Sr ages from mudstone from the Applecross Formation are 994 ± 48 Ma and 977 ± 38 Ma and have been interpreted to date diagenesis (Turnbull *et al.* 1996). The Glenfinnan and Loch Eil groups are intruded by the *c.* 870 Ma West Highland Granite Gneiss Suite (Friend *et al.* 1997; Millar 1999) and this date is generally taken as the minimum age of Moine Supergroup. Thus, deposition of the Torridon Group occurred after ~1050 Ma and probably around *c.* 980 Ma, whilst deposition of the Morar Group occurred sometime between ~1030 and ~870 Ma, so that the age constraints overlap. It is likely that both the Applecross/Aultbea and the A 'Mhoine Formations were deposited between *c.* 1000 and 950 Ma.

Detrital zircon ages

Detrital zircon data from the Torridon, Morar and adjacent groups, obtained by Rainbird *et al.* (2001), Friend *et al.* (2003) and Cawood *et al.* (2004), are summarised in Figure 7. The detrital zircon age pattern of the A 'Mhoine Formation (Friend *et al.* 2003) shows a sharply defined dominant cluster at *c.* 1650 Ma, minor clusters at *c.* 1800 Ma and *c.* 1400 Ma and a few analyses between 1400 and 1000 Ma. Additionally, *c.*8 % of analysed grains were Archaean in age. The detrital zircon age patterns of the Loch Eil and Glenfinnan groups (Friend *et al.* 2003; Cawood *et al.* 2004) differ considerably from the Morar Group pattern: most zircons are younger than *c.* 1500 Ma and there is no clearly defined 1650Ma cluster.

Similarly, the detrital zircon age patterns of the Applecross Formation and the Aultbea Formation both show a sharply defined cluster at *c.* 1650 Ma and a smaller cluster at *c.* 1800 Ma (Rainbird *et al.* 2001). Some Archaean grains (25% and 15% respectively) occur, as well as a small, broad cluster between *c.* 1200 and 1000 Ma. In contrast, the underlying Stoer Group shows a dominant Late Archaean detrital zircons population (Figure 7f), with a peak at 2900 – 2700 Ma and the youngest zircon is *c.* 1740 Ma (Rainbird *et al.* 2001).

Overall, the detrital zircon age patterns of the Morar and Torridon groups have more in common (including the same dominant peak at *c.* 1650 Ma) with each other than with the sequences with which they are normally associated.

Geochemistry

Stone *et al.* (1999) noted broad geochemical similarities between the 'Torridonian' and the Moine Supergroup, based on regional stream sediment geochemistry (Institute of Geological Sciences, 1982). In contrast, Stewart (2002) noted that boron concentrations in stream sediment over the Moine are 2 – 5 times lower than in the Torridon Group, and discounted a correlation on that basis. However, boron is a highly mobile element and can be depleted by a factor of 2 or more during medium-grade metamorphism (Moran *et al*. 1992). Therefore, significant boron depletion can be expected in the Morar metasediments and boron (and other fluid-mobile elements) should not be used to compare and contrast unmetamorphosed and metamorphosed rocks. Virtually all other elements analysed for stream sediment geochemistry in Sutherland show very similar values for the Torridon and Morar groups (Institute of Geological Sciences, 1982).

The analysed whole-rock geochemistry of the A 'Mhoine Formation psammites is compared in Table 1 with analyses from sandstones of the Applecross – Aultbea formations (van de Kamp & Leake 1997; Stewart & Donellan 1992) and Sleat Group (Stewart, 1991). Generally, the arkosic Sleat Group rocks contain more Al, Fe, Ca and Na, with concomitantly less Si; on the log (Fe_2O_3/K_2O) / log (SiO_2/Al_2O_3) plot (Herron, 1988) they plot close to the wacke field (Figure 6); these rocks are clearly less mature than the Morar and Torridon group rocks. The A 'Mhoine Formation and Torridon Group rocks are quite similar, and plot in overlapping fields (Figure 6). The range of SiO_2, TiO_2, Al_2O_3, Fe, MgO and K_2O within the Morar samples overlaps with those from the Torridon, similarly so for most trace elements. Calcium and strontium are both higher in the A 'Mhoine Formation (Table 1); this would suggest a higher component of calcic over sodic and potassic feldspar in the detritus; alternatively albitisation may have selectively affected the Torridon Group. The Torridon group sandstones are all arkosic, whilst some A 'Mhoine Formation rocks are subarkosic. Also, the Chemical Index of Alteration (CIA = Al_2O_3 /(Al_2O_3 + CaO+ Na_2O + K_2O; Nesbitt & Young, 1982) is somewhat lower for the A 'Mhoine Formation. Overall, the small differences between the

A 'Mhoine Formation and the Applecross and Aultbea formation rocks can be well explained by better sorting and slightly higher maturity of the A 'Mhoine Formation, as this tends to lower the CIA by removing more clay from the sand (Nesbitt *et al*. 1996). Better sorting is expected if the Morar Group was deposited farther downstream from the Torridon Group. There are no significant differences between the geochemistry of the Applecross, Aultbea and A 'Mhoine formations, and geochemistry can certainly not be used to discount a correlation (*cf*. Stewart 2002). Overall, we conclude that the Applecross-Aultbea Formation and the A 'Mhoine Formation can be correlated, without much lateral variation, across the Moine Thrust.

Detritus provenance

Williams (2001) and Stewart (2002) suggested the Lewisian Gneiss Complex as a source area for the Applecross Formation, whilst van de Kamp & Leake (1997) and Rainbird *et al.* (2001) suggested the Grenville Orogen as the main source. For the Moine Supergroup as a whole, Friend *et al.* (2003) and Cawood *et al.* (2004, 2007) suggested a more general Laurentian provenance. All suggested source areas lie to the west, consistent with the dominant palaeocurrent directions.

Broadly speaking, the Laurentia craton (and the Lewisian Gneiss) is dominated by Late Archaean rocks with subordinate *c.* 2100 – 1800 Ma Palaeoproterozoic orogenic belts (e.g. Torngat, Trans-Hudson see Figure 8). Only some of these belts produced juvenile crust, others mainly reworked Archaean crust (Hoffman 1988), so that Palaeoproterozoic felsic igneous rocks are relatively rare. A large belt of juvenile crust dated between 1800 – 1700 Ma (Yavapai and Mazatzal Province and Ketilidian – Makkovik belt) lies south and southwest of the Archaean craton. In Labrador, abundant Mesoproterozoic anorogenic magmatism occurred between 1460 and 1420 Ma and between 1350 and 1290 Ma (Nain Plutonic Suite). Most of these latter plutons lie north of the Grenville Front.

The Grenville Orogen in North America comprises several Meso-Palaeoproterozoic terranes that were amalgamated, reworked and exhumed between 1100 – 950 Ma. About 50% of the currently exposed rocks of the Eastern Grenville Orogen are of igneous origin (Figure 8), but only a small proportion are syn-Grenville granitoids (Gower *et al*. 1991; Rivers 1997 and Gower & Krogh 2002). The bulk of the felsic igneous rocks are older and include Pre-Labradorian 1780 – 1710 Ma granitic orthogneisses and large volumes of Labradorian (1710 – 1600 Ma) calc-alkaline igneous rocks in the northern part of the orogen. The latter include the 600 km long, *c.* 1650 Ma Trans-Labrador batholith. In contrast, the southern part of the Grenville Orogen is dominated by Pinwarian granitoid intrusions (1520 - 1460 Ma) and the Adirondian anorthosite-mafic-granite suite (1200 – 1130 Ma). In eastern Canada, the main Grenville orogenic activity spanned the period between 1080 and 970 Ma, whilst syn- to post-orogenic granitic plutonism occurred between *c.* 1025 to 920 Ma. Ar/Ar cooling ages suggest significant uplift and erosion between 980 and 930 Ma (Haggart *et al.* 1993).

From the aerial extent of magmatic rocks, it is possible to predict in a qualitative manner what age ranges of detrital minerals would be expected from either the Grenville Orogen or from Laurentia outwith the Grenville Belt, bearing in mind that high-level parts of the orogen are missing, having already been unroofed. Two such 'predictive' detrital mineral age patterns for the Grenville Orogen and the Laurentian cratonic interior are shown in Figure 7g, h.

The dominant *c.* 1650 Ma cluster of the Applecross, Aultbea and Morar zircons can be confidently linked to the Trans-Labradorian batholith (see also Rainbird *et al.* 2001), on the northern side within the Grenville orogen, (Figures 7, 8). The ~1200 - 1000 Ma cluster is derived from the Grenville orogen itself. The *c.* 1800 Ma cluster in the Torridon Group is most likely derived from the Ketilidian – Makkovik belt; it is highly unlikely that they are derived from the 'Laxfordian' *c.* 1850 Ma intrusions within the Lewisian Complex since these intrusions are minor (<2 %) in aerial extent compared to Archaean gneisses.

Noteworthy is also the scarcity (and absence in case of the Applecross Formation) of zircons dated between 1600 and 1250 Ma. Igneous rocks in this age bracket are common in Labrador and Greenland in the foreland of the Grenville Orogen, but are rare in the northern part of the orogen itself. This would suggest that during deposition of the basins, the immediate foreland of the Grenville orogen was covered and not available as a source area (Figures 7,8; see also Cawood *et al.* 2004, 2007). An exception is the small *c.* 1450 Ma cluster in the A 'Mhoine Formation. If this cluster is significant it may correlate with the Pinware terrane (see also Cawood *et al.* 2004), and relate to occasional southward stream capture across a drainage divide in the Grenville orogen.

The relatively minor, variable component of Archaean age argues against the Lewisian Gneiss or the Laurentain Craton as the *main* source. Nevertheless, the 8 – 25% Archaean grains must have come from the cratonic interior, as little or no Archaean material appears to be incorporated into the Grenville Orogen (Figures 7, 8). In the lowermost Applecross Formation, some Archaean grains may be of Lewisian origin because the high (100-600m) palaeorelief means that Lewisian hills remained exposed while the first few hundred metres of Applecross sandstones were being deposited.

Overall, the Grenville Orogen is likely to have provided the bulk of the detritus of the Torridon and Morar Group, with a small input from the Makkovikian-Ketilidian and the Archaean Laurentian Foreland. A general Laurentian source outwith the Grenville Orogen, let alone a Lewisian Gneiss source, is not compatible with the detrital zircon age patterns (see also Cawood *et al*. 2004, 2007).

Basin interpretation

If the Morar and Torridon groups can be correlated and were deposited in the same basin, what was its setting? Previously, the Torridon and Morar groups have been interpreted as separate rift basins (Stewart 1982; Williams 2001; Stewart 2002 and references therein; Soper *et al*. 1998) but this interpretation is problematic.

Rift sedimentation and subsidence is primarily controlled by episodic faulting and basin subsidence. This results in alternating periods of quiescence and progradation of coarse clastic sediment into finer-grained and commonly lacustrine basinal settings. The net result is a stratigraphical framework replete with lateral and vertical facies changes, e.g. the Tertiary extensional basins in the Death Valley region, USA (Wright & Troxel 1999), the Suez Rift (Jackson *et al.* 2006) and the Jurassic basins of the North Sea (Underhill 1998). In addition, volcanic, evaporitic and lacustrine deposits are common in rift-basins. The Torridon and Morar groups exhibit none of these features. In fact, few, if any rift basins (particularly half grabens) are characterised by >5km vertically and >200 km horizontally similar siliciclastic sediments (see also Nicholson, 1993; Prave 1999; Cawood *et al*. 2004).

The detrital zircons show a distal, rather than proximal source. Continental rift-basins typically have a proximal source, with commonly a large age difference between the youngest age of detritus and the onset of sedimentation (e.g. Stoer Group, Figure 7f, Rainbird et al. 2001).

The Minch Fault (Figure 1) has been invoked as a large-scale basin-bounding fault to the suggested Torridon rift basin (Williams 1969b, 2001, Stewart 2002). Williams (1969b, 2001) argued that the Torridon Group consisted of a series of alluvial megafans with their apexes near the Minch Fault. Nicholson (1993), however, showed that the palaeocurrents do not support such fans. Moreover, the pebble content and the detrital zircon data do not match a detrital source in the Outer Hebrides (composed mainly of Archaean rocks). Also, there is no evidence of syn-depositional fault activity; nowhere along the basal Torridon unconformity, well exposed over several hundred kilometres, is there evidence for syn-Applecross-Formation extensional faults.

The abundance of soft-sedimentation deformation in the Torridon Group has also been used to argue for frequent seismic activity and hence rifting. However, convolute bedding can be generated without seismicity by bed liquidisation during rapid deposition of water-saturated sand - in combination with a high water table (Selley *et al.* 1963; Selley 1969; Williams 1970; Nicholson 1993; Owen 1995; Williams 2001). The lack of terrestrial vegetation during the Neoproterozoic would have exacerbated such conditions (e.g. Eriksson *et al*. 2001).

Nicholson (1993) and Cawood *et al*. (2004) suggested an intracratonic basin setting for the Torridon Group and Moine Supergroup, respectively. Intracratonic basins, however, are typically long-lived and slowly subsiding, are sensitive to environmental change and hence contain significant vertical facies changes, the Neoproterozoic to Palaeozoic Taoudeni Basin (West Africa) being a good example (Bertrand-Sarfati *et al.* 1991). A major problem, therefore, is to provide sufficient accommodation space for rapid deposition of a 5 km of laterally and vertically uniform siliciclastic succession.

Foreland Basin setting

In contrast, there is a growing body of work that suggests that the Torridon Group was deposited as a non-marine molasse, in a foreland basin setting (Rainbird *et al.,* 2001; Kinnaird *et al.,* 2007). This model explains the distal provenance of the detrital zircons analysed from the Torridon Group. Deposition in a trunk river system in an axial, orogen-parallel foreland-basin setting, best explains the features observed in both the Applecross-Aultbea and A 'Mhoine formations. The envisaged basin would be analogous to the modern-day Ganges basin, in that the preserved part of the basin would have been deposited in a braided river system flowing in front of, and generally parallel to, the orogen. The position of the Grenville Orogen to the south (present-day orientation), and the easterly to north-northeasterly directed palaeocurrents fit such a palaeogeography. An orogen-parallel foreland-basin setting is further supported by:

1) Age. Accepting that the age of deposition of the Applecross-Aultbea and A 'Mhoine formations is broadly equivalent, then the constraint for their deposition at between *c.* 1000 and 950 Ma overlaps with the last stages of the Grenville Orogeny. The intrusion of late-orogenic granites, decompression metamorphism and metamorphic cooling in the Grenville Orogen all occurred between 1025 – 950 Ma (e.g. Gower *et al.* 1991; Haggart *et al.* 1993; Gower & Krogh 2002; Cox *et al.* 2002); such processes are generally accompanied by overall unroofing of the orogen, resulting in the formation of an approximately coeval foreland basin.
2) Sedimentology. The Applecross-Aultbea and A 'Mhoine Formations comprise a *c.* 5 km thick sequence of alluvial-fluvial siliciclastic rocks deposited in a wide braid plain system. The basin was characterised by large, relatively deep rivers, high peak run-off and rapid deposition. Rapid deposition of a thick sequence requires rapid, sustained subsidence. These are features typical for molasse-type foreland basin (e.g. Pfiffner 1986). Foreland basins typically have subsidence rates 3 – 10 times faster than most rift basins, and can achieve 2-3 km of subsidence in less than 10 Ma (e.g. Homewood *et al.* 1986); this provides a good explanation for the deposition of a great thickness of high-energy clastic sediments over a wide area.
3) Provenance. The detrital zircon age patterns suggest that the Grenville Orogen was the *main* source of detritus; this detritus comprises both syn-orogenic and pre-orogenic material uplifted in the orogen (e.g. the *c.* 1650 Ma cluster). Such a combination of syn-orogenic and pre-orogenic material is common in foreland basins, as shown by Hercynian and Alpine detrital micas in the North Alpine Foreland Basin (von Eynatten & Wijbrans 2003). Orogen-parallel foreland basins have a fore-bulge, so that part of the drainage and hence a minor component of the detritus originate from the cratonic interior. This is consistent with the variable amount of *c.* 1800 Ma and Archaean grains present in the successions; this detritus most likely originated from the area north of the Grenville orogen, e.g. Ketilidian and cratonic parts of Laurentia.

Many foreland basins show an evolution from deep-water clastic sedimentation ('flysch') during early orogenesis, followed by shallow marine and finally non-marine ('molasse') sedimentation (e.g. Pfiffner 1986; Miall 1995). The earliest sediments are commonly caught up in foreland-propagating thrust systems and are uplifted and eroded, thus having a low preservation potential. The younger and shallower ‘molasse’ sediment onlap far onto the foreland and parts of this ‘molasse’ system may thus escape subsequent thrusting, uplift and erosion. It is this part of the foreland basin system that is preserved in the Morar and Torridon groups. The 1080 – 1050 Ma Flinton Group in Eastern Ontario, Canada, may represent earlier, more varied and partially marine foreland basin rocks caught up in the Grenville orogen (Moore & Thompson 1980), but similar rocks appear not to be present in Scotland.

Displacement on the Moine Thrust

The Moine Thrust separates the Torridon and Morar groups, and the displacement along this major structure must be taken into account for their correlation or otherwise. The total displacement of the Moine Thrust Zone *as a whole* is generally assumed to be greater than 100 km (Strachan *et al.* 2002). However, Torridon Group rocks occur in the highest thrust sheets, so that the Torridon basin must have extended considerably farther east with respect to the Foreland.

Consequently, it is only the Moine Thrust itself and its associated mylonites that truly separate the Torridon and Morar groups. The total displacement taken up by these structures is difficult to constrain. It is more than 20 km, as evidenced by the down-faulted block of Moine Mylonites at Faraid Head (Peach *et al.* 1907) and must be sufficient to have emplaced medium-grade metamorphic rocks over unmetamorphosed rocks. A reasonable estimate is probably *c.* 100 km.

The broadly eastward palaeocurrents in the sediments are approximately co-axial to the WNW-directed thrust transport direction and there is no evidence for major (>100 km) strike slip movement along the Moine Thrust or its trace. Therefore the simplest original relationship between the Torridon and Morar Group is that the latter was deposited some 100 – 200 km downstream from the former. Such a distance is in fact very small for braided river systems in sedimentary basins, which can easily measure >1000 km along their axis of flow, as seen in both ancient and modern examples (e.g. Bridge 2003; Smith & Rogers 1999).

Regional implications

We have shown that the Applecross-Aultbea formations and the A ‘Mhoine Formation are correlative parts of the same sequence, simply repeated by the Moine Thrust. This invalidates the formal distinction between the Torridon Group and the

Morar Group and hence the Moine Supergroup (*cf*. Holdsworth *et al*. 1994; Trewin 2002), and implies that the Proterozoic stratigraphical framework in Scotland needs to be revised. One solution is to include the Torridon Group into the Moine Supergroup, but abandon the term Morar Group. Alternatively, the term 'Moine Supergroup' could be abandoned, and the A 'Mhoine Formation included in the Torridon Group, as the latter is better exposed.

Correlations farther south in the Skye, Morar and Knoydart areas are also likely, but their details require further study, partially because the stratigraphy of both the 'Torridonian' and the Morar Group in these areas is more diverse (Ramsay & Spring, 1962; Sutton & Watson 1964; Holdsworth *et al*. 1994; Stewart 2002). Sutton & Watson (1964) proposed the correlation Sleat Group = lower Morar Group and Torridon Group = upper Morar Group (Figure 2); this proposal deserves renewed attention. Furthermore, it is unclear whether the A 'Mhoine Formation correlates southward with the Upper or the Lower Morar Psammite Formation in Morar, since the intervening ground has never been mapped in detail. It is prudent to await the outcomes of further studies before erecting a revised stratigraphy in Scotland, while noting that the current framework is unsatisfactory.

In addition, the 'Hebridean Terrane' and the 'Northern Highlands Terrane' (Bluck *et al*. 1992) share much of their pre- and post-Caledonian evolution and should be regarded as parautochthonous, and not as exotic to each other (Bluck *et al.* 1997; Oliver 2002). The Moine Thrust is better regarded as the Caledonian orogenic front, rather than a significant terrane boundary.

CONCLUSIONS

The A 'Mhoine Formation (Morar Group) in the Northern Highlands is characterised by *c.* 5 km of uniform psammite, devoid of marker horizons, and was deposited in a high-energy fluvial environment characterised by braided rivers flowing from the west. The A 'Mhoine Formation and the Applecross-Aultbea Formation (Torridon Group) are similar in terms of their age of deposition, sedimentology, stratigraphical position, geochemistry, detrital zircon age pattern, age constraints and overall sediment transport direction. The detrital zircon distributions in both groups show that they share a similar, distal source, namely parts of the Grenville Orogen, the final stages of which overlap the age of deposition. It is therefore concluded that the

Applecross-Aultbea and the A 'Mhoine formations are direct correlatives and formed part of an axial trunk fluvial system flowing in front of the Grenville Orogen, forming an orogen-parallel foreland basin. This reinterpretation implies that the currently accepted Proterozoic stratigraphical framework for the Scottish Highlands is in need of revision. The two groups should be regarded as parautochthonous

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List & Captions for Figures

Fig. 1. Geological map of the Northern Highlands l. Moine-undivided: includes the East Sutherland Moine (ESM), the Tarskavaig Moine (TM) and the Rosemarkie - Cromarty Moine Inliers (RC). Other abbreviations: BHT = Ben Hope Thrust; CF = Coigach Fault; OIFZ = Outer Isles Thrust Zone; MT = Moine Thrust; NTZ = Naver Thrust Zone, SBT = Sgurr Beag Thrust. Inset shows location of Figure 3. Modified after British Geological Survey (1989 a, b).

Fig. 2. Stratigraphy of the Torridonian sequence and Morar Group in Northern Scotland (all thicknesses are approximate; units higher than the Glenfinnan Group not shown). (**a**) Torridonian sequence in NW Highlands; (**b**) Morar Group in Northern Highlands; (**c**) Torridonian sequence on Skye; (**d**) Morar Group in Morar. Compiled after Holdsworth *et al.* (1994) and Stewart (2002).

Fig. 3. (**a**) Geological map of the Ben Hee and Glen Cassley area. Areas with well-preserved sedimentary structures are outlined. (**b**) Schematic cross-sections through the Ben Hee - Cassley area. The A'Mhoine Formation occurs west (below) the Achness Thrust, whereas the psammite east (above) the Achness Thrust are assigned to the Altnaharra Formation.

Fig. 4. Photographs showing sedimentary structures within the A 'Mhoine Psammite Formation in the Ben Hee and Glan Cassley area.
(**a**) Slightly deformed gritty psammite showing coarse, gritty grain sizes and feldspar clasts. Carn nam Bò Maolo [NC 4431 0904], BGS Photo 616530.
(**b**) Nested co-sets of trough cross-beds in medium psammite (scale bar is 10 cm long). Sediment transport was broadly NNE directed. Eastern slopes of Beinn an Eòin [NC 4087 0941], BGS Photo 616564.
(**c**) Succession displaying interstratified nested trough cross-bed and plane-parallel sets at base overlain by planar cross-stratified sets (the topmost set is thinned due to erosion by the overlying trough cross-bed set) followed by large (metre-scale) trough cross-bed sets forming the upper part of the outcrop (map case is 30 cm high). Sediment transport associated with trough cross-beds was NNE to ENE and the planar

cross-strata display east-directed lateral migration. Carn Mor north of Strath Oykel [NC 4038 0453]. BGS Photo 616551.
(**d**) Nested, m-scale co-sets of stacked trough cross-beds infilling an overall channel form. Note decrease in size of sets up to the base of next overlying channel (the erosive base of this channel is just to right of the ~1.8m geologist) [NC 440 389].
Soft-sediment deformation structures; note how each interval is erosionally truncated by overlying, undeformed stratification: (**e**) convolute bedding and oversteepened foresets in fine-medium psammite (compass is 9 cm wide) NW of Glencassley Castle [NC 4358 0807] BGS Photo 618131; (**f**) 2.5m scale dewatering pipes in coarse psammite, just below ~1.8m geologist [NC 4349 3899].

Fig. 5. Sedimentary log of a typical section of the A 'Mhoine Formation showing interstratified nature of trough and planar cross-bedding and planar stratification. Most bed geometries at outcrop scale are lens shaped and define nested channels having high width:depth ratios. Note that grain size indications, particularly for the finer size ranges, can only be qualitative due to metamorphic recrystallisation. Eastern slopes of Beinn Direach, Ben Hee Area [NC438 393].

Fig. 6. a) Classification plot for sandstones and shales (Herron 1988) with samples from Morar, Torridon and Sleat groups. **b)** Al_2O_3 – K_2O – CaO+Na_2O diagram (top half only). Arrows indicate weathering trend from a granitic bedrock source and sorting trend (Nesbitt *et al.*, 1996).

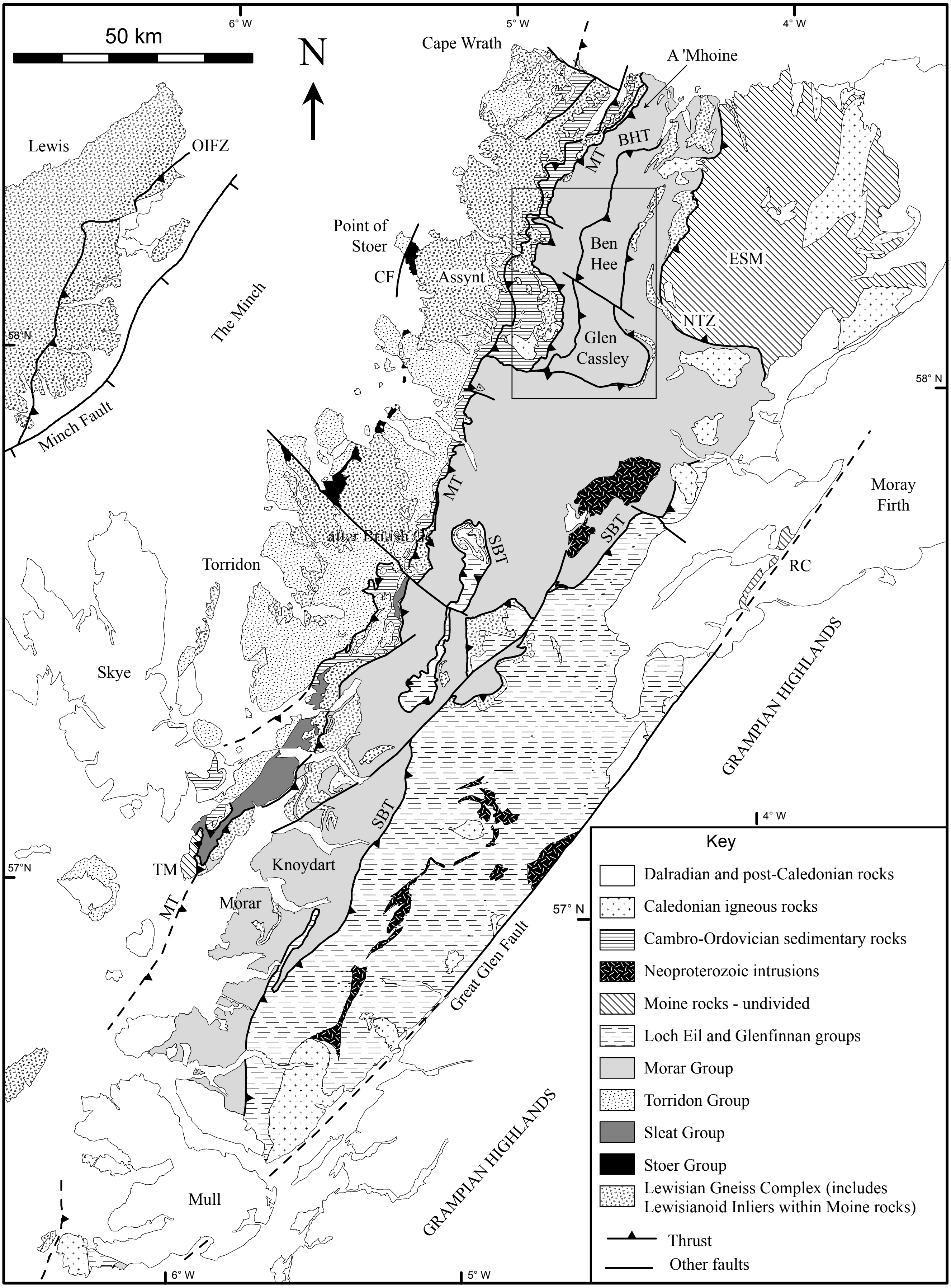
Fig. 7. Detrital zircon age patterns for (**a**) Loch Eil Group, (**b**) Glenfinnan Group and (**c**) Morar Group (A 'Mhoine Formation) (Friend *et al.* 2002; Cawood *et al.* 2004), (**d, e**) Torridon Group (Rainbird *et al.* 2001), (**f**) Stoer Group, (Rainbird *et al.* 2001) and (**g**) predicted detrital zircon ages for detritus derived from the Grenville Orogen (based on data from Gower & Krogh 2002) and (**h**) Laurentia outwith the Grenville Orogen (based on data from Hoffman 1988). Note: inherited grains refers to zircons from partial melts within the metasedimentary successions.

Fig. 8. Laurentia and Baltica in a possible Early Neoproterozoic reconstruction – note that the exact position of Baltica is uncertain. Only juvenile Palaeoproterozoic belts are shown; belts of reworked Archaean rocks are not shown. Position of Torridon and

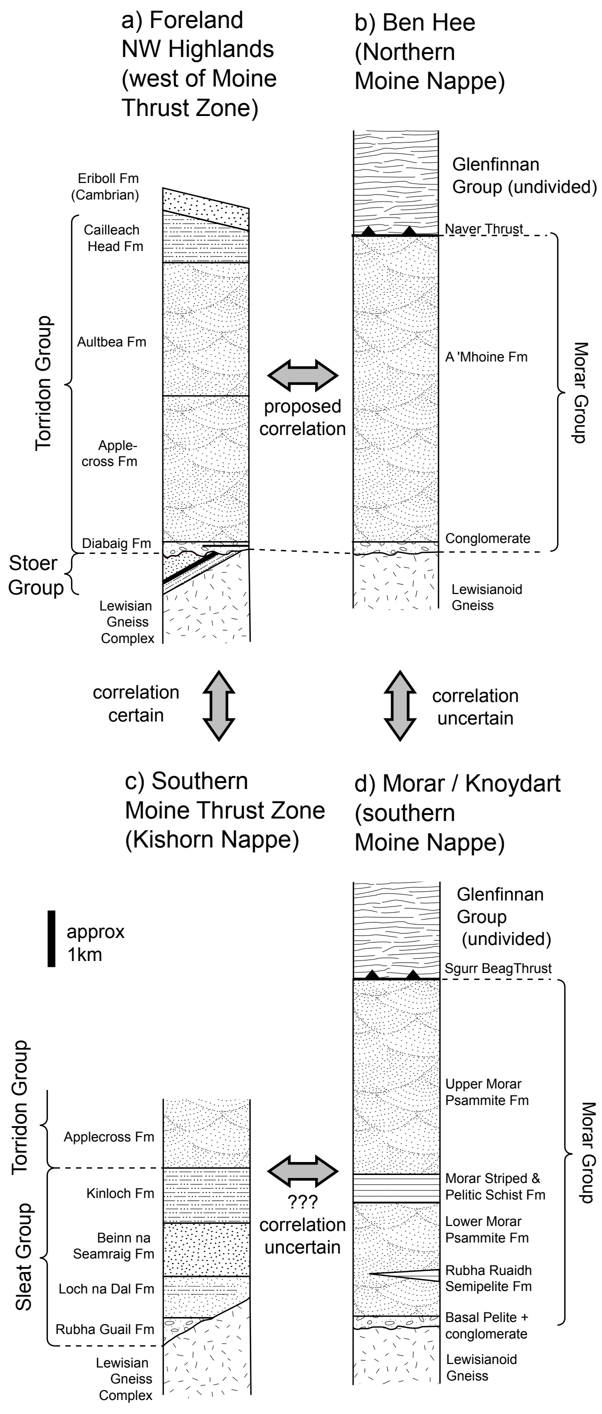
Morar groups is shown. Inset shows the Grenville Orogen in Eastern Canada. After Hoffman (1988), Winchester (1988), Rivers (1997) and Rainbird *et al.* (2001).

Table 1. Chemical analyses of sandstones and psammites from the Torridon Group, A 'Mhoine Formation and Sleat Group. A 'Mhoine Formation samples are ordered stratigraphically.

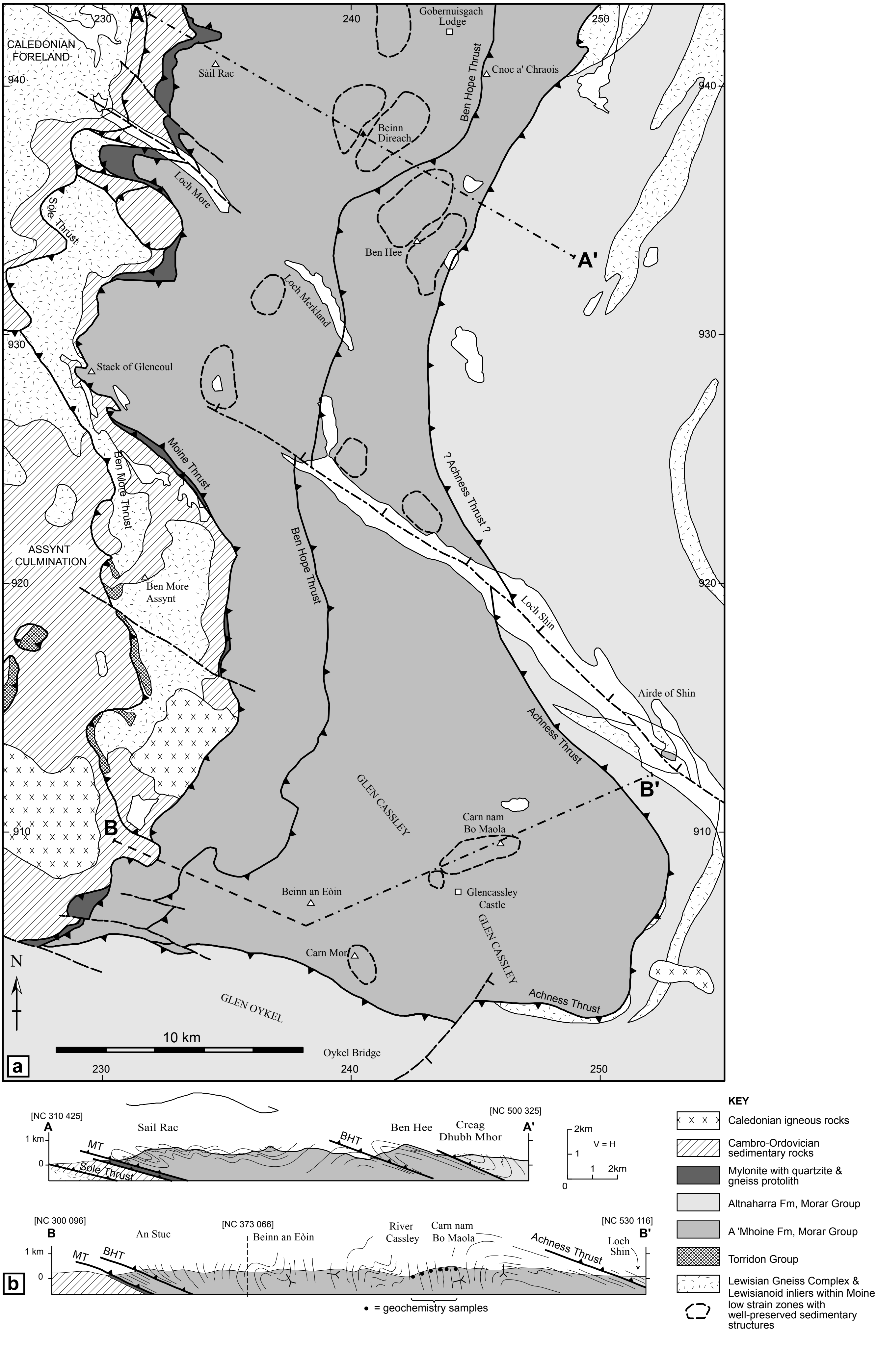
(1) BGS analyses; this study; (2) after van de Kamp & Leake (1997); (3) after Stewart & Donnelan (1992); (4) after Stewart (1991). CIA = Chemical Index of Alteration (Nesbitt et al. 1996)



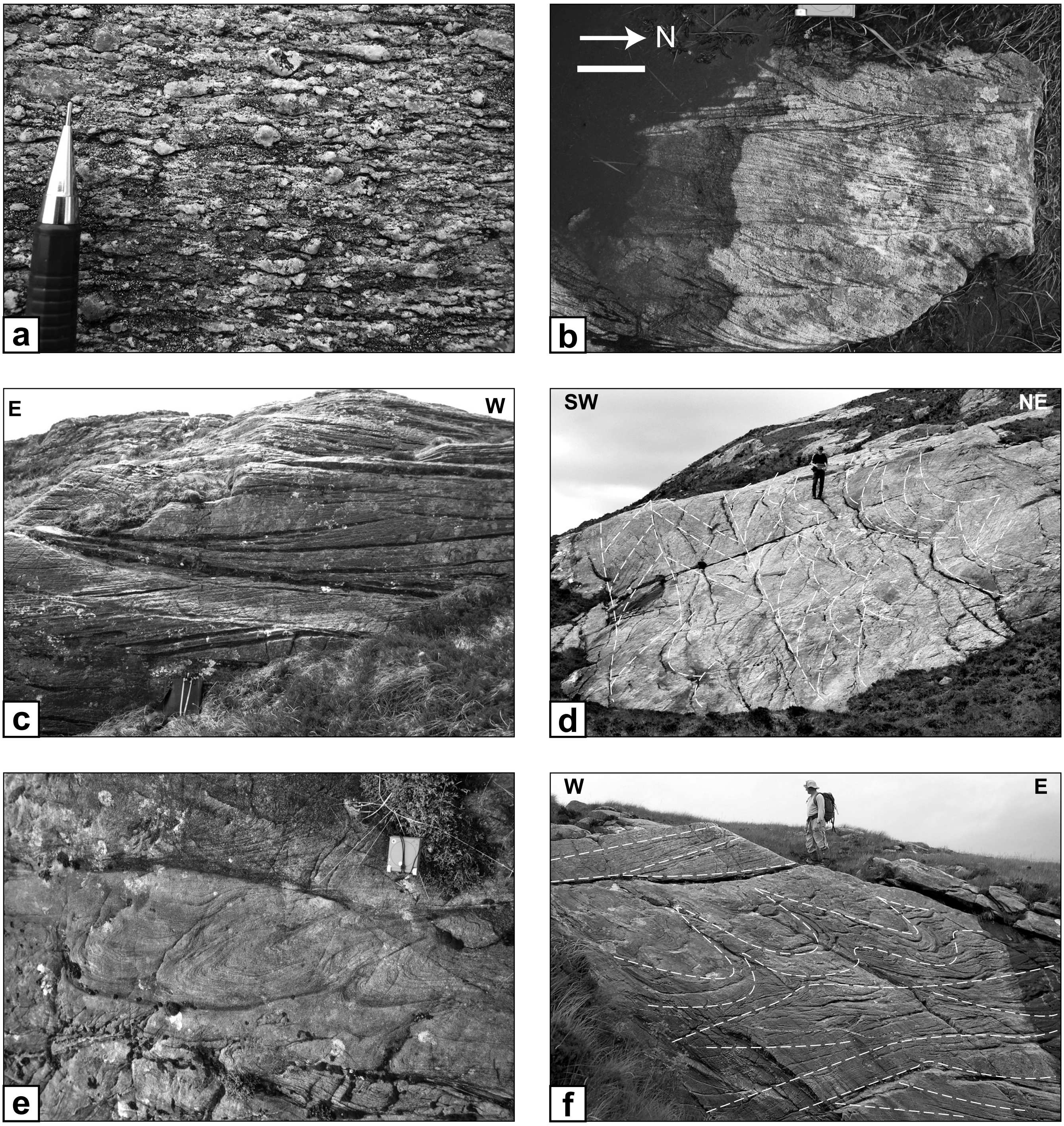
50 km
N
6° W
5° W
4° W
Cape Wrath
A 'Mhoine
Lewis
OIFZ
MT
BHT
Point of
Stoer
CF
Assynt
Ben
Hee
ESM
The Minch
NTZ
Glen
Cassley
58° N
Minch Fault
Moray
Firth
SBT
Torridon
RC
Skye
GRAMPIAN HIGHLANDS
Knoydart
TM
Morar
57° N
Great Glen Fault
Mull
Key
Dalradian and post-Caledonian rocks
Caledonian igneous rocks
Cambro-Ordovician sedimentary rocks
Neoproterozoic intrusions
Moine rocks - undivided
Loch Eil and Glenfinnan groups
Morar Group
Torridon Group
Sleat Group
Stoer Group
Lewisian Gneiss Complex (includes
Lewisianoid Inliers within Moine rocks)
Thrust
Other faults

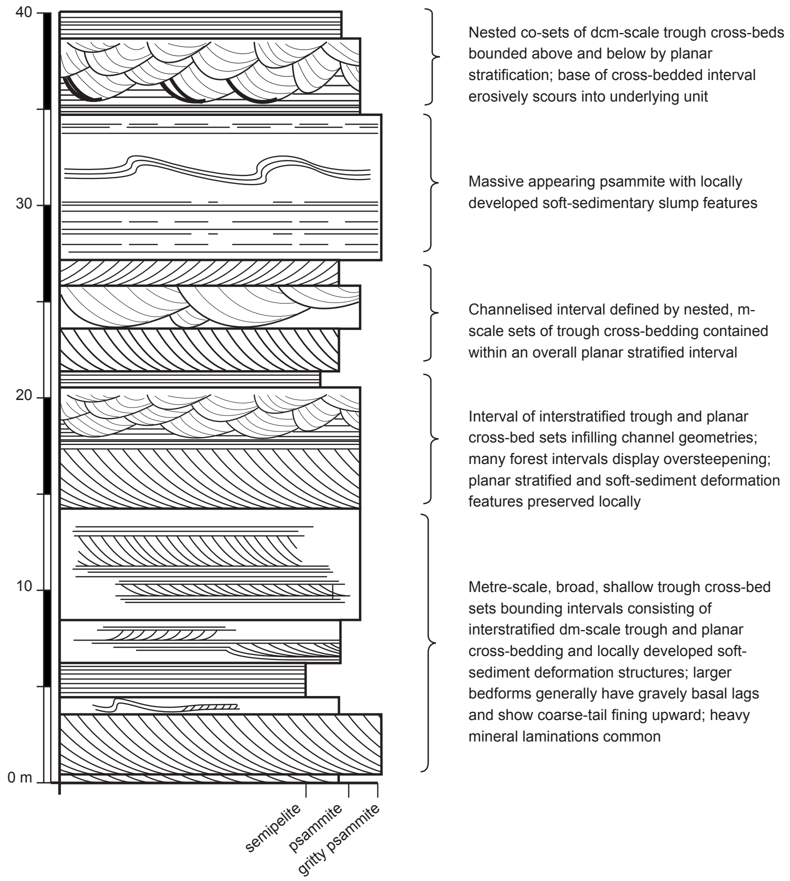


a) Foreland NW Highlands (west of Moine Thrust Zone)
b) Ben Hee (Northern Moine Nappe)
Eriboll Fm (Cambrian)
Cailleach Head Fm
Aultbea Fm
Torridon Group
Apple-cross Fm
Diabaig Fm
Stoer Group
Lewisian Gneiss Complex
proposed correlation
Glenfinnan Group (undivided)
Naver Thrust
A 'Mhoine Fm
Morar Group
Conglomerate
Lewisianoid Gneiss
correlation certain
correlation uncertain
c) Southern Moine Thrust Zone (Kishorn Nappe)
d) Morar / Knoydart (southern Moine Nappe)
approx 1km
Torridon Group
Applecross Fm
Kinloch Fm
Sleat Group
Beinn na Seamraig Fm
Loch na Dal Fm
Rubha Guail Fm
Lewisian Gneiss Complex
??? correlation uncertain
Glenfinnan Group (undivided)
Sgurr BeagThrust
Upper Morar Psammite Fm
Morar Striped & Pelitic Schist Fm
Lower Morar Psammite Fm
Rubha Ruaidh Semipelite Fm
Basal Pelite + conglomerate
Lewisianoid Gneiss
Morar Group

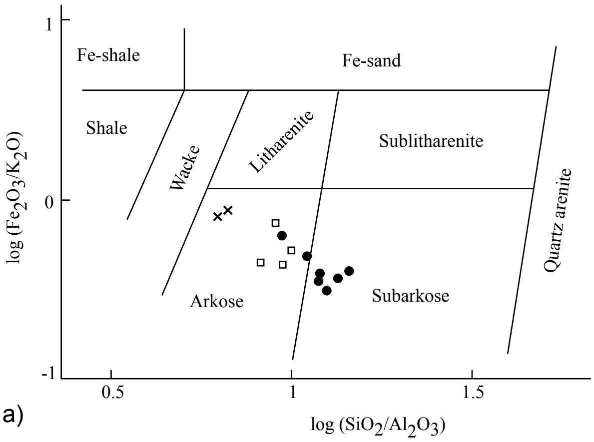


A
A'
B
B'
CALEDONIAN FORELAND
ASSYNT CULMINATION
Sàil Rac
Gobernuisgach Lodge
Cnoc a' Chraois
Beinn Direach
Loch More
Sole Thrust
Ben Hope Thrust
Ben Hee
Loch Merkland
Stack of Glencoul
Moine Thrust
Ben More Thrust
Ben More Assynt
? Achness Thrust ?
Loch Shin
Airde of Shin
Achness Thrust
GLEN CASSLEY
Carn nam Bo Maola
Beinn an Eòin
Glencassley Castle
Carn Mor
GLEN OYKEL
Oykel Bridge
N
10 km
230
240
250
940
930
920
910
a
[NC 310 425]
Sail Rac
1 km
0
MT
Sole Thrust
BHT
Ben Hee
Creag Dhubh Mhor
[NC 500 325]
2km
1
V = H
1
2km
0
[NC 300 096]
An Stuc
[NC 373 066]
Beinn an Eòin
River Cassley
Carn nam Bo Maola
Achness Thrust
[NC 530 116]
Loch Shin
b
● = geochemistry samples
KEY
Caledonian igneous rocks
Cambro-Ordovician sedimentary rocks
Mylonite with quartzite & gneiss protolith
Altnaharra Fm, Morar Group
A 'Mhoine Fm, Morar Group
Torridon Group
Lewisian Gneiss Complex & Lewisianoid inliers within Moine
low strain zones with well-preserved sedimentary structures

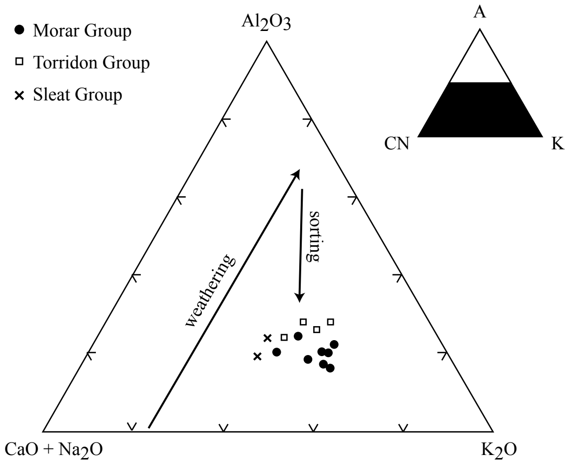

a
N
b
E
W
c
SW
NE
d
e
W
E
f



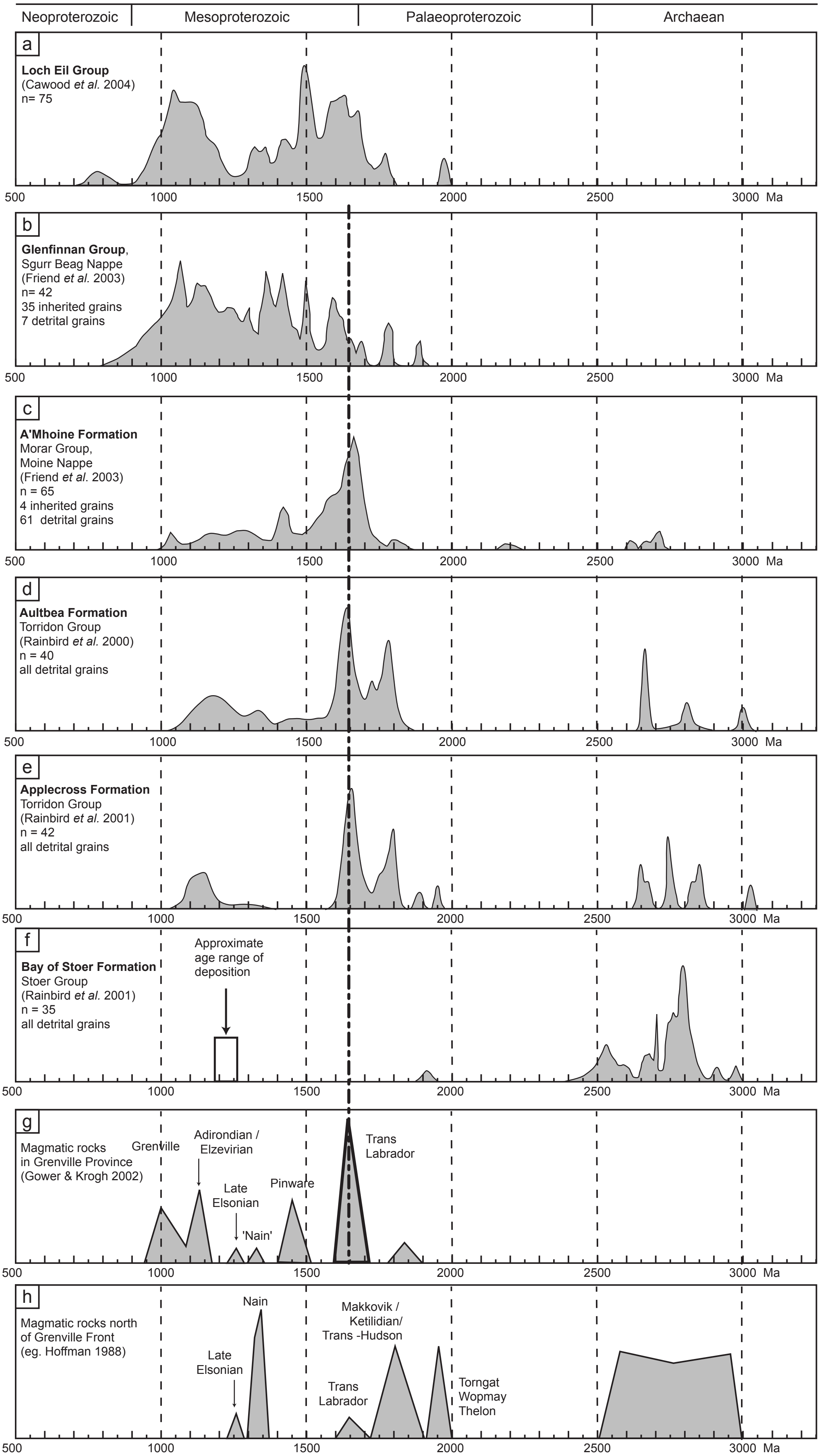
40
30
20
10
0 m
semipelite
psammite
gritty psammite
Nested co-sets of dcm-scale trough cross-beds bounded above and below by planar stratification; base of cross-bedded interval erosively scours into underlying unit
Massive appearing psammite with locally developed soft-sedimentary slump features
Channelised interval defined by nested, m-scale sets of trough cross-bedding contained within an overall planar stratified interval
Interval of interstratified trough and planar cross-bed sets infilling channel geometries; many forest intervals display oversteepening; planar stratified and soft-sediment deformation features preserved locally
Metre-scale, broad, shallow trough cross-bed sets bounding intervals consisting of interstratified dm-scale trough and planar cross-bedding and locally developed soft-sediment deformation structures; larger bedforms generally have gravely basal lags and show coarse-tail fining upward; heavy mineral laminations common


Fe-shale
Fe-sand
Shale
Wacke
Litharenite
Sublitharenite
Quartz arenite
Arkose
Subarkose
log (Fe_2O_3/K_2O)
1
0
-1
0.5
1
1.5
log (SiO_2/Al_2O_3)

a)


Morar Group
Torridon Group
Sleat Group
Al_2O_3
A
CN
K
sorting
weathering
CaO + Na_2O
K_2O

b)



Neoproterozoic
Mesoproterozoic
Palaeoproterozoic
Archaean
a
Loch Eil Group
(Cawood et al. 2004)
n= 75
b
Glenfinnan Group,
Sgurr Beag Nappe
(Friend et al. 2003)
n= 42
35 inherited grains
7 detrital grains
c
A'Mhoine Formation
Morar Group,
Moine Nappe
(Friend et al. 2003)
n = 65
4 inherited grains
61 detrital grains
d
Aultbea Formation
Torridon Group
(Rainbird et al. 2000)
n = 40
all detrital grains
e
Applecross Formation
Torridon Group
(Rainbird et al. 2001)
n = 42
all detrital grains
f
Bay of Stoer Formation
Stoer Group
(Rainbird et al. 2001)
n = 35
all detrital grains
Approximate
age range of
deposition
g
Magmatic rocks
in Grenville Province
(Gower & Krogh 2002)
Grenville
Adirondian /
Elzevirian
Late
Elsonian
'Nain'
Pinware
Trans
Labrador
h
Magmatic rocks north
of Grenville Front
(eg. Hoffman 1988)
Nain
Late
Elsonian
Makkovik /
Ketilidian/
Trans -Hudson
Trans
Labrador
Torngat
Wopmay
Thelon
500
1000
1500
2000
2500
3000 Ma

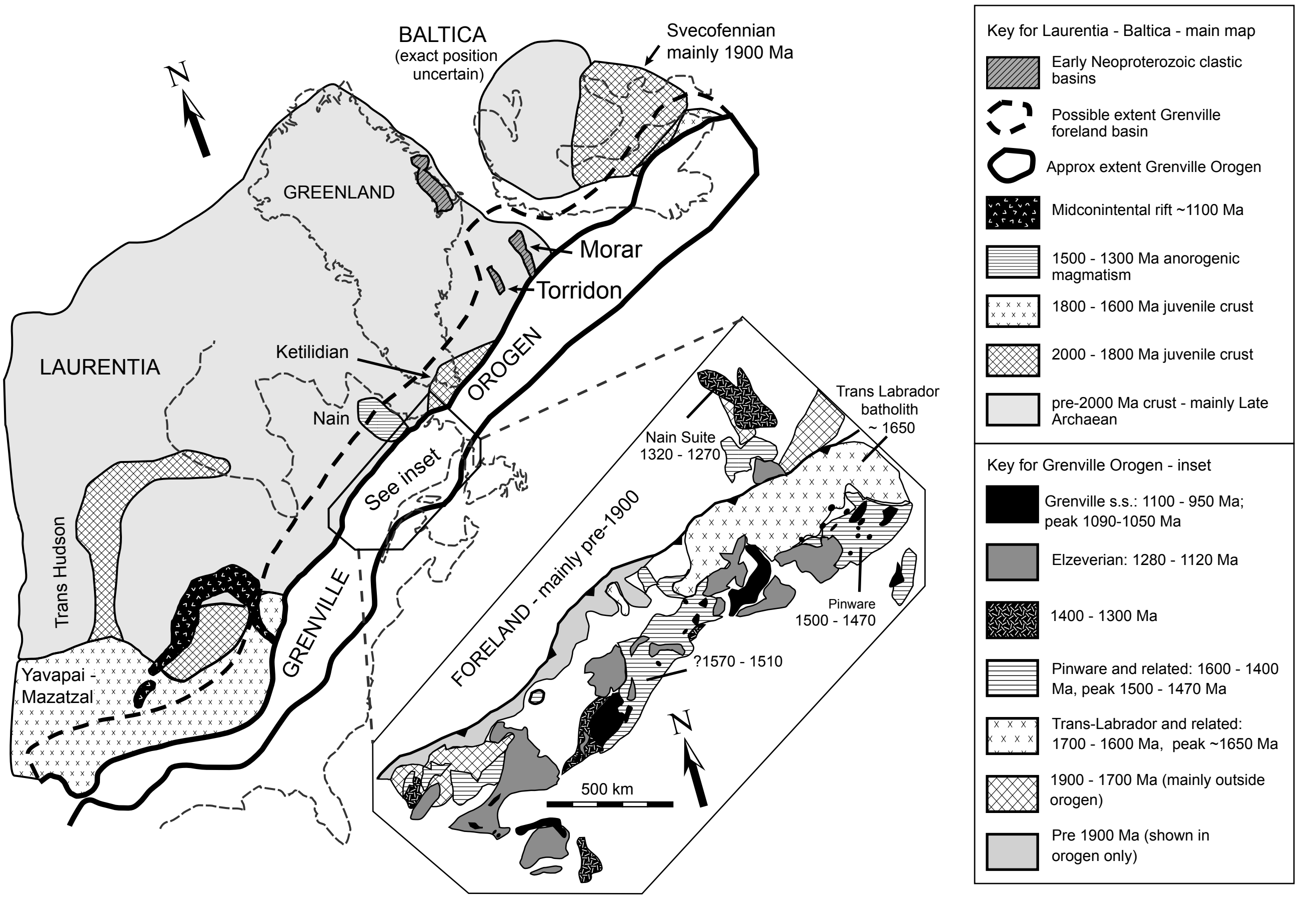

BALTICA
(exact position uncertain)
Svecofennian mainly 1900 Ma
N
GREENLAND
Morar
Torridon
LAURENTIA
Ketilidian
Nain
OROGEN
See inset
Trans Hudson
Yavapai - Mazatzal
GRENVILLE
FORELAND - mainly pre-1900
Nain Suite 1320 - 1270
Trans Labrador batholith ~ 1650
Pinware 1500 - 1470
?1570 - 1510
500 km
N
Key for Laurentia - Baltica - main map
Early Neoproterozoic clastic basins
Possible extent Grenville foreland basin
Approx extent Grenville Orogen
Midcontinental rift ~1100 Ma
1500 - 1300 Ma anorogenic magmatism
1800 - 1600 Ma juvenile crust
2000 - 1800 Ma juvenile crust
pre-2000 Ma crust - mainly Late Archaean
Key for Grenville Orogen - inset
Grenville s.s.: 1100 - 950 Ma; peak 1090-1050 Ma
Elzeverian: 1280 - 1120 Ma
1400 - 1300 Ma
Pinware and related: 1600 - 1400 Ma, peak 1500 - 1470 Ma
Trans-Labrador and related: 1700 - 1600 Ma, peak ~1650 Ma
1900 - 1700 Ma (mainly outside orogen)
Pre 1900 Ma (shown in orogen only)

Table 1. Chemical analyses of sandstones and psammites from the Torridon group, A ' Mhoine Formation and Sleat Group. (1) BGS analyses; this study; (2) after van de Kamp & Leake (1997); (3) after Stewart & Donnelan (1992); (4) after Stewart (1991).
A 'Mhoine Formation samples are ordered stratigraphically. CIA = Chemical Index of Alteration (Nesbitt et al. 1996)

	Morar Group A 'Mhoine Fm (1)								**Torridon Group** Applecross Fm			Aultbea Fm	**Sleat Group** Beinn na Seamraig Fm	Kinloch Fm
	ZY294	ZY288	ZY289	ZY290	ZY291	ZY292	ZY293		General (2)	Raasay (3)	Coigach (3)	Coigach (3)	Skye (4)	Skye (4)
	medium-coarse psammite (high in stratigraphy)	medium-coarse psammite	coarse psammite	medium-coarse psammite	coarse, gritty psammite	coarse, gritty psammite	coarse psammite (low in stratigraphy)	Median n = 7	n = 18	n = 10	n = 59	n = 25	n = 11	n = 16
Oxides as %														
SiO_2	81.8	84.71	87.93	86.16	85.66	86.71	84.12	85.91	82.82	85.27	82.9	82.55	75.43	76.65
TiO_2	0.36	0.2	0.14	0.12	0.22	0.16	0.33	0.18	0.3	0.31	0.32	0.29	0.61	0.55
Al_2O_3	8.45	7.49	5.91	6.68	6.98	6.27	7.45	6.83	8.61	8.27	9.01	9.85	11.75	11.68
Fe_2O_3 + FeO	1.92	1.34	1.01	0.96	1.12	1.11	1.62	1.115	1.48	1.48	2.27	1.8	3.39	3.13
MnO	0.04	0.03	0.04	0.02	0.02	0.03	0.04	0.03	0.04	0.03	0.03	0.02	0.07	0.06
MgO	0.4	0.28	0.14	0.2	0.24	0.17	0.25	0.22	0.86	0.23	1.24	0.83	0.64	0.52
CaO	0.87	0.4	0.49	0.48	0.32	0.32	0.47	0.435	0.17	0.26	0.08	0.01	1.74	1.07
Na_2O	1.8	1.4	1.15	1.22	1.03	1.14	1.24	1.185	1.38	1.94	1.78	1.52	2.34	2.61
K_2O	3.02	2.82	2.51	3.07	3.15	3.04	3.37	3.055	3.46	2.86	3.06	4.06	3.89	3.6
P_2O_5	0.03	0.01	<0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.09	0.04	0.04	0.28	0.26
H_2O									0.79					
LOI	0.56	0.62	0.35	0.31	0.62	0.42	0.56							
Total	99.37	99.39	99.77	99.32	99.45	99.47	99.58		99.93	100.74	100.73	100.97		
Trace elements (ppm)														
Ba	653	653	652	631	653	661	714	653		613	636	691		
Ce	38	30	18	24	23	20	37	23.5			37	53		
La	15	15	9	10	9	6	14	9.5			19	25		
Ni	6	5	3	4	4	4	5	4			4	2		
Rb	86	77	59	76	84	71	87	76.5		80	79	92		
Sr	168	131	148	121	117	135	140	133		98	60	61		
Th	5	4	3	3	4	4	5	4			6	7		
Y	14	9	6	7	7	6	9	7			8	12		
Zn	17	13	6	8	8	11	12	9.5		12	10	9		
Zr	212	116	79	79	101	98	172	99.5		173	172	206		
Na_2O/K_2O	0.60	0.50	0.46	0.40	0.33	0.38	0.37	0.39	0.40	0.68	0.58	0.37	0.60	0.73
SiO_2/Al_2O3	9.68	11.31	14.88	12.90	12.27	13.83	11.29	12.58	9.62	10.31	9.20	8.38	6.42	6.56
Rb/Sr	0.512	0.588	0.399	0.628	0.718	0.526	0.621	0.575			1.317	1.508		
Ca_2O/Na_2O	0.483	0.286	0.426	0.393	0.311	0.281	0.379	0.367	0.123	0.134	0.045	0.007	0.744	0.410
CIA	0.60	0.62	0.59	0.58	0.61	0.58	0.59	0.60	0.63	0.62	0.65	0.64	0.60	0.62