

**Tracking the evolution of the Grenvillian Foreland Basin:
constraints from sedimentology and detrital zircon and rutile in the Sleat
and Torridon groups, Scotland**

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Abstract

The Grenville Orogen, although occupying a key position in the Rodinia supercontinent, lacks a clear foreland basin in its type area in eastern Canada. Early Neoproterozoic siliciclastic rocks in northern Scotland, however, are now interpreted as remnants of a proximal Grenvillian foreland basin. Analysis of the sedimentology and detrital zircon and rutile of the Torridon and underlying Sleat groups provide new constraints on the evolution of this basin. Youngest U-Pb detrital zircon grains yield ages of 1070-990 Ma in both groups, consistent with a Grenvillian source. The proportions of older age components vary throughout the stratigraphy. The lower Sleat Group shows a dominant ca. 1750 Ma peak, likely derived from local Rhinnian rocks in Scotland and Ireland uplifted within the Grenville Orogen. In the upper Sleat Group and Torridon Group, detrital zircon peaks at ca. 1650 Ma and ca. 1500-1100 Ma become increasingly important. These latter peaks correspond with Labradorian Pinwarian, Elzevirian and early Grenvillian protolith ages within the eastern Grenville Province in Canada, and reflect exhumation and erosion of different mid-crustal complexes within that sector of the orogen. There is no difference in detrital zircon ages across the low-angle Sleat/Torridon unconformity. Detrital rutile in the Torridon Group yields a significant ca. 1070 Ma, Grenville-age peak, but older grains (1700-1200 Ma) also occur, suggesting derivation from the cool ($T < 600^{\circ}\text{C}$) upper orogenic crust. The detrital mineral data and sedimentology suggest the following evolution of the Grenvillian foreland basin in Scotland: i) early deposition in a narrow marine foreland basin (lower Sleat Group), sourced from the Irish-Scottish sector of the Grenville Orogen, with orogen-normal fill; ii) within the narrow Sleat Group basin a gradual switch to more distal sources in the Canadian sector of the Grenville Orogen, via axial transport; iii) an abrupt switch in basin dynamics (but not in source) across the Sleat-Torridon boundary to fluvial braidplain deposition in a much wider, Torridon-Morar basin; iv) followed by a gradual retrogradation of that basin. The Torridon-Morar groups represent a major denudational event of the Grenville Orogen that we infer was linked to more distal deposits in East Greenland, Svalbard and Norway.

1. Introduction

The 1.1-0.9 Ga Grenville Orogen, which played a central role in the assembly of the supercontinent Rodinia, was among the largest in Earth's history (Van Kranendonk and Kirkland, 2013). Its exposed remnants stretch from Texas, through inliers in the Appalachians and the 2000 km long Grenville Province in eastern Canada, thence via small inliers in Ireland and Scotland to southern Norway and Sweden, where it is known as the Sveconorwegian Orogen (Fig. 1; Gower, 1985; Rivers, 1997; Davidson, 2008; Bingen et al., 2008; Slagstad et al., 2013). In its type area, the Grenville Province in eastern Canada, and in the Sveconorwegian Orogen, the Grenville Orogen lacks a clear foreland basin (Rainbird et al., 2001, 2012; Davidson, 2008; Rivers et al., 2012). With the advent of detrital mineral dating, however, a number of early Neoproterozoic (c. 1000-960 Ma) successions in Arctic Canada, Scotland, East Greenland, Svalbard and Norway (Fig. 1) are now known to contain detrital zircon that can be linked to the Grenville Orogen (Rainbird et al., 1992, 1997, 2001, 2012; Watt and Thrane, 2001; Cawood et al., 2004, 2007, 2015; Dhuime et al., 2007; Kalsbeek et al., 2000; Kirkland et al., 2007, 2008; Petterson et al., 2009a; Kamo et al., 2011; Agyei-Dwarko et al., 2012). Most of these sequences were deposited at considerable distance from the Grenville Orogen, implying their detritus was transported across Laurentia by continental-scale river systems (Rainbird et al., 1992, 1997, 2012, in press). Similarly, remnants of more distal deposits, sourced from the Grenville Orogen occur in the southern United States (e.g., Mulder et al., 2017). These distal sequences were not deposited in foreland basins *sensu stricto*, that is basins in which accommodation space is primarily created by the load of the adjacent mountain belt (e.g., Beaumont, 1981; Jordan, 1995).

In North America, there are a number of remnants of more proximal sequences that were sourced from the Grenville Orogen and are interpreted to represent parts of the foreland basin *sensu stricto*, but these are concealed, strongly deformed or occur in a hybrid rift-foreland basin setting. They include (Fig. 1): (i) Small intra-orogenic basins, such as the Flinton Group, deposited between ca. 1225 and 1090 Ma (Moore and Thompson, 1980; Easton, 1992; Sager-Kinsman and Parrish, 1993), and the Battle Harbour succession, deposited between ca. 1200 and 1030 Ma (Kamo et al., 2011). These and other supracrustal remnants (Rivers et al., 2012) were folded and metamorphosed during the Grenvillian Orogeny, and thus record only early Grenvillian denudation; (ii) The Middle Run Formation, which contains detrital zircon originating from the Grenville Orogen and was deposited after ca. 1050 Ma. This sequence is situated in the Grenville foreland, is undeformed and unmetamorphosed, but is entirely concealed beneath Phanerozoic strata hampering detailed analysis (Hauser, 1993; Santos et al., 2002; Baranoski et al., 2009); (iii) The Oronto and Bayfield groups, which comprise the upper part of the

Keweenaw Supergroup in the Mid-Continent Rift system, and are inferred to have been deposited in a combined rift basin–foreland basin setting (e.g., Craddock et al., 2013); (iv) The Hazel Formation, a small elongate foreland basin exposed at the Grenville Front in west Texas. The basin fill, deposited between 1130-1035 Ma, consists of fluviatile siltstone and conglomerate and is deformed into late Grenvillian, km-scale recumbent folds (Soegaard and Callahan, 1994; Grimes and Mosher, 2003; Mulder et al., 2017).

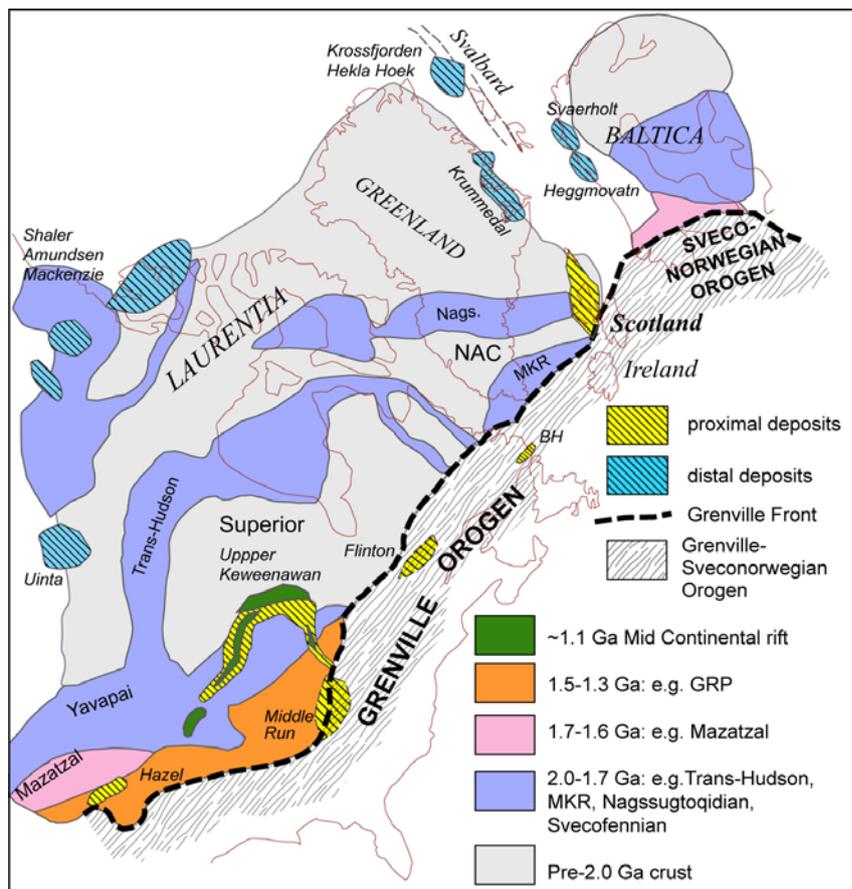


Fig. 1. Sketch map showing Laurentia, Baltica and the Grenville-Sveconorwegian Orogen in a pre-lapetus reconstruction, with broad division of Archaean cratons and Palaeoproterozoic belts in the orogenic foreland (after Hoffman, 1988; Buchan et al., 2000; Rivers et al., 2012). Early Neoproterozoic sequences, in italics, containing detritus originating from the Grenville Orogen (Watt and Thrane, 2001; Rainbird et al., 1992, 2001, 2012; Kirkland et al., 2007; Pettersson et al., 2009a; Kamo et al., 2011; Agyei-Dwarko et al., 2012; Rivers et al., 2012) are shown as distal and proximal basins (their outcrops are enlarged for clarity). The Krummedal sequence may include the Nathorstland and Smallefjord groups. BH = Battle Harbour, GRP = Granite-Rhyolite Province, MKR = Makkovik-Ketilidian-Rhinnian, NAC = North Atlantic Craton, Nags = Nagsugtoqidian.

Altogether, the evolution of the Grenvillian foreland basin, and hence the denudational history of the Grenville Orogen, is not well constrained in North America. Arguably, some of the largest, best preserved and most accessible records of a true Grenvillian foreland basin are to be found in the early Neoproterozoic sequences preserved in the Northern Highlands of Scotland

(Fig. 2). A major part of this record is the > 6 km thick, braided-river-dominated Torridon Group in the NW Highlands, deposited in an orogen-parallel foreland-basin setting (Rainbird et al., 2001; Kinnaird et al., 2007; Krabbendam and Rainbird, 2012); but see Williams (2001) and Williams and Fodden (2011) for alternative interpretations. The undeformed Torridon Group has been correlated with the Morar Group (Krabbendam et al., 2008; Bonsor et al., 2012), which was deformed and metamorphosed within the Phanerozoic Caledonian Orogen, thus extending the outcrop of the Grenvillian foreland basin farther east in the Northern Highlands, and extending the available stratigraphic record upwards by some 3 km. The Torridon Group is in part underlain by the ca. 3.5 km thick Sleat Group (Stewart, 1988). The Sleat Group has previously been interpreted as an extensional rift basin, different in both source and setting from the Torridon Group (Stewart, 2002; Kinnaird et al., 2007).

In this paper we test the hypothesis that the Sleat Group (Fig. 2) formed an early part of the Grenvillian foreland basin, and that the combined stratigraphic and provenance record of the Sleat, Torridon and Morar groups in Scotland can be linked to the evolution of the Grenville Orogen. To do this, we present detrital zircon and rutile ages from the Sleat and Torridon groups, as these minerals record different aspects of the source region. We also present additional sedimentological analysis of the Sleat Group to evaluate its compatibility with a foreland basin setting, assess its relationship to the overlying Torridon Group, and discuss the overall depositional evolution of the early Neoproterozoic sequence in the Northern Highlands. On the basis of these results, we propose a model for the evolution of the Grenvillian foreland basin in the Scottish sector of the Grenville Orogen involving a transition from an early narrow foreland basin to a later, much wider foreland basin. Finally, we relate this evolution to other, more distal sequences with Grenvillian detritus elsewhere in the North Atlantic region.

2. Geological Setting

2.1 The Grenville Orogen in Scotland and Ireland

In eastern Canada, the Grenville Orogen is well exposed over a wide area (Fig. 3), with limited younger cover (Gower, 1996; Rivers, 1997; 2008; Rivers et al., 2012). In contrast, much of Scotland and Ireland is covered by younger sedimentary rocks, or comprises older Archaean-Palaeoproterozoic basement: only two small inliers occur that unequivocally record Grenvillian tectono-metamorphic activity.

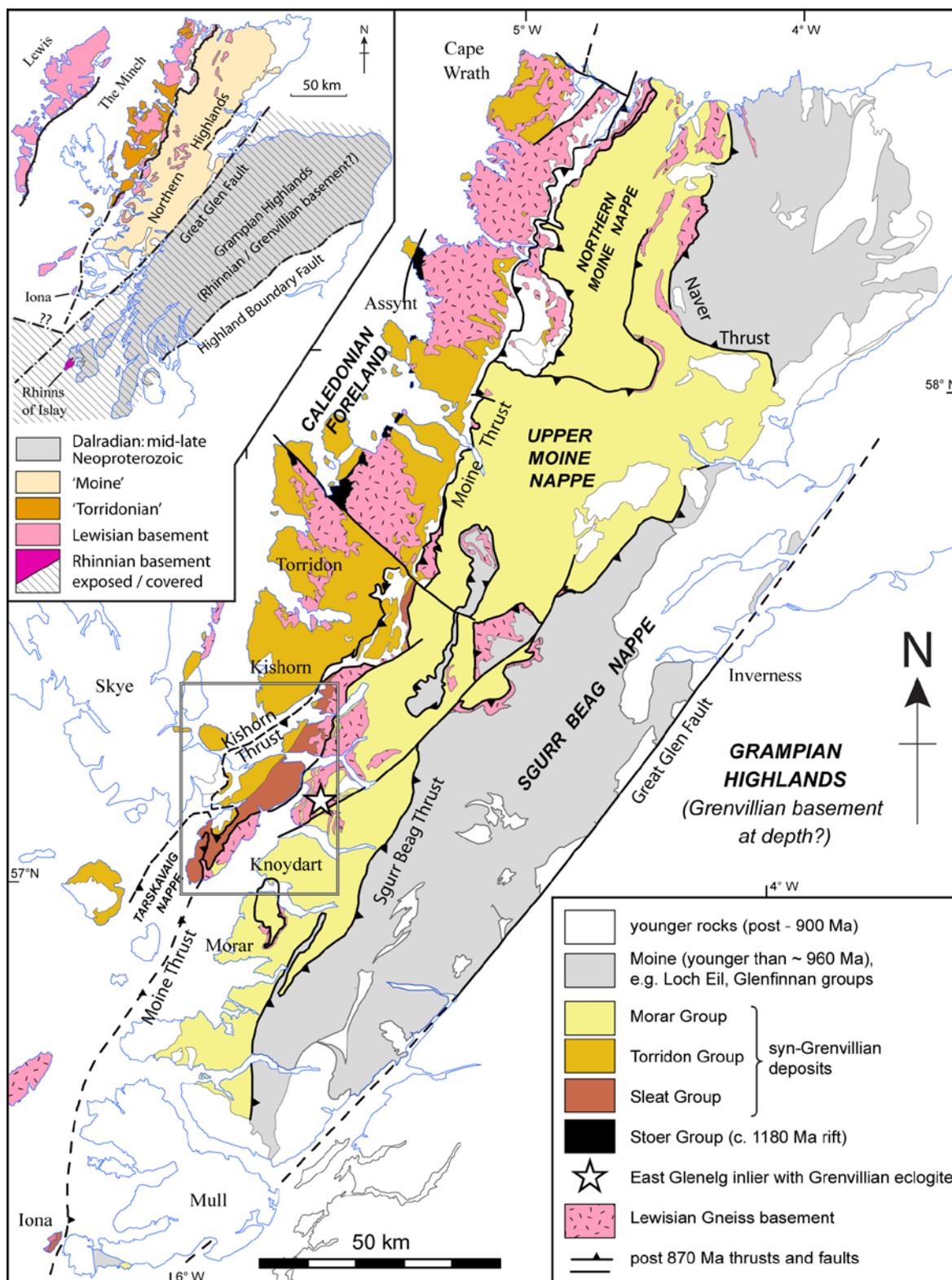


Fig. 2. Geological map of northwest Highlands of Scotland highlighting Early Neoproterozoic Sleat, Torridon and Morar groups, Moine rocks younger than c. 960 Ma, and their relationship to the Archaean-Palaeoproterozoic basement. Caledonian thrusts and East Glenelg eclogite indicated. Simplified after British Geological Survey (2007) and Krabbendam et al. (2008). Inset shows broad subdivision of Northern Scotland, including inferred extent of Rhinnian basement. Box shows location of Figure 4.

In Scotland, the Eastern Glenelg Inlier (Fig. 2) comprises orthogneiss and paragneiss with abundant eclogite and metapelitic high-pressure rocks (e.g., Storey et al., 2005; Storey, 2008); eclogite-facies metamorphism has been dated at 1082 ± 24 and 1010 ± 13 Ma (Sm-Nd on garnet; Sanders et al., 1984), and decompression at 995 ± 8 Ma (U-Pb on zircon; Brewer et al., 2003). The Eastern Glenelg Inlier occurs in the hangingwall of the much later Caledonian Moine Thrust (Fig. 2). In northwest Ireland, the Annagh Gneiss Complex comprises orthogneisses with ca. 1755 Ma protolith ages that were intruded by granitoid rocks between ca. 1015 and 980 Ma, experienced metamorphic zircon growth at ca. 960 Ma and have yielded U-Pb titanite cooling ages of 943 ± 8 Ma (Daly, 1996; Daly and Flowerdew, 2005). These two inliers show that high-grade Grenvillian events occurred in northern Scotland and Ireland, and provide a link between the Grenville Orogen in eastern Canada and the Sveconorwegian Orogen in southern Scandinavia.

Basement exposed to the north and northwest of these two inliers, e.g. the Lewisian Gneiss complex, does not show evidence for high-grade Grenvillian overprinting, and the pre-Grenvillian ca. 1180 Ma Stoer Group (Stewart, 2002; Parnell et al., 2011), which unconformably overlies the Lewisian Gneiss, is unmetamorphosed. Pseudotachylite formation in Lewisian Gneiss has been dated at between 1300-1200 Ma and 1030-980 Ma (Sherlock et al., 2008) and documents brittle faulting but not metamorphic overprinting. No evidence of Grenvillian overprinting has been found in Palaeoproterozoic basement rocks exposed in the Rhinns of Islay, in western Scotland (Fig 2, inset). Collectively this suggests that northwestern Scotland constituted part of the foreland to the Grenville Orogen and was located north or northwest of the Grenville Front, defined in Canada as the limit of ductile deformation and associated metamorphism. The exact position of the Grenville Front in Scotland is obscured by later Caledonian deformation (Winchester, 1988; Krabbendam et al., 2014), and it is likely that the two Grenvillian inliers (Eastern Glenelg and Annagh Gneiss) were transported by Caledonian thrusts (e.g. Moine Thrust, Fig. 2) towards the northwest from an original location farther southeast within the Grenville Orogen.

2.2 Basement ages of Laurentia – Grenville foreland

The basement of eastern Laurentia (Canada, Greenland, NW Scotland, Fig. 3) is principally composed of Archaean cratons (e.g. Superior and North Atlantic cratons), welded together by 2.0-1.7 Ga Palaeoproterozoic orogenic belts (e.g., Hoffman, 1988). These orogens are either dominated by juvenile crust (e.g., New Quebec), or largely consist of reworked Archaean crust (e.g., Trans-Hudson, Nagsugtoqidian, Torngat). In the North Atlantic region, all these units are truncated by the accretionary Palaeoproterozoic 1.9-1.7 Ga Makkovik-Ketilidian-Rhinnian orogen

(MKR), which occupies a broad band between the Archaean rocks of the North Atlantic Craton and the Grenville Orogen to the south. In northern Scotland and Ireland, the basement north of Iona (Fig. 2) is the Lewisian Gneiss complex, part of the North Atlantic Craton, and is dominated by late Archaean protoliths with ages in the range 3000-2700 Ma, partially reworked by metamorphic and igneous events at ca. 2500 Ma, and between 1900-1670 Ma (Kinny and Friend, 1997; Friend and Kinny, 2001; Park, 2005; Goodenough et al., 2013), in part similar to the Nagssugtoqidian Orogen of Greenland. To the southwest, the basement is the Rhinnian Complex (or Rhinns Complex), locally exposed on the islands of Islay and Colonsay in western Scotland and in northwest Ireland as orthogneisses with crystallization ages ranging from ca. 1900-1740 Ma (Marcantonio et al., 1988; Muir et al., 1992; Daly et al., 1991, 2009; Loewy et al., 2003; Park, 2005). Rhinnian-age rocks also make up the basement of the Rockall Bank (Dickin, 1992; Hitchen et al., 2013), with some evidence for Grenvillian magmatism in the southern Rockall Bank (Miller et al., 1973). The Rhinnian Complex can be broadly correlated with the 1880-1740 Ma Ketilidian and the 1890-1710 Ma Makkovik orogens in south Greenland and Labrador respectively (Garde et al., 2002; Ketchum et al., 2002; Park, 2005).

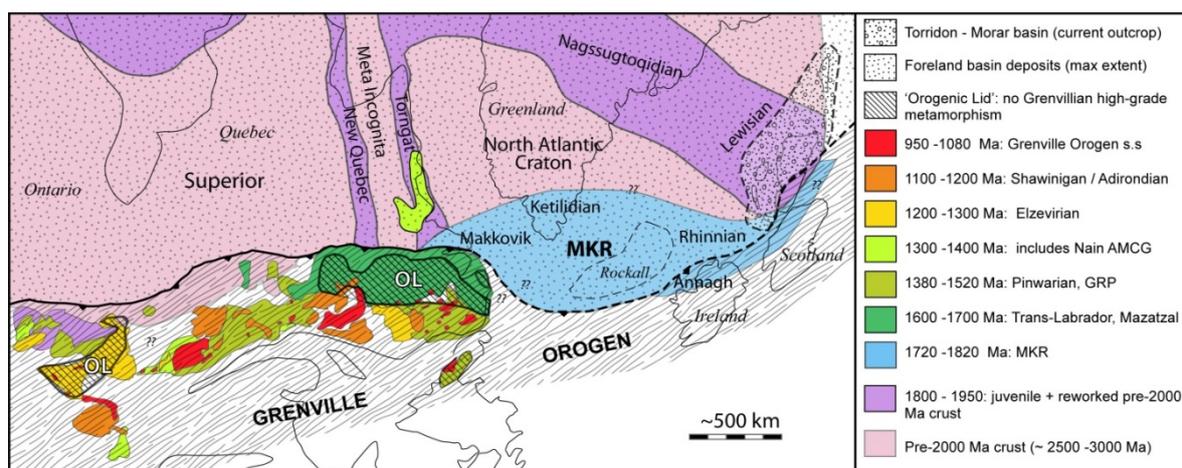


Fig. 3. The Grenville Orogen and its foreland in the North Atlantic region. Crustal protolith ages shown in colour (after Rivers, 1997; Rainbird et al., 2001; Gower and Krogh, 2002; Park, 2005). Within eastern Grenville Orogen only outcropping protolith shown. Inferred extent of foreland basin deposits shown by dot pattern (this study, but see also Rainbird et al., 2012). AMCG = anorthosite-mangerite-charnockite granite; GRP = Granite-Rhyolite Province, MKR = Makkovik, Ketilidian and Rhinnian. OL = Orogenic Lid, after Rivers (2008, 2012).

2.3 Protolith ages within the Grenville Orogen

In the Grenville Orogen as exposed in the Grenville Province in eastern Canada, Archaean and Palaeoproterozoic rocks extend into the northern parautochthonous part of the orogen immediately southeast of the Grenville Front, but do not outcrop southeast of a major ductile shear zone known as the Allochthon Boundary (Rivers, 1997). Southeast of the Allochthon

Boundary most rocks are of latest Palaeoproterozoic and Mesoproterozoic age (Fig. 3), inferred to have formed in a long-lived continental arc and associated backarc settings on southeast Laurentia, prior to the Grenvillian continent-continent collision (e.g., Gower 1996; Carr et al., 2000; Rivers and Corrigan, 2000; Rivers et al., 2012). Labradorian, ca. 1.65 Ga orthogneisses are widespread in the northeastern Grenville Province, whereas the Pinwarian 1.5-1.4 Ga orthogneisses are widespread farther south. More localised intrusions that crystallized between ca. 1.3-1.2 Ga are referred to as Elzevirian, and those between 1.2 – 1.1 Ga as Shawinigan or Adirondian (Rivers, 1997; Gower and Krogh 2002). All these rocks have been deformed and metamorphosed to variable degrees within the Grenville Orogen. Igneous rocks of Grenvillian age (1100-980 Ma) are rather sparse and occur mainly as distributed mafic and granitoid plutons (Rivers, 1997).

In northern Scotland and Ireland, the protoliths of units within the Grenville Orogen are much less well constrained, if only because so few Grenvillian rocks are exposed. The protoliths of the Eastern Glenelg Inlier are poorly dated, and may contain reworked Archaean elements (Storey, 2002), but direct correlation with the Lewisian Gneiss is unlikely, given the very different lithologies present. The Annagh Gneiss Complex in NW Ireland represents ca. 1750 Ma Rhinnian basement that was reworked within the Grenville Orogen (Daly, 1996; Daly and Flowerdew, 2005). A variety of geochemical, isotopic and inherited zircon data suggests that basement with similar late Palaeoproterozoic ages extends eastwards beneath Dalradian (late Neoproterozoic) metasedimentary cover in the central and southern Scottish Highlands (Dickin and Bowes, 1991; Pidgeon and Compston, 1992; Muir et al., 1994) to the south and east of the probable location of the Grenville Front (Winchester, 1988). Thus we surmise that the Irish-Scottish sector of the Grenville Orogen was dominated by rocks with 1700-1800 Ma Rhinnian protolith ages, as opposed to the post-1700 Ma protolith ages that dominate the Canadian sector of the Grenville Orogen (Fig. 3).

2.4 Early Neoproterozoic siliciclastic sequences in northern Scotland

Much of northern Scotland is covered by early Neoproterozoic siliciclastic sequences known as the 'Torridonian' and Moine Supergroup (Figs. 2,4,5). 'Torridonian' is an informal term referring to unmetamorphosed siliciclastic rocks located in the Caledonian foreland west of the Moine Thrust and within the low-grade metamorphic Moine Thrust zone. The 'Torridonian' comprises three distinct groups, the Stoer, Sleat, and Torridon groups. The oldest of the three, the Stoer

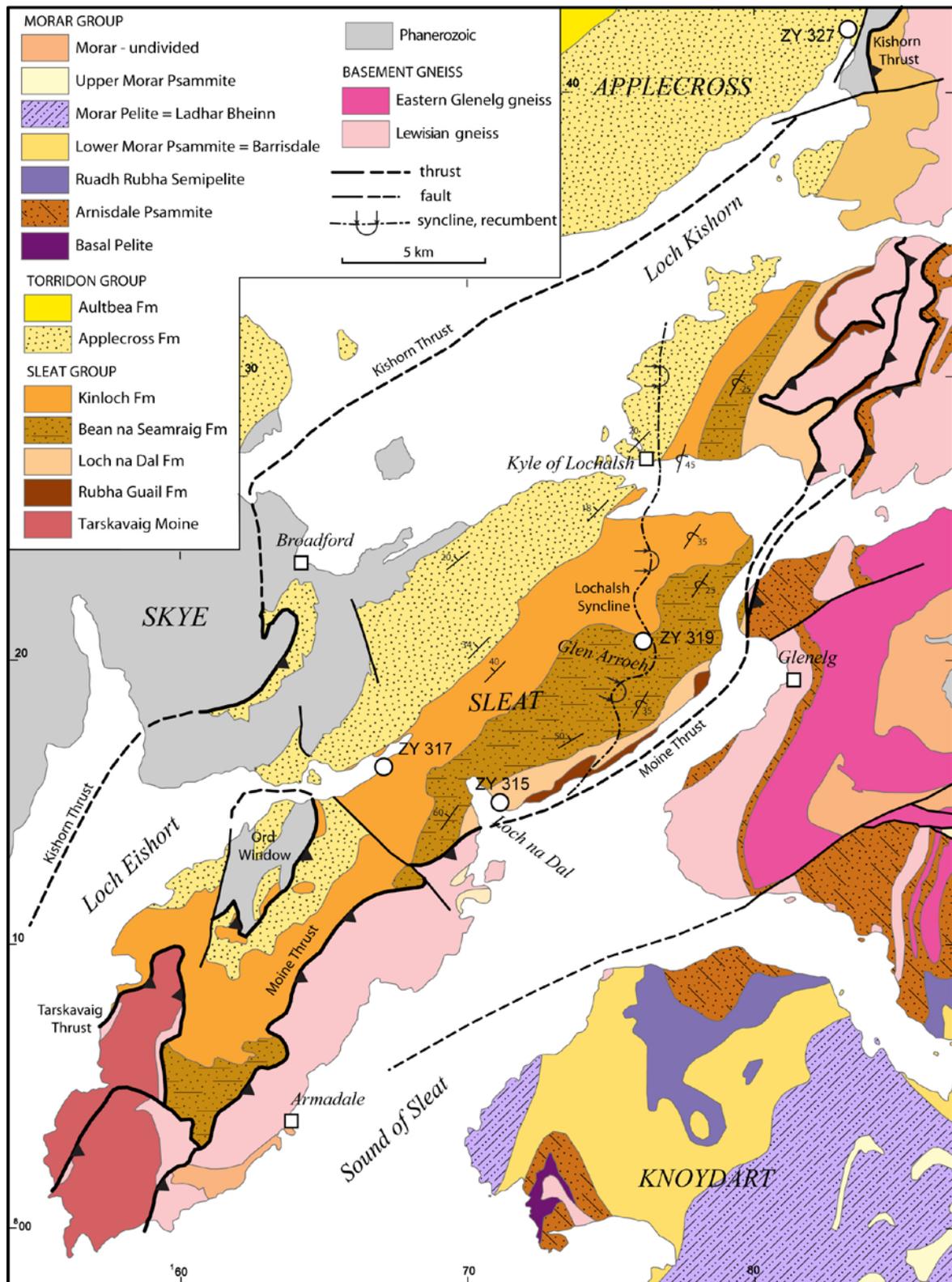


Fig. 4. Geological map of Sleat and surrounding area, showing Precambrian rocks and Caledonian structures. Sample localities shown. After Geological Survey of Scotland (1909), Sutton and Watson (1964), British Geological Survey (2002) and mapping by the authors.

Group, is generally interpreted as a late Mesoproterozoic ca. 1180 Ma rift basin with locally sourced sediment (Rainbird et al., 2001; Stewart, 2002; Parnell et al., 2011); it is pre-Grenvillian and not further considered here. The Moine rocks, of which the lowest Morar Group rocks are relevant here, are situated in the hanging wall of the Moine Thrust, and are deformed and metamorphosed to amphibolite-facies conditions.

2.4.1 Sleat Group

The Sleat Group comprises ca. 3500 m of siliciclastic deposits. Its outcrop extent is limited to the Kishorn Nappe in the southernmost Moine Thrust zone (Fig. 2) where it is folded within the large-scale recumbent Lochalsh syncline (Fig. 4), so that some sections are right-way-up and others inverted (Sutton and Watson (1964)). Although the Sleat Group has undergone low-grade metamorphism, with metamorphic chlorite and locally epidote growth in the basal part of the sequence, original sedimentary structures are generally well preserved in outcrops in southern Skye and Kyle of Lochalsh (Fig. 4). Metamorphism was too low grade for any zircon recrystallisation. The Group was deposited unconformably onto Lewisian Gneiss basement and is stratigraphically overlain by the Torridon Group. Stewart (2002) stated that this upper contact is conformable, but Kinnaird et al. (2007) mapped a low-angle unconformity between the two groups and concluded, on the basis of detrital zircon data, that the Sleat and Torridon groups were sourced from different areas and have contrasting basin settings. Both Stewart (2002) and Kinnaird et al. (2007) suggested the Sleat Group was deposited in an extensional setting rather than a foreland-basin setting. Pebbles within the Sleat Group (above the basal Rubha Guail Formation) include rhyolite and rhyodacite as well as felsic gneiss, suggesting a mixed upper crustal magmatic-arc and lower crustal source region (Stewart, 2002). At its most northerly exposure near Kishorn, the Sleat Group thins to some 1400 m and it is absent farther to the north.

2.4.2 Torridon Group

The Torridon Group comprises > 6km of red sandstone (Fig. 5) with subordinate mudstone (Stewart 2002). In the south, the Torridon Group overlies the Sleat Group, but farther north it was deposited directly upon an old, hilly landscape of exposed Lewisian Gneiss basement (Peach et al., 1907; Stewart 2002). There is no evidence of a basin margin in Scotland (Krabbendam and Rainbird, 2012). The Group is dominated by the thick sandstone sequences that show an overall fining-upward trend from coarse sandstone with pebble beds in the Applecross Formation to medium-fine sandstone in the Aultbea Formation, matched by increasing sorting and maturity (Stewart and Donnellan, 1992). Pebble lithologies include vein quartz, quartzite, rhyolitic rocks,

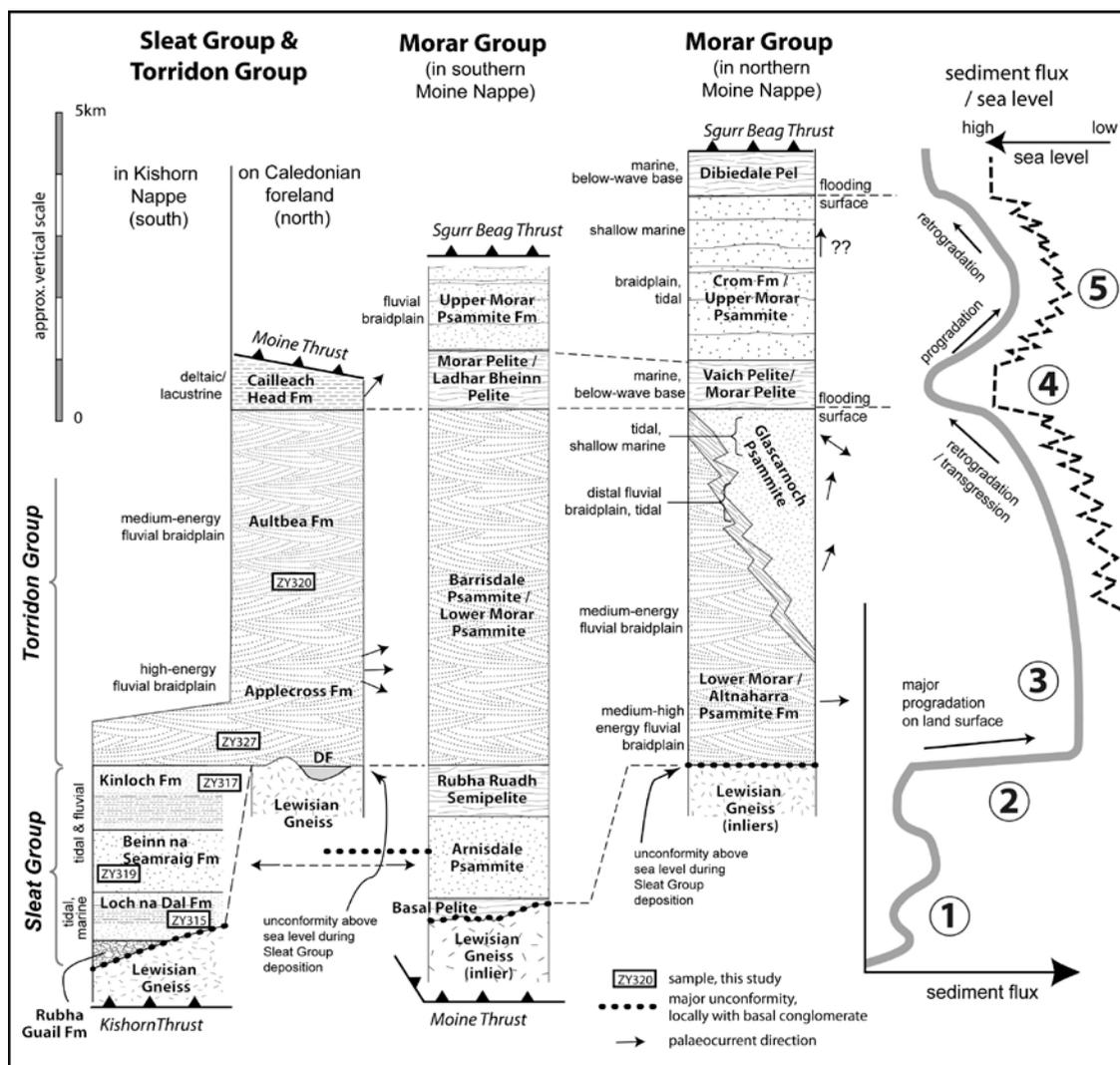


Fig. 5. Combined stratigraphy of Sleat, Torridon and Morar groups, with interpreted correlations, sediment flux and progradation/retrogradation cycles. After Stewart (2002); Bonsor and Prave (2008); Krabbendam et al. (2008); Bonsor et al. (2010, 2012) and this study. Stratigraphic position of the 5 samples in the Sleat and Torridon groups are shown. Circled numbers refer to different phases of the sedimentological evolution as explained in the discussion. DF = Diabeag Formation.

chert/jasper, mylonitic rocks, felsic gneiss and micaceous schist (Williams, 1969). Combined with geochemistry and detrital mineral ages, this precludes sourcing from the local Lewisian Gneiss basement (Van de Kamp and Leake, 1997; Rainbird et al., 2001; Stewart, 2002). The uppermost Cailleach Head Formation is composed of cyclic alternations of grey shale and tabular, cross-bedded fine sandstone, commonly with desiccation cracks and wave ripples interpreted by Stewart (1988, 2002) as a deltaic/lacustrine deposit.

2.4.3 Morar Group

The siliciclastic Morar Group, the lowest unit of the Moine Supergroup, occurs within the Moine Nappe (Figs. 2, 4) and was deformed and metamorphosed during mid-Neoproterozoic

Knoydartian and the Ordovician-Silurian Caledonian orogenies (e.g., Strachan et al., 2002, 2010). On the basis of sedimentology, stratigraphic position, geochemistry and detrital zircon ages, the lower parts of the Morar Group in the northern Moine Nappe have been correlated with the Torridon Group (Krabbendam et al., 2008; Bonsor et al., 2012). In the northern Moine Nappe, two kilometre-scale progradational-retrogradational cycles have been recognised, superimposed on an overall deepening trend over at least 6–9 km of siliciclastic sediment (Fig. 5; Bonsor et al., 2010, 2012). The medial retrogradation (phase 4 in Fig. 5) is represented by the Vaich Pelite, inferred to represent a major marine transgression (Bonsor et al., 2012), and likely correlates with the deltaic/lacustrine deposition of the Cailleach Head Formation (Stewart 2002) at the exposed top of the Torridon Group.

In the southern Moine Nappe in Knoydart and Morar, the stratigraphy is more complex (Figs. 4, 5). Correlation between the Vaich Pelite, Morar Pelite, Ladhar Bheinn Pelite and hence the Cailleach Head Formation is most probable, as well as between the Altnaharra Psammite, Lower Morar Psammite, Barrisdale Psammite and Applecross formations (Krabbendam et al. 2014). This means there are some lower units (Rubha Ruadh Semipelite, Arnisdale Psammite and basal Pelite) present in the southern Moine Nappe, that are absent farther north. The Arnisdale Psammite is sedimentologically remarkably similar to the Beinn na Seamraig Formation of the Sleat Group (Krabbendam et al., 2014), and the units as a whole both record a subtle progradational-retrogradational cycle (phases 1 and 2 in Fig. 5). On this basis, the Arnisdale Psammite and Rubha Ruadh Semipelite likely correlate across the Moine Thrust with the Beann na Seamraig and the Kinloch formations of the Sleat Group respectively (Krabbendam et al., 2014).

Several isolated outcrops of Neoproterozoic siliciclastic deposits occur on the western isles of Scotland. Two of these are potentially coeval with the Sleat or Torridon groups: the Iona Group, comprising a ca. 700 m thick sequence of conglomerate, arkosic sandstone and subordinate mudstone unconformably overlying Lewisian Gneiss on the island of Iona (e.g., Stewart, 2002; McAteer et al., 2014), and the allochthonous Tarskavaig Group on southeast Skye which occurs in a Caledonian nappe of the same name (Figs. 2, 4).

3. Detrital zircon and rutile geochronology

3.1 Introduction

U-Pb analyses were determined from detrital zircon and rutile in order to maximise the information gathered on the sediment sources as to their igneous and metamorphic history across different source lithologies. Zircon occurs most commonly in felsic igneous rocks, but is

rare in mafic igneous rocks. Rutile, in contrast, occurs most commonly in mafic igneous rocks and high-grade metapelites, and is a signature mineral of many high-pressure metamorphic rocks such as eclogite, high-pressure granulite and upper-amphibolite facies rocks (e.g., Force, 1980; Zack et al., 2004, 2011; Meinhold, 2010). Rutile can also occur as very small (<40 μm) needles in other lithologies, but these are unlikely to survive transport as detrital grains.

Detrital zircon ages are interpreted as representing the crystallisation ages of the igneous rocks from the source region. Although metamorphic zircon may crystallise on grain exteriors during high-grade metamorphic events, these are commonly removed by abrasion during fluvial transport. Zircons derived from an igneous rock that has been metamorphosed without significant new zircon formation, thus record the original magmatic crystallisation age, which may be much older than the orogeny in which the subsequent metamorphism occurred. In contrast, rutile can be reset by high-grade metamorphism: if this occurs the rutile age will represent the age of metamorphism of the source rocks or its cooling thereafter, rather than the age of the protolith. The temperature at which this resetting occurs depends on the grain size, and varies from ca. 450 °C to ca. 600 °C for grains $\geq 100 \mu\text{m}$ (Cherniak, 2000). Detrital rutile analyses of modern rivers draining ancient mountain ranges commonly return a unimodal age peak, representing the main metamorphic event of the source mountain belt; thus modern rivers in the Grenville Province in Labrador show a unimodal Grenvillian detrital rutile peak at 1000-950 Ma (Thomsen et al., 2015). Our expectation was therefore that detrital rutile from our samples would return mostly Grenvillian ages, indicating that the source rocks had experienced high-grade Grenvillian metamorphism. In addition, coarser grains are more likely to survive mechanical abrasion during fluvial transport and are more readily captured by standard mineral separation methods, so a general bias towards coarse-grained intrusive rocks over their fine-grained equivalents might be expected.

3.2 Analytical methods

In all cases large samples (10-20 kg) were taken in order to recover sufficient zircon and rutile. Zircon and rutile U-Pb analyses were performed by laser ablation (LA) multi-collector (MC-) or single collector sector field (SC-SF-) inductively coupled plasma mass spectrometry (ICP-MS) at the NERC Isotope Geosciences Laboratory Geochronology and Tracers Facility (NIGL-GTF), British Geological Survey. Analytical methods followed those described in Thomas et al. (2010; 2013) using a Nu Instruments Nu Plasma MC-ICPMS or Attom SC-SF-ICP-MS coupled to an ESI (New Wave Research Division) UP193SS laser ablation system fitted with a low volume ablation cell (Horstwood et al., 2003). Data are discussed using the date (inferring no geological meaning) vs.

age (inferring geological meaning to the date) terminology of Schoene et al (2013). Data processing, uncertainty propagation and reporting follow Horstwood et al. (2016). Youngest detrital zircon date uncertainties from this study are fully propagated for systematic components of uncertainty. (Age uncertainties quoted from previous studies are as appear in those publications and may not represent equivalent levels of uncertainty expansion.) Modifying the approach of Dickinson and Gehrels (2009), *youngest group* ages are estimated as the average \pm 2SD of 3 or more data points overlapping within 2s (without systematic uncertainty propagation). Note that this is not a weighted mean calculation and does not imply that the grouped dates represent a single geological population. Instead, using an average and 2SD of the values, we are describing the distribution of the younger age components of the data for each sample so that a similarity comparison can be made between samples. Supplementary files S1 and S2 contain the

	Sample number	Unit	Location	Grid reference	Description	Comment
TORRIDON GROUP	ZY320	Aultbea Formation	3 km NW of Melon Udrilge on the Aultbea Peninsula	NG 88977 97698	Sandstone; thick-bedded (1-5 m thick beds) and medium-grained throughout, with rare gritty beds with jasper pebbles. Outcrops show ubiquitous soft-sediment contortions affecting beds 4-5 m thick.	Sample close to the locality of sample GY96-56 analysed by Rainbird et al. (2001)
	ZY327	Applecross Formation	River Kishorn, Applecross	NG 8332 4227	Arkosic sandstone; coarse-grained and locally gritty. Beds are typically 1-2 m thick, with abundant planar cross-bedding, with abundant heavy mineral bands; locally some soft-sediment deformation structures.	Sample taken at a similar stratigraphic level as sample GY96-4 of Rainbird et al. (2001), but ca. 60 km further south
SLEAT GROUP	ZY317	Kinloch Formation	Loch Eishort on Sleat	NG 6711 1637	Sandstone; grey and medium-to fine-grained. Sandstone beds in 10 cm thick stacks alternate with more shaly beds. Laminations and ripple lamination occur in the sandstone beds.	
	ZY319	Beinn na Seamraig Formation	Glen Arroch on Sleat	NG 7614 2064	Sandstone; fine-grained, green-grey, thick-bedded but otherwise showing few defined sedimentary structures	
	ZY315	Loch na Dal Formation	Type section at Loch na Dal on Sleat	NG 7102 1517	Sandstone sample from well-bedded highly variable sequence of mudstone and sandstone with poorly sorted, gritty beds.	

Table 1. Sample description, location and grid reference, British National Grid. Samples in stratigraphic order.

metadata, sample results and validation results for this study. Data are interpreted considering those within 5% of concordance for zircon and 20% for rutile, due to the size of the data point uncertainties.

3.3 Samples and Detrital zircon data

Five samples were analysed: three from the Sleat Group and two from the Torridon Group: their locations are shown in Figure 4 and their stratigraphic positions in Figures 5 and 6; sample descriptions are given in Table 1. The Torridon Group samples were taken at similar stratigraphic levels as those analysed by Rainbird et al. (2001) which had a low number of analyses. Only the Torridon group samples contained sufficient rutile; zircon and rutile were analysed from the same samples (see Section 3.4). A summary of the detrital zircon ages for all samples is given in Table 2 with their probability density profiles shown in Figure 6. A comparison of youngest dates and youngest groups is shown in Figure 7 and discussed below.

In all five samples, the youngest U-Pb zircon dates within 5% of concordance range from 1070-990 Ma, coeval with the Grenvillian Orogeny in eastern Canada. All samples also show a low proportion (2-15%) of pre-2000 Ma zircons; most of these ages fall between ca. 2900-2500 Ma. Mid-or early Archaean zircons have not been found; equally very few zircons dated between 2500-2000 Ma have been found (5 dates across all samples).

Sample and Formation	Youngest date (Ma)	Youngest group (Ma)	Younger populations (Ma)	Dominant population (Ma)	Older populations (Ma)	Oldest date (Ma)	Concordant/ Total analyses (n)
Rutile							
ZY320 Aultbea	1051±39	1073±32	c. 1065, 1165, 1535	c. 1875	c. 1875	1925±70	36/65
ZY327 Applecross	1049±46	1074±37	c. 1080, 1535, 1685	c. 1080	c. 1865	2645±114	40/64
Zircon							
ZY320 Aultbea	992±52	1039±42	c. 1020-1450	c. 1640	c. 2560-2800	2846±98	92/203
ZY327 Applecross	1071±55	1105±48	c. 1090-1475	c. 1680	c. 2500-2800	2844±112	136/209
ZY317 Kinloch	1061±33	1121±28	c. 1130, 1220-1400	c. 1630-1760	c. 2580	2755±69	95/144
ZY319 Beinn na Seamraig	1064±33	1088±41	c. 1380	c. 1670 -1850	c. 2725, 3000	3032±72	105/117
ZY315 Loch na Dal	996±40	1380±28	c. 1400	c. 1750	c. 2635, 2920	2963±101	151/210

Table 2. Summary of detrital zircon and rutile data, in stratigraphic order. Uncertainties for youngest and oldest dates represent 2s after propagation for all systematic components whereas uncertainties for youngest group represent 2SD (see supplementary information for further details).

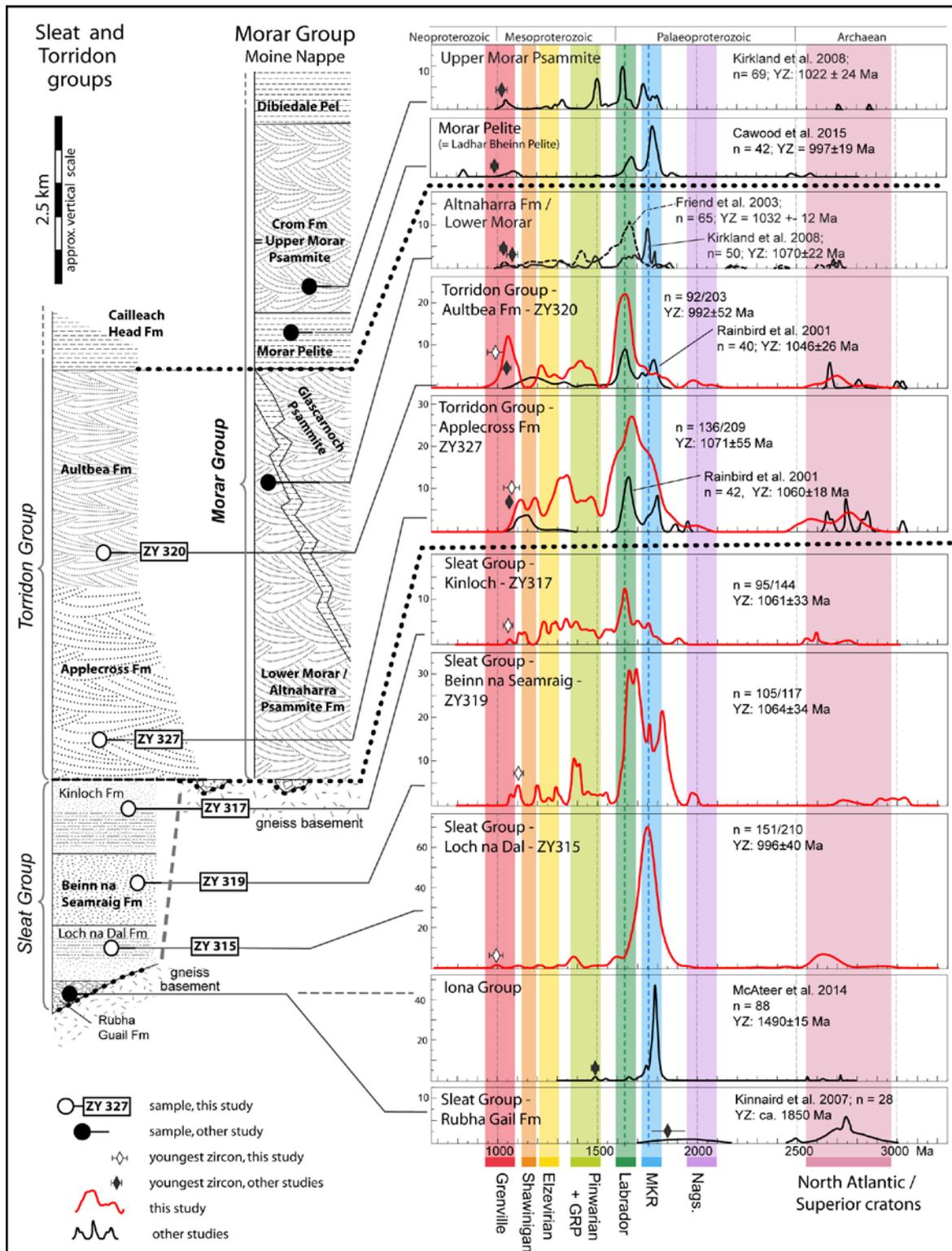


Fig. 6. Detrital zircon age probability density plots, showing absolute frequency against the combined stratigraphy of Sleat, Torridon and Morar groups. This study (red) and other studies (black; Rainbird et al., 2001; Friend et al., 2003; Kinnaird et al., 2007; Kirkland et al., 2008; McAteer et al., 2014; Cawood et al., 2015). YZ = youngest detrital zircon. GRP = Granite-Rhyolite Province, MKR = Makkovik-Ketilidian-Rhinnian, Nags = Nagssugtoqidian.

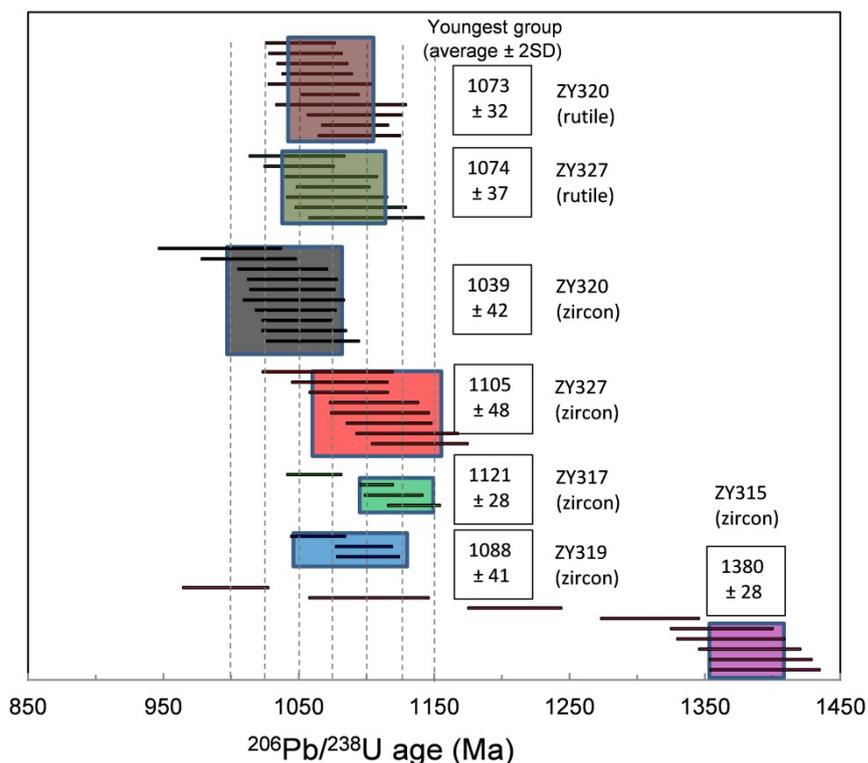


Fig. 7. Dates and youngest groups for Sleat-Torridon samples. Youngest groups are calculated as average \pm 2SD for populations with MSWD = 1 or at least 3 points overlapping within 2s. Boxes represent this age range.

Loch na Dal Formation (sample ZY315)

Sample ZY315 shows a single dominant ca. 1750 Ma population with ca. 70% of ‘concordant’ data (within 5% of concordance). Post-1600 Ma zircons make up 9% of the population with pre-2000 Ma constituting 13% of the data. The youngest group of zircons (1380 ± 28 Ma, 2SD, $n=5$), is significantly older than the youngest date (992 ± 40 Ma) but other younger dates (at ca. 1300 Ma, 1200 Ma and 1100 Ma) attest to the presence of younger material in this sample, indicating that the maximum depositional age is substantially younger than the youngest group of zircons.

Beinn na Seamraig Formation (sample ZY319)

The dominant ca. 1670-1850 Ma population constitutes ca. 65% of ‘concordant’ data; post-1600 Ma zircons (20% of concordant data) are more common than in the Loch na Dal Formation, with small peaks between 1400 and 1100 Ma. The youngest date (1064 ± 33 Ma) is part of the youngest group of zircons (1088 ± 41 Ma, 2SD, $n=3$), suggesting deposition post-1090 Ma.

Kinloch Formation (Sample ZY317)

In sample ZY3217, a dominant ca. 1630 Ma population has subordinate populations up to ca. 1760 Ma but a greater component of post-1600 Ma zircons (52%) than in the Beinn na Seamraig

Formation, with near-continuous dates down to the youngest at 1061 ± 33 Ma, distinct from the youngest group (1121 ± 28 Ma, 2SD, $n=3$). Pre-2000 Ma zircons constitute 7% of the population.

Applecross Formation (sample ZY327)

The dominant ca. 1680 Ma population has a broad peak extending between ca. 1600-1750 with a more subdued dominant peak age when compared to the Sleat Group samples. Post-1600 Ma zircons make up 42% of the population, and pre-2000 Ma zircons make up 12%. The youngest date (1071 ± 55 Ma) is part of the youngest group of zircons (1105 ± 48 Ma, 2SD, $n=8$), suggesting a maximum depositional age post-1100 Ma.

Aultbea Formation (sample ZY320)

The dominant ca. 1640 Ma population exhibits a skew towards 1800 Ma. Post-1600 Ma zircons make up 42% of the population, and pre-2000 Ma zircons make up 8%. The youngest date (992 ± 52 Ma) is part of the youngest group of zircons (1039 ± 42 Ma, 2SD, $n=10$), suggesting a maximum depositional age post-1040 Ma.

3.4 Detrital rutile data

Insufficient rutile was recovered from the Sleat Group samples, so only Torridon Group results are presented here (Table 2, Fig. 8). Due to the size of the uncertainties, data are interpreted using a discordance criterion of <20%. Using <5% discordance would make little difference to the interpretation but would reduce the number of accepted data points considerably.

The youngest rutiles in the Applecross Formation (ZY327) and Aultbea Formation (ZY320) (1049 ± 46 Ma and 1051 ± 39 Ma respectively) are essentially identical (Table 2, Fig. 8) and both are members of the youngest group of rutiles, at 1074 ± 37 and 1073 ± 32 Ma respectively (Fig. 7). These results suggest a maximum depositional age of ca. 1075 Ma. The distribution of the youngest peak in the Applecross Formation sample is skewed towards ca. 1220 Ma, with a small peak at ca. 1350 Ma, and more significant peaks at ca. 1550, 1680 and 1810-1910 Ma (Fig. 8). One Neoproterozoic grain (c. 2650 Ma) is present. The Aultbea Formation shows a major peak at 1050-1090 Ma, minor clusters at 1160-1180 Ma and 1500-1570 Ma and a second major peak at 1850-1930 Ma.

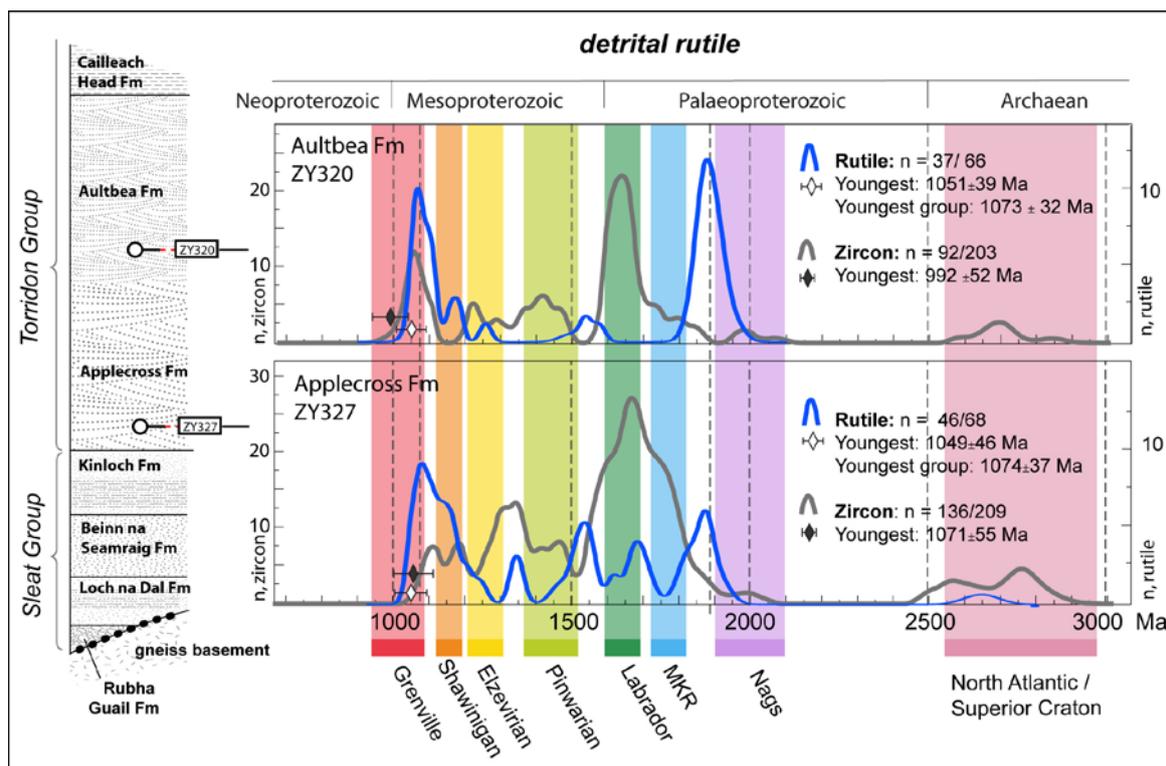


Fig. 8. Detrital rutile and zircon age probability plots from Aultbea and Applecross samples, Torridon Group, showing absolute frequency (this study). Rutile and zircon recovered from the same samples.

3.6 Zircon similarity analysis

Useful methods illustrating similarity in detrital zircon data include multi-dimensional scaling (MDS), cumulative distribution functions (CDF) and kernel density estimates (KDE). The plots in Figure 9 were constructed using the ‘provenance’ package for the statistics package ‘R’, after Vermeesch et al. (2016). MDS plots (Fig. 9a) allow the visualisation of similarity between samples using the two-sample Kolmogorov-Smirnov statistic to quantify the degree of difference as distance between points, plotted in 2-dimensions. Similar samples plot closer together, whereas dissimilar samples plot farther apart.

The MDS zircon plot of the samples in this study (Fig. 9a) shows that the Kinloch (ZY317), Applecross (ZY327) and Aultbea (ZY320) samples have strong similarities, with the Beinn na Seamraig (ZY319) sample not too dissimilar. However, the Loch na Dal (ZY315) sample is more

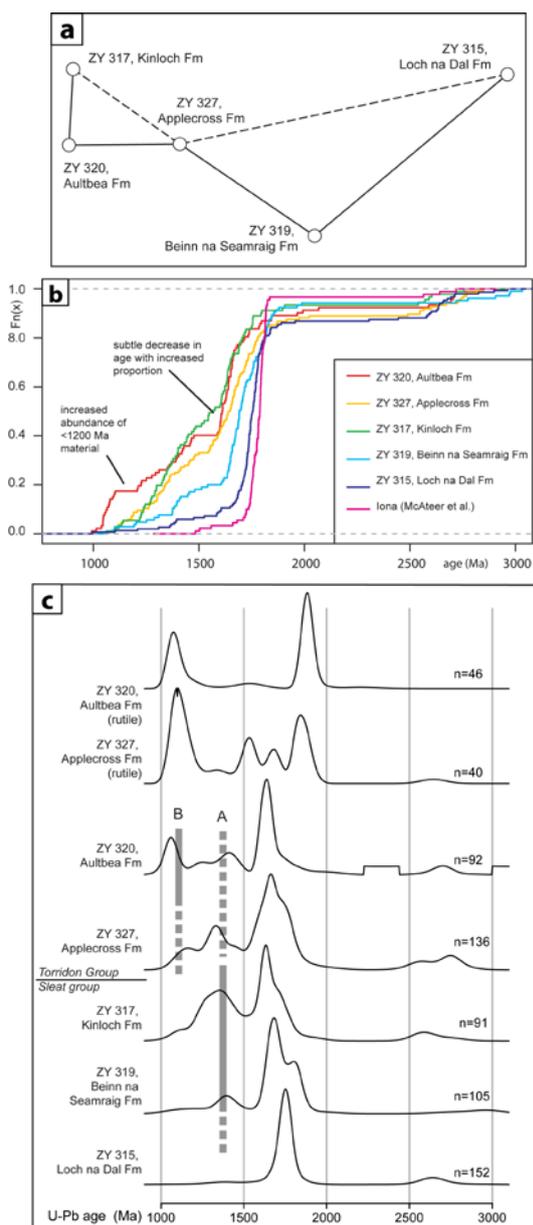


Fig. 9. (a) Multi-dimensional scaling (MDS) plot of the Sleat and Torridon Group samples. Solid lines show nearest neighbours and most similarity, dashed lines show larger distance and less similarity. (b) Cumulative distribution function (CDF) plot of the Sleat and Torridon Group samples, in stratigraphic order. (c) Kernel Density Estimate (KDE) plot of the Sleat and Torridon Group samples. See text for discussion.

dissimilar, plotting significantly further away from the other samples, but is most similar to the Beinn na Seamraig sample. The CDF plot (Fig. 9b) shows the subtle nature of the age shift of the dominant late Paleoproterozoic peak through the sequence, changing from ca. 1750 Ma in the lower Sleat Group to a ca. 1650 Ma peak higher up in the sequence. This younging occurs *within* the Sleat Group: the Loch na Dal Formation (lower Sleat Group) appears distinctly different from stratigraphically higher units, with an older peak age that dominates the sample population, whilst the ca.1650 age peak essentially becomes the same in the Kinloch (ZY317) and Aultbea (ZY320) samples. The overall similarity of CDF form between the Kinloch (ZY317) and Applecross

(ZY327), and the Beinn na Seamraig (ZY319) and Aultbea (ZY320) samples is notable, illustrating that there is no significant difference in the analysed zircon populations across the Sleat-Torridon boundary. The CDF plot for zircon and rutile also illustrates well the larger abundance of <1200 Ma material in the Aultbea (ZY320) sample. Figure 9c shows the data plotted as KDE's using the same band width. Here the similarities and subtle differences become more apparent, as well as the dissimilarity of the Loch na Dal formation (ZY315). Trend A shows the appearance (Beinn na Seamraig, ZY319), growth (Kinloch, ZY317) and reduction (Applecross and Aultbea, ZY327 and ZY320 respectively) of the ca.1350 Ma peak (Figs. 6, 9c.) Trend B shows the appearance (Applecross) and growth (Aultbea) of the ca.1050 Ma peak. These relationships are consistent with a continuous evolution of the source upward through the stratigraphy. All samples contain only small populations (< 15%) of pre-2000 Ma zircon, most of which have ages between ca. 2900-2500 Ma; early Palaeoproterozoic (2.5-2.0 Ga) zircon grains are very rare.

4. Stratigraphy and sedimentology

4.1 Sleat Group

The Sleat Group (Figs. 4, 5) comprises four formations (Clough, in Peach et al., 1910; Stewart, 1988, 2002) that have previously been interpreted to reflect distinct depositional settings. Stewart (2002) interpreted the basal coarse (conglomeratic) Rubha Guail Formation to represent alluvial fans prograding from basement hills into a lake, whereas he considered the overlying Loch na Dal Formation to represent shallow-marine, lacustrine and/or deltaic deposits. The Beann na Seamraig and Kinloch formations were interpreted as fluvial braidplain deposits with shallow marine or lacustrine incursions. We present here new sedimentological observations and a review of palaeo-environmental interpretations of the Sleat Group, above the basal Rubha Guail Formation, which was not examined in this study.

4.1.1 Loch na Dal Formation

The Loch na Dal Formation is typified by 5-10 m thick coarsening-upward facies sequences composed of ripple laminated mudstone, interbedded on a decimetre-centimetre scale with fine, tabular or ripple-laminated beds of micaceous grey sandstone, 5–15 cm thick (Fig. 10a). Abrupt, laterally continuous gravel lags are common at the bases of sandstone beds with rapid fining of grain size above the lags (Fig. 10a). The sandstone beds increase in frequency and thickness upwards in the facies sequences.

The predominance of complex wavy, lenticular and flaser bedding in mudstone, interbedded with planar cross-bedded sandstone units at the base of the coarsening-upward

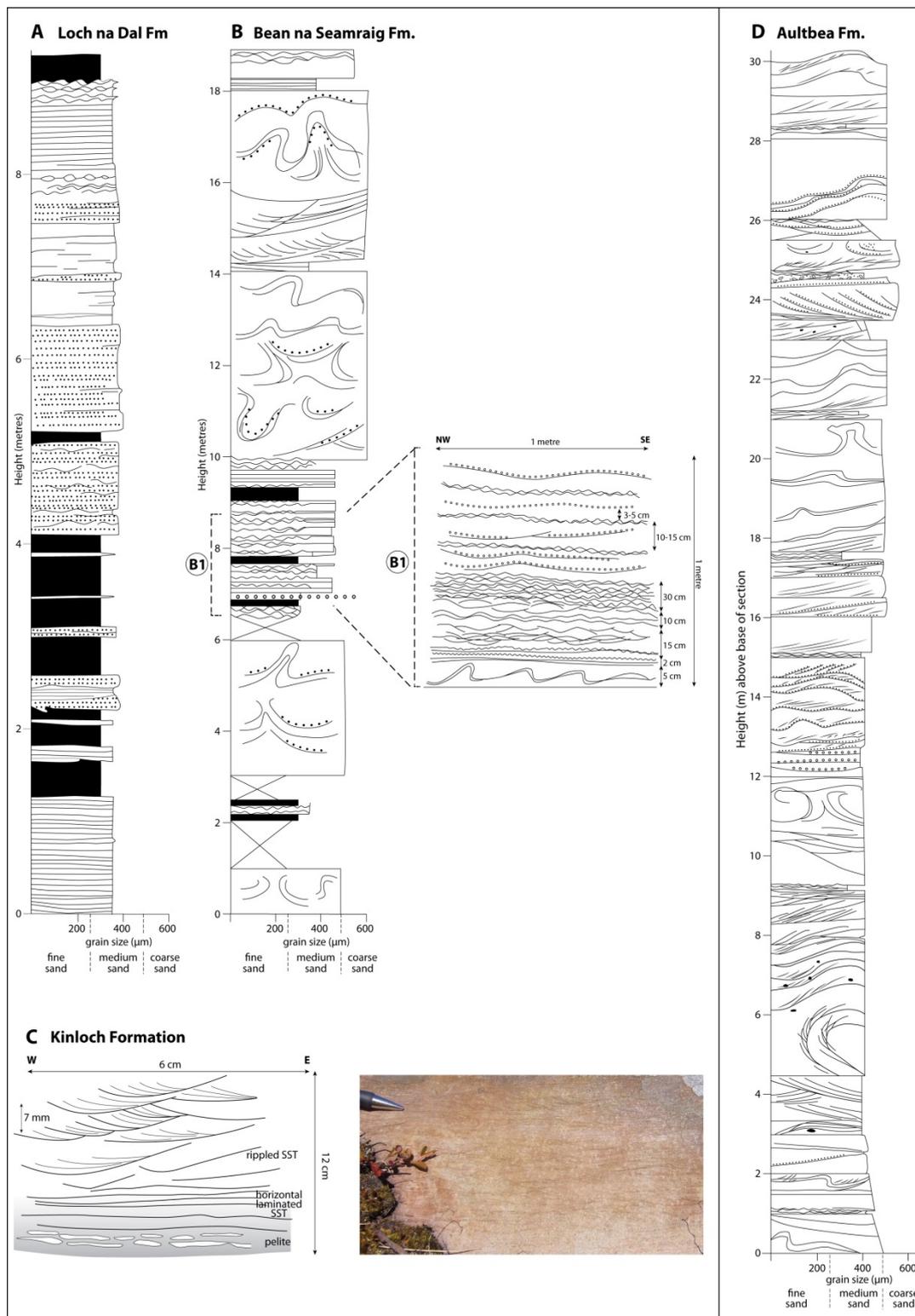


Fig. 10 Sedimentary logs from (a) Loch na Dal Formation, Sleat Group at Loch na Dal [NG 7197 1503], after Stewart (2002); (b) Bean na Seamraig Formation, Sleat Group, at Glen Arroch [NG 7535 2080]; (c) Kinloch Formation, Loch Kinloch [NG 6710 1620] with inset photograph showing typical ripple lamination; (d) Aultbea Formation, Mellon Udrigle, Aultbea [NH 8926 9730]. The annotation of the sedimentological logs is drawn directly from field observations rather than representing a symbology.

sequences, indicates sedimentation under variable and oscillatory energy conditions. The continued upward presence of these mudstone facies, presence of complex ripple bedforms in sandstone beds and the prevalence of mud drapes in bedforms, indicate repeated episodes of slack water throughout deposition. Collectively, these features suggest deposition under tidal currents for at least some periods of time (Walker 1992; Roberts 2007; Varban & Plint 2008), most likely within a shallow marine or tidally influenced shoreface setting, where progradational distributary channels deposited sediment. This interpretation is consistent with, but more specific than, the shallow-marine, lacustrine and/or deltaic setting proposed by Stewart (2002).

4. 1. 2 Beann na Seamraig Formation

The higher Beann na Seamraig Formation is quite distinct from the Loch na Dal Formation (Fig. 10b). The formation is mainly sandstone lithofacies, with 15-20 m thick coarsening-upward sequences, consisting mainly of trough-scalloped, erosional based cross-bedded sandstone with gravel lags. Very rapid fining of grain size is observed on a centimetre-scale above the gravel lags. The sandstone is pale-red and less micaceous than that in the Loch na Dal Formation. Rapid deposition is indicated by the prevalence of truncated, pinched, cusped soft-sedimentation deformation features in the thickest (> 0.5 m) sandstone beds, likely formed by high sedimentation rates that generated unstable and over-pressurized water-laden sediment and dewatering. Soft-sediment deformation is generally confined to single beds, suggesting that seismic triggering of the soft-sediment deformation was rare (e.g., Owen, 1995). Mudstone facies are subordinate (30%) and occur predominantly at the base of the facies sequences, where pinstripe and lenticular ripple bedding is ubiquitous. These features, together with mud drapes within the sandstone cross-beds in the central parts of the sequences, indicate variable oscillatory flow energy conditions and slack water periods throughout deposition. Overall, the Beann na Seamraig Formation is interpreted to record a distal distributary network of shallow channels with some tidal influence, deposited in a shallower and higher energy environment than the Loch na Dal Formation.

4. 1. 3 Kinloch Formation

The Kinloch Formation represents an upward fining of the Beann na Seamraig Formation and is characterised by 10-20 m thick coarsening-upwards facies sequences, dominated by fine, ripple-laminated sandstone units (Fig. 10c). The bases of the sequences are typified by mudstone units with flaser, pinstripe and ripple lamination. Above these, the frequency and thickness of horizontally laminated and centimetre-scale rippled sandstone beds increase upwards in the sequences (Fig. 10c). The upper few metres of the facies sequences are almost entirely

sandstone, but the thick cross-bed sandstone units as observed in the Beann na Seamraig Formation are absent. Soft-sediment deformation features are less frequent than in the Beann na Seamraig Formation. Collectively, the Kinloch lithofacies indicates a decrease in depositional energy and less rapid deposition. The presence of gravel lags and prevalence of mud drapes within sandstone bedforms do, however, indicate continuing variability in depositional energy. The persistence of thin units of complex mudstone facies that display wavy, lenticular and flaser bedding at the base of the facies sequences also suggests some continued tidal influence (Fig. 10c). Overall, the Kinloch facies are interpreted to record deposition in a distal distributary network of shallow channels, with some tidal influence, at slightly lower energy conditions than the Beann na Seamraig facies. This interpretation is compatible with Stewart (2002), who also interpreted these units as fluvial braidplain deposits with shallow marine or lacustrine incursions.

4. 1. 4 Facies Succession in the Sleat Group

Despite discontinuous outcrop, an overall trend of lithofacies can be recognised. Collectively the three formations define a coarsening-upward succession from shallow marine, tidally influenced shoreline (Loch na Dal lithofacies), to tidally-influenced distal distributary channel systems (Beann na Seamraig and Kinloch lithofacies). The trend is most apparent from the increasing proportion of sandstone to mudstone in the lithofacies, and is also supported by the contemporaneous changes in bedforms – from predominantly complex tidally-influenced mudstone facies, to ripple-laminated and cross-bedded sandstone facies. Consistent with this interpretation, Stewart (1988, 1991, 2002) documented an associated overall upward trend of more mature mineralogy (more quartz, less matrix) and chemistry (more Si, Al, K; less Na, Ca, Fe).

4. 2 Torridon Group

The Torridon Group represents a kilometre-scale fining-upward succession (e. g., Stewart 2002), composed of pronounced fining-upward sequences of stacked cross-bedded and trough cross-bedded sandstone, with minimal deposition of fines (Fig. 10d), very different from the underlying Sleat Group. On Sleat, where only the basal 1 km of Applecross Formation occurs, the unit is somewhat finer-grained with fewer pebble-conglomerate beds than further north in Torridon and Assynt (Nicholson, 1993; Williams, 2001; Stewart, 2002).

The large bedform scale, strong normal grading of grain size within bedforms (from ca. 1 to 0.15 mm within a 0.5 m bedform), prevalence of water escape soft-sediment deformation features, the prevalence of gravel clasts (2-5 mm diameter) and lags which characterise the 20-30

m thick fining-upward facies sequences, all indicate a high-energy depositional environment. This is further supported by the minimal preservation of fines within the facies and the stacked cross-bedded channels. A slight reduction and gradual transition in depositional energy from the Applecross to the Aultbea formation is indicated by the gradual upward reduction in grain size and bedform size (from ca. 4 to 2 m bed thickness), and weakening of grain-size grading (see also Stewart, 2002). The well-sorted and sub-rounded nature of the sandstone facies, that rarely contains pebbles, indicates a mature braidplain setting, situated far enough downstream to avoid abundant coarse conglomeratic influxes of sediment.

The abundant soft-sediment deformation, affecting 50-60% of beds in the two formations, suggests high deposition rates combined with a high water table (e. g. Owen and Santos, 2014); the convoluted and pinched cusped deformation forms are generally truncated by overlying beds. Palaeocurrents are overall towards the east, but vary between SE to NE (Williams, 1969, 2001; Nicholson, 1993; Ielpi and Ghinassi, 2015). Both Nicholson (1993) and Ielpi and Ghinassi (2015) documented 8-13 m deep channels, suggesting very large and long (100s-1000s km) rivers. The Applecross and Aultbea formations are interpreted as medium-to-high energy terrestrial braidplain deposits, sourced from the west via a large-scale trunk–river system (Nicholson, 1993; Stewart, 2002; Ielpi and Ghinassi, 2015).

5. Discussion

5.1 Sleat Group: age, setting and extent

All Sleat Group samples contain youngest detrital zircons that are of Grenvillian age, ranging in age from 996 ± 40 to 1064 ± 33 Ma, overlapping with youngest zircons in the overlying Torridon Group (Table 2, Figs. 6, 7) and there is no difference in zircon age data across the Torridon-Sleat boundary. Thus, the Sleat Group is a syn-orogenic deposit similar to the Torridon Group; it cannot have been deposited prior to the Grenvillian Orogeny, as previously suggested (Kinnaird et al., 2007; Spencer et al., 2015). The Sleat and Torridon groups were thus both sourced directly from the Grenville Orogen, but the outcrop of the overlying Torridon Group is much larger than that of the Sleat Group. How large was the Sleat basin, and are there potential nearby correlatives of the Sleat Group?

The Sleat Basin did not extend north of Kishorn, as further north the younger Torridon Group was deposited directly onto exposed Lewisian Gneiss basement (Figs. 2, 11), indicating that the Sleat Group basin had a clear boundary to the north. Unfortunately the nature of this northern boundary (fault or onlap) cannot be determined, as the critical part of the record was uplifted and eroded during Caledonian orogenesis.

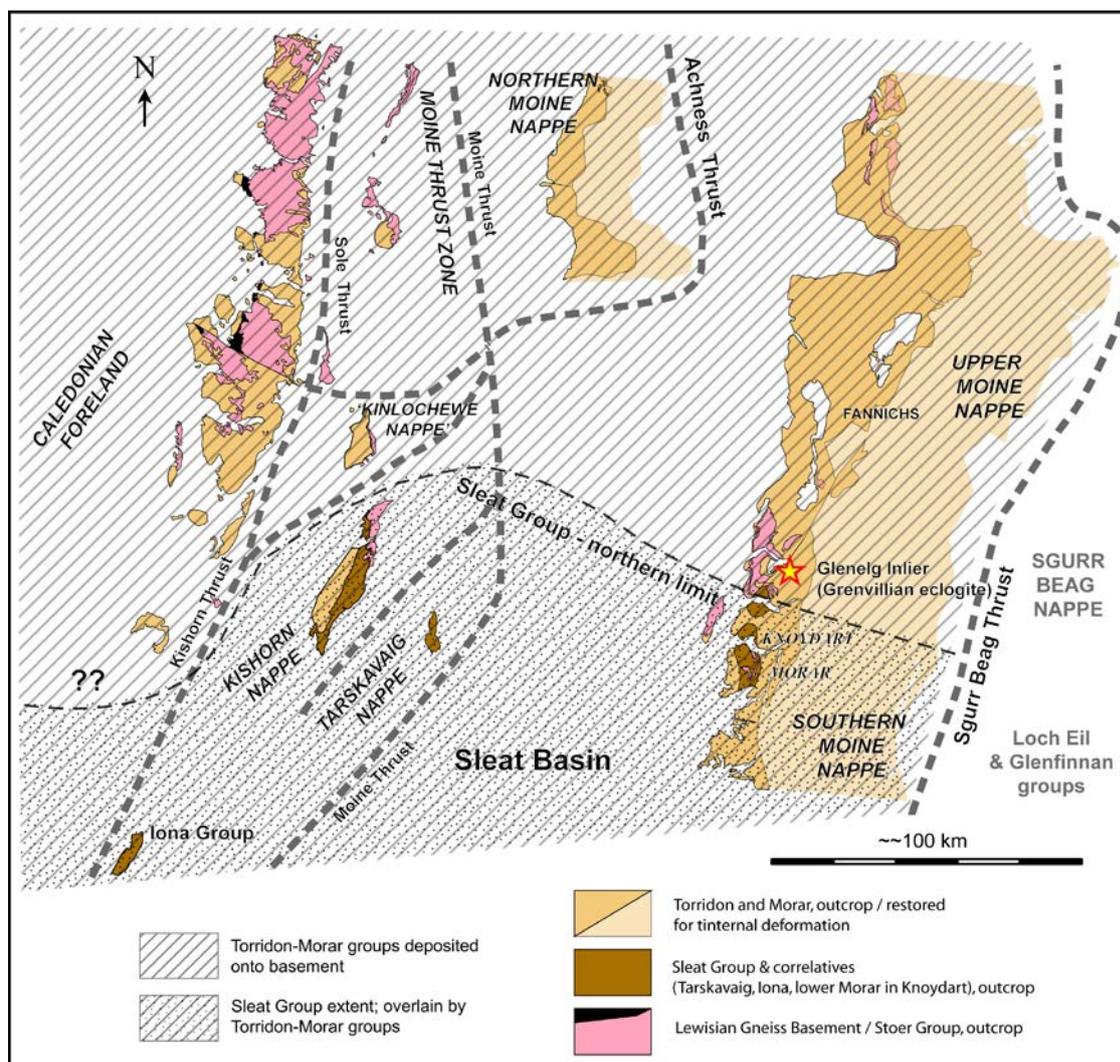


Fig. 11. Schematic reconstruction of the Grenville Foreland Basin in the northern Highlands of Scotland, applying minimum restoration of later Caledonian thrusts. The present-day outcrop and interpreted extent of the Sleat Group and its possible correlatives is shown. The basement north of the Sleat Group basin remained exposed until covered by later Torridon and Morar deposits.

The three basal formations in the lowermost Morar Group in the southern Moine Nappe (Basal Pelite, Arnisdale Psammite and Rubha Ruadh Semipelite; Fig. 5) are similar in lithology and sedimentology (as far as can be established in these metamorphosed rocks) to the Sleat group and likely correlate with it (Krabbendam et al., 2014). These three formations only occur south of the Glenelg Inlier (Fig. 4), and thus possess a similar northern limit as the Sleat Group (Fig. 11). The Tarskavaig Moine, a poorly studied sequence occurring in a Caledonian thrust sheet tectonically sandwiched between Sleat rocks below and Morar rocks above (Fig. 4), is similarly also likely to have been part of the Sleat basin (Stewart, 1982; Cheeney and Krabbendam, 2009). McAteer et al. (2014) analysed detrital zircon from the Iona Group, an isolated conglomerate-sandstone unit that directly overlies Lewisian Gneiss basement on Iona (Fig. 2), some 80 km SSW of Sleat. Although McAteer et al. (2014) preferred a correlation with the late-Neoproterozoic

Grampian Group (Dalradian Supergroup), we note here that the detrital zircon signature of the Iona Group shows the same dominant ca. 1750 Ma peak as the lower Sleat Group (Fig. 6). The Iona and Sleat groups have the same unconformable relation with Lewisian gneiss basement, and both occur in the footwall of the Caledonian Moine thrust. Despite the rather old (1490 ± 15 Ma; analytical uncertainty only) youngest detrital zircon (McAteer et al., 2014), we propose that the Iona Group was deposited in the same basin as the Sleat Group. In summary, we suggest that the Sleat Basin included the Tarskavaig Moine, the Arnisdale Psammite and Rubha Ruadh Semipelite (lowest Morar Group) and the Iona Group (Fig. 5). Overall, we conclude that the Sleat Group represents an early part of the Grenvillian foreland basin sequence, with deposition in a basin that may have been several 100 km long and 10s km wide, but was restricted to the north as shown in Figure 11.

5.2 Provenance interpretation – detrital zircon

The scarcity of pre-2000 Ma detrital zircon in the Sleat and Torridon groups indicates that the Archaean-Palaeoproterozoic Laurentian craton NW of the Grenville Orogen (Fig. 1) was not an important source region, either because it was not uplifted, or because it was covered, or both.

The ca. 1750 Ma detrital zircon age peak in the lower Sleat Group is also dominant in the Iona Group (McAteer et al., 2014) and remains present in the middle Sleat Group and in the Applecross Formation (this study). These zircons were likely generated within the 1900-1700 Makkovik-Ketilidian-Rhinnian (MKR) orogens. North of the Grenville Front, MKR terranes are bordered by Archaean basement (Fig. 3). The rarity of Archaean detrital zircon and absence of 2500-2000 Ma zircons in the Sleat Group suggests it is not plausible that the MKR orogens *in front* (north) of the Grenville Orogen were the main source of these samples. Archaean zircons are abundant in the pre-Grenvillian Stoer Group (Rainbird et al., 2001); Archaean basement is thus 'zircon-fertile' (Moecher and Samson, 2006) and the rarity of Archaean zircon is therefore significant. Instead, we suggest that the ca. 1750 Ma peak is the result of erosion of MKR-age rocks that were uplifted within the Grenville Orogen. The Scottish-Irish sector of the Grenville Orogen, although poorly exposed, probably largely comprised reworked 'Rhinnian' rocks (see section 2.3) and is the most likely source for this major ca. 1750 Ma zircon peak in the lower Sleat Group.

Higher up in the stratigraphy, ca. 1750 Ma zircons remain present in the Torridon Group (see also data from Rainbird et al., 2001, plotted in Fig. 6), but are progressively replaced by ca. 1650 Ma zircon. The consistent ca. 1650 Ma peaks in the samples of the upper Sleat Group (Kinloch and Beinn na Seamraig formations) and Torridon Group were most likely sourced from

the large, mid-crustal Trans-Labrador batholith (Fig. 3), exposed over a distance of ca. 500 km within the northern Grenville Province in Labrador (Gower, 1996; Rivers, 1997, 2008; Rainbird et al., 2001; Gower and Krogh, 2002). Detrital zircons with 1500–1000 Ma ages were also likely sourced from the Grenville Orogen in Labrador and Quebec, with the ca. 1500-1400 Ma grains originating from the Pinware Terrane farther to the southeast. The smaller age peaks at ca. 1200 Ma were probably sourced from Elzevirian intrusions, with post-1100 Ma 'Grenvillian' zircon not becoming a significant component of the population until Aultbea Formation deposition, likely marking the unroofing of syn-Grenvillian intrusions and migmatites. These sources were previously suggested by Rainbird et al. (2001), who postulated transport to Scotland by a large-scale trunk river system. This conclusion is further supported by a study of detrital zircon in sediments from *modern* rivers in Labrador draining the Grenville Province (Thomsen et al., 2015), which reported a dominant peak at ca. 1650 Ma, minor peaks at 1500-1200 Ma, and only sparse Grenvillian zircon, a pattern very similar to the detrital zircon spectra discussed here.

In the Morar Group, detrital zircon samples from the Altnaharra Formation in the northern Moine nappe also show a dominant ca. 1650 Ma peak (Friend et al., 2003). In contrast, Kirkland et al. (2008) documented a major peak at ca. 1750 Ma in the stratigraphically equivalent Lower Morar Psammite Formation in the southern Moine Nappe. As the southern Moine Nappe would have been situated closer to the Irish-Scottish sector of the Grenville Orogen (Fig. 11), this is consistent with Rhinnian-age zircons being derived from the Irish-Scottish sector of the Grenville Orogen. Higher up in the Morar Group, in the low energy, marine Morar Pelite Formation (= Ladhar Bheinn Pelite), Cawood et al. (2015) recorded a dominant age peak at ca. 1750 Ma, with only a minor 1650 Ma peak (Fig. 6). It is feasible that this formation was, like the lower Sleat Group, also largely sourced from the Irish-Scottish sector of the Grenville Orogen. The zircon spectrum of the highest unit considered, the Upper Morar Psammite Formation sampled in the southern Moine Nappe, shows three peaks at 1750 Ma, 1650 Ma and 1450-1500 Ma (Kirkland et al., 2008). The provenance of this formation could be a mix of Rhinnian-age zircon from the Irish-Scottish sector and Trans-Labrador and Pinware-age zircon sourced from the Canadian sector of the Grenville Orogen. This sample also exhibits a small Grenvillian peak at ca. 1050 Ma.

In summary, we infer that the entire stratigraphy of the Sleat – Torridon – Morar groups was sourced from the Grenville Orogen, but that source switching and mixing has occurred, with the relative amounts of detritus from the more proximal Irish-Scottish sector and the more distal Canadian sector varying in both time and space.

5.3 Provenance interpretation – detrital rutile

As anticipated, rutile ages from the two Torridon Group samples do show major peaks of Grenvillian age (Figs. 8, 9c), confirming the Grenville Orogen as the main source of detritus. However, both samples also contain significant amounts of older detrital rutile, the source rocks of which evidently did not experience sufficiently high-grade Grenvillian metamorphism to reset the rutile ages. This is in contrast to detrital rutile data from modern rivers in Labrador which show a unimodal detrital rutile peak at 1000-950 Ma (Thomsen et al., 2015).

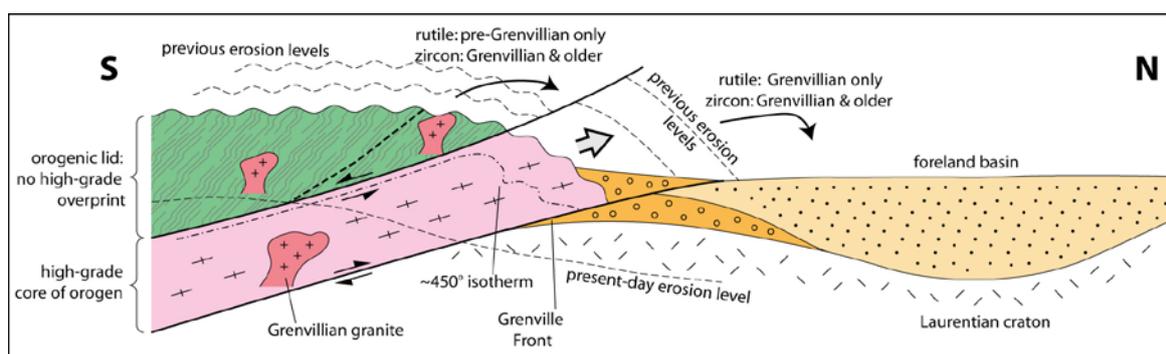


Fig. 12. Schematic cross-section across the northern part of the Grenville Orogen and its foreland in eastern Canada, during the Ottawa orogenic phase. The orogenic lid, remains of the orogenic upper crust, is defined by pre-Ottawan cooling ages, and is underlain by an extensional detachment system (Rivers, 2008; 2012). The high-grade orogenic core is inferred to be extruded towards the northwest, exhuming high-grade rocks, similar to the channel flow model for Himalaya-Tibet.

The solution to this apparent conundrum may lie in recent models suggesting that the upper orogenic crust of the Grenville Orogen is characterised by pre-Grenvillian (pre-1090 Ma) cooling ages (Fig. 12), and did *not* experience penetrative, high-grade Grenvillian metamorphism (Rivers, 2008, 2012). These upper orogenic crustal domains, remnants of which are termed the ‘orogenic lid’, are separated by extensional detachments from the lower orogenic crust that was subjected to high-grade Grenvillian metamorphism (Rivers, 2008, 2012). Two sizeable remnants of the orogenic lid, each covering several thousand km², occur within the Grenville Province: one in Labrador in which the protolith is dominated by the ca. 1650 Ma Trans-Labrador batholith; and one farther west in Quebec and Ontario that is largely composed of rocks with Elzevirian protolith ages (Fig. 3). However, in Grenville times, the area of upper orogenic crust would have been many times larger, and during denudation it would have been a major source of syn-orogenic detritus into the foreland basin. The structural and geomorphic situation *during* the Grenvillian Orogeny, schematically shown in Fig. 12, was probably similar to the modern setting of the Nepal-Tibet Himalayas, where high-grade metamorphic rocks are being extruded and eroded from below the South Tibetan detachment, and low-grade rocks are eroded from above

the detachment (e.g., Hodges et al., 1992; Hodges, 2006). Applied to the Grenville Orogen, the upper orogenic crust above the main detachment(s) would shed older, pre-Grenvillian rutile and zircon, whereas the extruding high-grade, lower crustal orogenic core would shed syn-Grenvillian rutile and pre-Grenvillian zircon from older, reworked igneous rocks. Minor syn-Grenvillian zircon could come from syn-orogenic intrusions from either setting. The relative abundance of pre-Grenvillian rutile is thus, paradoxically, consistent with syn-orogenic deposition, as upper orogenic crust was still present but being actively eroded. It is *post-orogenic* depositional systems that are likely to return a unimodal rutile peak, as found in modern streams (Thomsen et al., 2015), as the upper orogenic rocks are largely or wholly removed from such settings.

More puzzling however, is the oldest major rutile peak at ca. 1900 Ma in the Torridon Group samples, it being *older* than the oldest major zircon peaks at 1650 Ma in the *same* samples (Figs. 8, 9c). Although ca. 1900 Ma rutile could potentially have been sourced from Archaean cratonic crust that was reworked during the Palaeoproterozoic Nagssugtoqidian Orogeny, this is not plausible as such a source area would *also* have provided abundant pre-1900 Ma zircons, which instead are rare in these samples. The ca. 1900 Ma rutile, therefore, must have originated from a source that crystallized or reset rutile at ca. 1900 Ma, but did not produce zircon. At the moment this source remains uncertain, but a mafic protolith appears likely. A plausible source would be an ophiolitic unit from the Makkovik-Ketilidian-Rhinnian Orogen that either crystallized, or was metamorphosed and cooled through the rutile closure temperature, at ca. 1900 Ma and subsequently became incorporated in the cool superstructure of the Grenville Orogen. The orogenic sector in which this putative unit occurred (Canadian, Rockall or Irish-Scottish) is unconstrained.

5.4 Evolution of the Grenville foreland basin: a preliminary model

The sedimentological evidence suggest several distinct phases of deposition (circled numbers in Fig. 5). These can be combined with the detrital zircon and rutile ages and the overall disposition of the various units (Fig. 11) to constrain a multiphase evolution of the Grenvillian foreland basin in Scotland.

- 1) The first foreland basin deposition in Scotland (Figs. 5, 13a) took place as tidally-influenced shoreface facies in a shallow-marine basin (lower Sleat Group, phase 1 in Fig. 5). The basin was bound to the north, and hence relatively narrow (Fig. 11); basement remained exposed in the north.

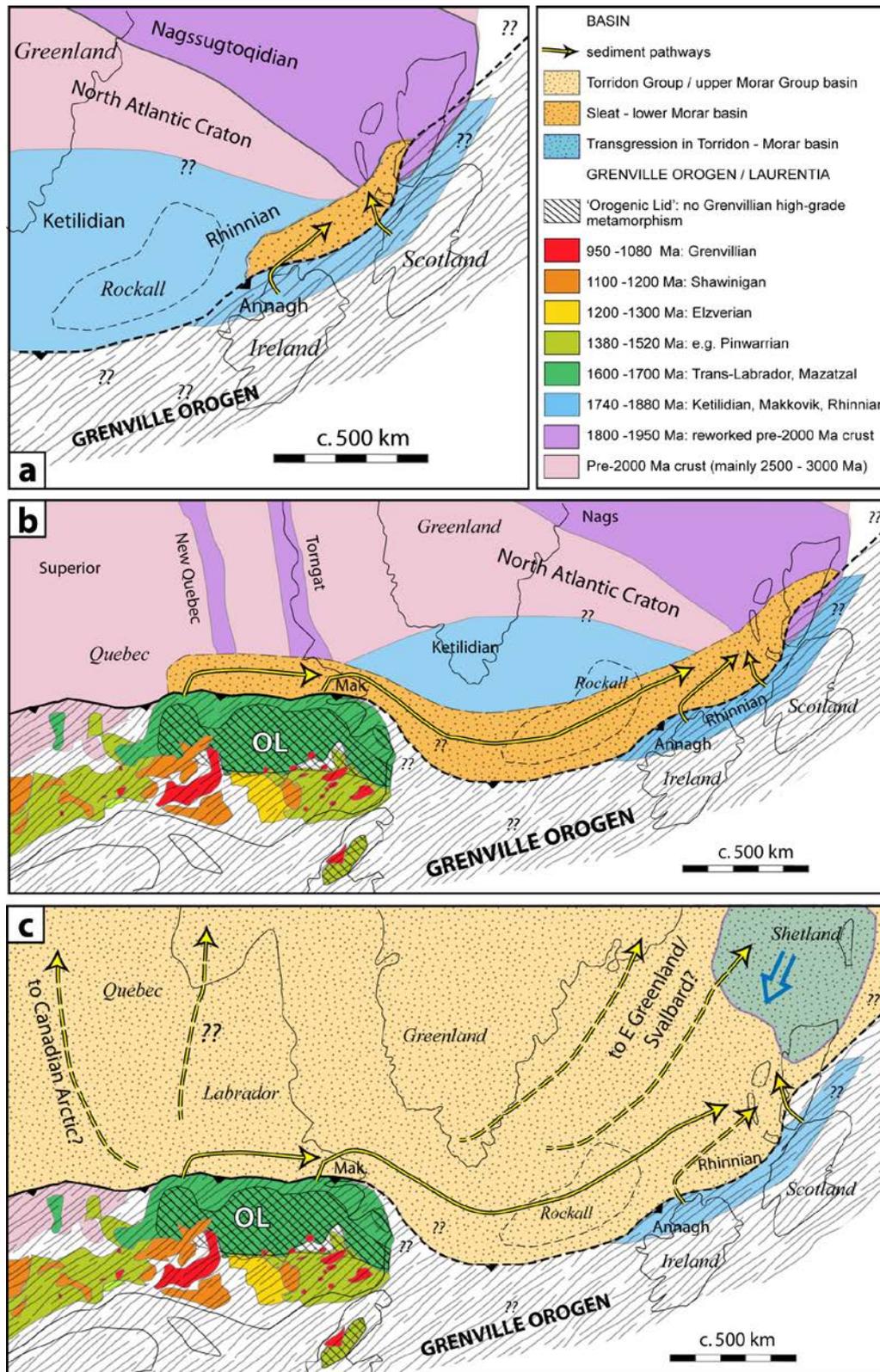


Fig. 13. Proposed temporal evolution of eastern Grenville Foreland Basin: (a) Grenvillian foreland basin in early Sleat times, in relation to the Irish-Scottish sector of the Grenville Orogen. (b) Grenvillian foreland basin in mid to late Sleat times. (c) Grenvillian foreland basin in Torridon-Morar times. Pathway to Canadian Arctic after Rainbird et al. (1992, 1997, 2012). Blue areas and open blue arrow north of Scotland indicate possible origin of marine transgression in the upper Morar Group.

Detritus, dominated by ca. 1750 Ma zircon ages, originated from the Scottish-Irish sector of the Grenville Orogen. Transport was broadly normal to the orogen, with short transport distance, consistent with the relative immaturity of the sediment. Although the Lewisian Gneiss basement to the north remained exposed at this time, little Archaean material entered the basin, suggesting that Grenvillian uplift and erosion to the south or southwest far outweighed any erosion of the Archaean basement in the north.

- 2) A switch in source is indicated by the incoming of ca. 1650 Ma detritus in the middle Sleat Group (Bean na Seamraig and Kinloch formations, Fig. 6). Deposition evolved from shoreface to distal tidally-influenced fluvial deposition, concomitant with an increase in sediment maturity (phase 2 in Fig. 5). Detritus most likely originated largely from the Canadian sector of the Grenville Orogen, provided by the orogenic reworking and uplift of the Trans-Labrador batholith. This implies that transport in the basin changed from orogen-normal to axial (Fig. 13b) via a trunk-river system, with an increase in transport distance. The basin remained narrow and basement in the foreland to the north remained exposed, but provided little detritus.
- 3) A major switch in basin dynamics (Fig. 13c) occurred across the Sleat-Torridon boundary, marked by a low angle unconformity. The Applecross Formation in the west and the Altnaharra-Lower Morar formations in the east represent a major large-scale progradation with rapid and sustained deposition in high- to medium-energy braided river systems that spilled over onto previously exposed basement (phase 3 in Fig. 5). This indicates a massive sediment flux and dramatic expansion of the basin, creating a much broader accommodation space, with migration of the flexural hinge point and the depocentre away from the orogen. However, this significant change of sedimentation was *not* associated with a change in source area: the detrital zircon ages do not change and the main source of the sediment remained the Canadian sector of the Grenville Orogen, dominated by ca. 1650 Ma detritus from the uplifted Trans-Labrador batholith. The cause of this massive flux of detritus was most likely a fast but sustained period of uplift and erosion of the Grenville Orogen. A large-scale, sustained retrogradation trend is recorded in the west by the gradual upward fining of the high-energy Applecross Formation into the medium-energy braidplain deposits of the Aultbea Formation (Nicholson 1993; Stewart, 2002); and in the east by the transition from distal fluvial braidplain deposits of the Altnaharra-Lower Morar Formation to tidally-influenced braidplain and shoreline deposits of the Glascarnoch Formation (Bonsor et al., 2010, 2012). This gradual fining upwards, together with increase in sorting and maturity of the sediment suggest a

gradual waning of this denudational pulse. Altogether, this deposition likely represents the signal of the major denudational phase of the Grenville Orogen.

- 4) The retrogradation of the succession culminated in a relatively rapid transgression and marine (below wave base) deposition in the Morar Pelite-Vaich Pelite formations (phase 4 in Fig. 5). The sharp base of this unit is interpreted as a flooding surface (Bonsor et al., 2010, 2012). In the Torridon Group in the west, the rise in base level led to a change from fluvial deposition to lacustrine/deltaic deposition in the Cailleach Head Formation (Stewart, 2002). Together, this implies that subsidence, partially driven by sediment loading, outpaced deposition. The dominant ca. 1750 Ma detrital zircon peak from the Morar Pelite (Cawood et al., 2015, see also Fig. 6) can be explained by a return to more proximal source areas from the Scottish-Irish sector of the Grenville Orogen. This is consistent with a sea level rise so that rivers originating in the Canadian sector no longer reached Scotland, but rather deposited their loads closer to source.
- 5) A further progradation-retrogradation sequence is preserved in the upper Morar stratigraphy in the east (phase 5 in Fig. 5; any higher stratigraphic record of the Torridon Group has been removed by erosion). Deposition changed from shallow-marine to tidally-influenced distal braidplain settings in the Crom Psammite-Upper Morar Psammite (Bonsor and Prave, 2008; Bonsor et al., 2010, 2012). Detrital zircon ages from the Upper Morar Psammite (Kirkland et al., 2008) are very similar to those of the earlier sandstone sequences (Fig. 6), suggesting that axial flow via large-scale river systems routing detritus from the Canadian sector was restored. This pulse was followed by a second retrogradation to shallow marine conditions, resulting in the below-wave-base deposits of the Dibiedale Pelite, the base of which is inferred as another flooding surface. This represents the last phase of foreland deposition preserved in Scotland.

Aside from the low-angle unconformable transition between the Sleat and Torridon group deposits, the entire Sleat-Morar-Torridon succession is characterised by very gradual and systematic facies changes in several-kilometre-thick transgressive and regressive sequences (Fig. 5). Such facies changes indicate a sustained high-volume delivery of sediment to the basin, whereby depositional changes in the basin were most likely driven by variable rates of subsidence and the creation of accommodation space relative to rate of sediment flux, a pattern typical in foreland settings (Tankard 1986; Varban & Plint 2008; Yang & Miall 2010).

5.5 Constraints on timing of deposition

The growing dataset of youngest detrital zircon and rutile grains, as well as the recognition herein that the Sleat, Torridon and Morar groups were deposited in the same system, provide new and improved constraints on the time of deposition of the Grenvillian foreland basin deposits in Scotland (Fig. 14). In this section we discuss how the timing of basin evolution can be linked not only to the tectonic evolution of the Grenville Orogen, but also to basin development elsewhere in the North Atlantic region.

The Sleat, Torridon and Morar groups all contain zircon generated during the main 1080-1020 Ma Ottawan phase of the Grenvillian Orogeny (Figs. 9, 14). The youngest rutile grains are also of Ottawan age. The youngest zircons show a broad younging from ca. 1100-1050 Ma in the Sleat Group, lower Torridon Group and Lower Morar Psammite, to ca. 1050-990 Ma in the upper Torridon Group and upper parts of the Morar sequence. In a syn-orogenic foreland basin setting, deposition during the interval 1050-960 Ma is likely. This age range is consistent with the 994 ± 48 and 977 ± 39 Ma Rb-Sr whole-rock ages for diagenesis in the Torridon Group (Turnbull et al., 1996). Nevertheless, in the formations discussed here, there are no hard constraints on the *minimum* age of deposition. Other early Neoproterozoic sequences in the North Atlantic region, however, provide tighter time constraints on the minimum age of deposition (Fig. 14), as they were metamorphosed or intruded by granitoids during the ca. 980-910 Ma Renlandian Orogeny (Fig. 1) along the easternmost margin of Laurentia (Cawood et al., 2010). We note here that some authors (e.g. Kirkland et al., 2006; Lorenz et al., 2012) have suggested that a separate arm of the Grenville Orogen developed in East Greenland and Svalbard between Baltica and Laurentia. We reject this hypothesis because: i) in the period ca. 1050-980 Ma, this region was clearly a locus of deposition rather than orogeny (e.g. deposition of Krummedal, Svaerholt, Krossfjorden and similar latest Mesoproterozoic sequences – see below, and Malone et al., 2014); ii) there is no geochronological evidence for metamorphism or magmatism in basement rocks in this area during the same period (cf. Lorenz et al., 2012); and iii) there is, to our knowledge, no nearby source for the major ca. 1650 Ma detrital zircons so prominent in the Krummedal and Krossfjorden sequences (e.g. Watt and Thrane, 2001; Pettersson et al., 2009a). In essence, the hypothesis of Lorenz et al. (2012) confuses the mountains with the sea. In our view, the development of a later, separate probably accretionary Renlandian orogen outboard of Rodinia, not involving continent-continent collision (e.g., Cawood et al., 2010; Malone et al., 2014) is a more logical explanation.

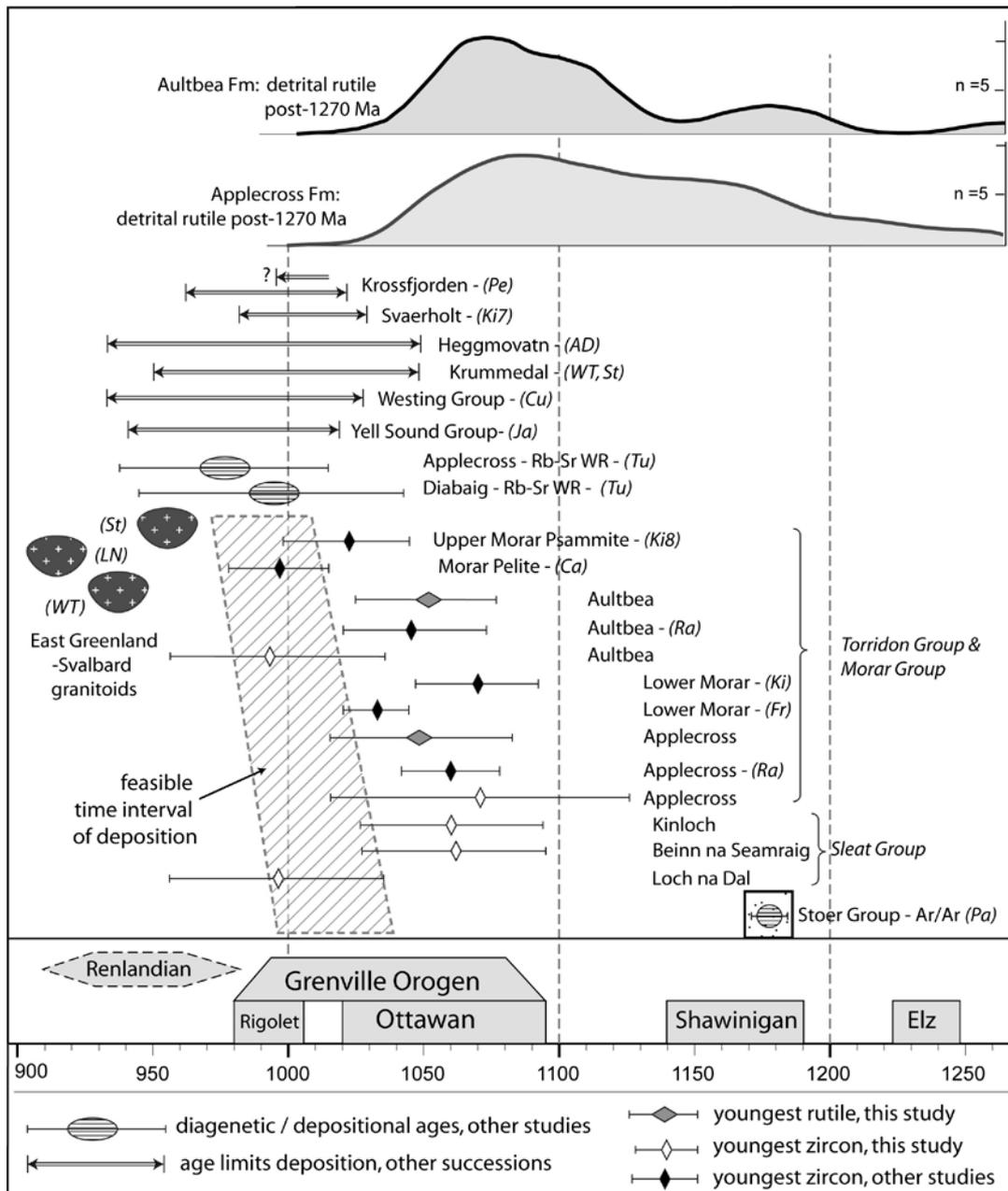


Fig. 14. Timing constraints on deposition of Sleat, Torridon and Morar groups in the Grenvillian foreland basin (hatched box labelled ‘feasible time interval of deposition’), plotted against Grenvillian orogenic phases and pre-Grenvillian accretionary orogenies (Rivers et al., 2012) and depositional time constraints for sequences in the North Atlantic region. Youngest detrital zircon dates of other studies: (*Ca*) = Cawood et al. (2015); (*Fr*) = Friend et al. (2003); (*Ki8*) = Kirkland et al. (2008); (*Ra*) = Rainbird et al. (2001). Depositional/diagenetic ages: (*Pa*) = Parnell et al. (2008); (*Tu*) = Turnbull et al. (1996). Timing constraints for sequences in North Atlantic region and East Greenland based on intrusion/migmatization ages: (*AD*) = Agyei-Dwarko et al. (2012); (*Cu*) = Cutts et al. (2009); (*Ja*) = Jahn et al. (2017); (*Ki7*) = Kirkland et al. (2007); (*LN*) = Leslie and Nutman (2003); (*Pe*) = Pettersson et al. (2009a, 2009b); (*St*) = Strachan et al. (1995); (*WT*) = Watt and Thrane, 2001.

Returning to the sedimentary sequence in the North Atlantic, the Westing Group and the Yell Sound group on Shetland were deposited between 1030-930 Ma and 1020-940 Ma respectively

(Cutts et al., 2009; Jahn et al. 2017); the Krummedal sequence in East Greenland between 1050-950 Ma (Kalsbeek et al., 2000; Watt and Thrane, 2001; Leslie and Nutman, 2003); the Krossfjorden Sequence on Svalbard between 1020-960 Ma (or possibly 1020-995 Ma) (Pettersson et al., 2009a, 2009b); and the Svaerholt and Heggmovatn successions in northern Norway between 1030-980 Ma and 1050-930 Ma respectively (Kirkland et al., 2007; Agyei-Dwarko et al., 2012). All these sequences have youngest detrital zircons of Grenvillian age, and many (specifically the Krummedal, Krossfjorden and Svaerholt groups) also have prominent ca. 1650 Ma zircon age peaks that are not represented in adjacent basement and were also likely derived from the Grenville Orogen. Thus, a regionally widespread episode of deposition occurred within the 1050-960 Ma interval (but possibly as short as 1020-980 Ma), sourced from the Grenville Orogen, but terminating before these deposits were deformed in the ca. 980-910 Ma Renlandian Orogeny. This raises the question how these more distal sequences relate to the proximal foreland basin record in Scotland.

Time-equivalence of these distal sequences with the Sleat Group is not plausible: a narrow shallow marine foreland basin is unlikely to transport detritus thousands of kilometres away from its mountain front. Instead, we suggest it was the main progradational pulse represented by the Torridon-Morar groups in Scotland that was responsible for transporting detritus from the Grenville Orogen to East Greenland, Svalbard and northern Norway (see also Kirkland et al., 2008). The implied massive braided river systems operating in a wide terrestrial foreland basin provide a plausible setting for the transportation of material over such large distances in a relatively short time frame. It is likely these systems were coeval with the transcontinental river systems transporting Grenvillian detritus to the Canadian Arctic (Rainbird et al., 1992; 2012; in prep). The major Torridon-Morar pulse of sedimentation and transport to Svalbard and East Greenland thus likely occurred between ca. 1050-960 Ma, feasibly in a shorter time interval of ca. 1020-980 Ma. The shorter time interval would be consistent with the rapid and sustained deposition implicit in the nature of the sediments. Most metamorphic cooling ages (rutile, titanite, monazite, hornblende) from the Grenville Province fall in the same time period (e.g., Haggart et al, 1993; Rivers, 2008, 2012; Rivers et al. 2012), so that the age constraints for the time of major deposition in the foreland basin overlap with those of the main phase of uplift and cooling, and hence denudation, of the hot mid crust in the source orogen.

6. Conclusions

We present detrital zircon and rutile U-Pb ages from the early Neoproterozoic Sleat and Torridon groups in NW Scotland and new sedimentological analysis of the Sleat Group that, together,

suggest both groups were part of the Grenvillian foreland basin. Youngest detrital U-Pb zircon dates in all units yield similar 1050-980 Ma ages, and youngest detrital rutile ages in the Torridon Group are within uncertainty of youngest detrital zircon ages. We interpret both the Sleat and Torridon groups to be sourced from the Grenville Orogen and to have been deposited in a Grenvillian foreland basin. Key older detrital zircon age peaks vary within the sequence. The lower Sleat Group shows a dominant cluster of ca. 1750 Ma, whereas in the upper Sleat Group and the Torridon Group ca. 1650 Ma ages become increasingly significant, as do age clusters between 1500-1100 Ma. These changes are interpreted to indicate a switch in source region from the Irish-Scottish sector of the Grenville Orogen during early Sleat Group deposition, to the more distal eastern Canadian sector of the Grenville Orogen during deposition of the late Sleat Group and Torridon-Morar groups. Grenvillian (ca. 1050 Ma) ages become more significant in detrital zircon populations higher up in the foreland basin stratigraphy, recording the progressive unroofing of the orogen. There is no difference in the source of detritus across the Sleat/Torridon unconformity. The detrital rutile ages in the Torridon Group show a significant syn-Grenvillian cluster, but also older (1700-1200 Ma) ages, suggesting derivation from the cool upper orogenic crust of the Grenville Orogen, consistent with syn-orogenic deposition. An enigmatic 1900 Ma cluster may have been derived from a mafic (?ophiolitic) thrust sheet preserved in the orogenic superstructure.

The detrital mineral data, sedimentology and disposition of units suggest five distinct phases of foreland basin deposition:

- i) early deposition in a narrow, shallow marine foreland basin (lower Sleat Group), sourced from the Irish-Scottish sector of the Grenville Orogen;
- ii) a switch within the Sleat Group to more distal sources from the eastern Canadian sector of the Grenville Orogen, with sediment input via axial transport into a still narrow foreland basin;
- iii) a sudden and profound switch in basin dynamics across the Sleat-Torridon boundary to a wide, terrestrial braidplain-dominated ('molasse') foreland basin (Torridon-Morar group), but with no change in provenance, coeval with more distal deposition in East Greenland, Svalbard and northern Norway, and possibly the Canadian Arctic. This phase represents a major denudational phase of the Grenville Orogen,
- iv) a transgression, as recorded by marine and lacustrine deposition of the Morar Pelite and upper Torridon Group respectively and associated with more local sourcing from the Irish-Scottish sector of the Grenville Orogen;
- v) a subsequent regression, indicated by a return to tidally-influenced fluvial braidplain, followed by a final transgression recorded by shallow marine deposition in the uppermost Morar Group

and a concomitant return to sourcing from the eastern Canadian sector of the Grenville Orogen.

Temporal correlation with early Neoproterozoic sequences in East Greenland, Svalbard and northern Norway suggests that the main Torridon-Morar group deposition occurred within the interval 1020-980 Ma. Collectively, the Sleat, Torridon and Morar groups preserve a significant part of the record of the evolution of the Grenvillian foreland basin.

Supplementary files

S1: metadata

S2: sample results and validation results

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