First evidence of Renlandian (c. 950-940 Ma) orogeny in Mainland Scotland: implications for the status of the Moine Supergroup and circum-North Atlantic correlations

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Abstract:

Central problems in the interpretation of the Neoproterozoic geology of the North Atlantic region arise from uncertainties in the ages of, and tectonic drivers for, Tonian orogenic events recorded in eastern Laurentia and northern Baltica. The identification and interpretation of these events is often problematic because most rock units that record Tonian orogenesis were strongly reworked at amphibolite facies during the Ordovician-Silurian Caledonian orogeny. Lu-Hf and Sm-Nd geochronology and metamorphic modelling carried out on large (>1cm) garnets from the Meadie Pelite in the Moine Nappe of the northern Scottish Caledonides indicate prograde metamorphism between 950 - 940 Ma at pressures of 6-7 kbar and temperatures of 600°C. This represents the first evidence for c. 950 Ma Tonian (Renlandian) metamorphism in mainland Scotland and significantly extends its geographic extent along the palaeo-Laurentian margin. The Meadie Pelite is believed to be part of the Morar Group within the Moine Supergroup. If this is correct: 1) the Morar Group was deposited between 980 ± 4 Ma (age of the youngest detrital zircon; Peters, 2001, youngest published zircon date is 947 ± 189 (Friend et al., 2003)) and c. 950 Ma (age of regional metamorphism reported here), 2) an orogenic unconformity must separate the Morar Group from the 883 ± 35 Ma (Cawood et al., 2004) Glenfinnan and Loch Eil groups, and 3) the term 'Moine Supergroup' may no longer be appropriate. The Morar Group is broadly correlative with similar aged metasedimentary successions in Shetland, East Greenland, Svalbard, Ellesmere Island and northern Baltica. All these successions were deposited after c. 1030 Ma, contain detritus from the Grenville orogen, and were later deformed and metamorphosed at 950-910 Ma during accretionary Renlandian orogenesis along an active plate margin developed around this part of Rodinia.

1. Introduction

Interpretation of the Neoproterozoic geology of the North Atlantic region is problematic due to uncertainties in the ages of, and tectonic drivers for, Tonian metamorphic events recorded in parts of eastern Laurentia and northern Baltica. This causes ambiguity around the relative positioning of Laurentia and Baltica within the supercontinent Rodinia. In one palaeoreconstruction, Baltica is placed directly opposite East Greenland, and Tonian tectonometamorphic events in Svalbard, Norway, East

Greenland and Scotland at >900 Ma are regarded as collisional in nature, comprising a northern arm of the Grenville-Sveconorwegian orogen (Park 1992; Lorenz et al. 2012; Gee et al. 2015). In that context, younger tectonometamorphic events at 820-730 Ma in Scotland and Norway might represent the closure of intracratonic successor basins within Rodinia (Cawood et al. 2004). Alternatively, palaeomagnetic evidence (albeit fragmentary) supports the solution favoured here in which Baltica has a more southerly location relative to East Greenland (Fig 1; Elming et al., 2014; Li et al., 2008; Merdith et al. 2017; Pisarevsky et al., 2003; Cawood & Pisarevsky 2017). This places East Greenland, Svalbard, northern Norway and Scotland much closer to the periphery of Rodinia. An alternative hypothesis is therefore that Tonian deformation and metamorphism records the evolution of an external accretionary orogen developed above a continentward-dipping subduction zone (Fig 1; Cawood et al., 2010, 2015; Johansson, 2015; Kirkland et al., 2011; Malone et al., 2014, 2017). Cawood et al. (2010) termed this the 'Valhalla' orogen, distinguishing between >900 Ma 'Renlandian' and 820-725 Ma 'Knoydartian' orogenic events.

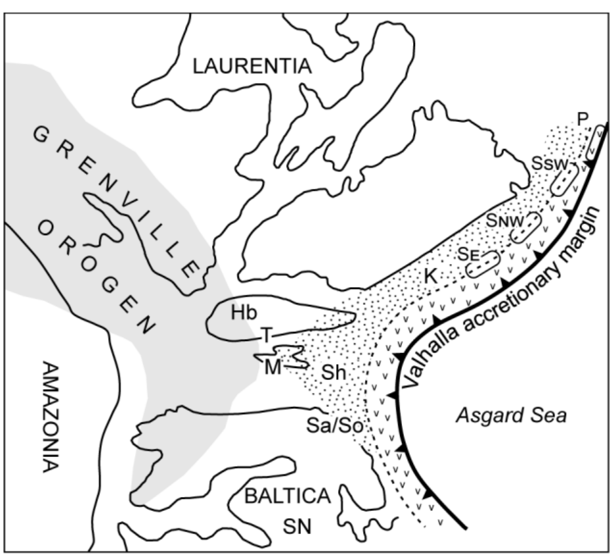

Fig. 1. Palaeogeographic reconstruction of the active peri-Laurentian-Baltican margin of Rodinia at c. 1100-1000 Ma (modified from Cawood et al. 2010 and Malone et al. 2017). Shaded area represents the Grenville orogen. Dotted area represents marginal basins developed between the continental interior and a magmatic arc-subduction zone. Hb, Hebridean foreland; T, Torridon Group; M, Moine Supergroup; Sh, Shetland; Sa, Særholt; So, Sørøy; K, Krummedal Succession; S_E, East Svalbard; S_{NW}, northwest Svalbard; S_{SW}, southwest Svalbard; P, Pearya (Ellesmere Island).

Further advances in understanding the evolution of this orogenic tract depend in part upon acquisition of additional geochronological constraints coupled with pressure-temperature (*P-T*) data from metamorphic assemblages. However, the identification and interpretation of Tonian tectonometamorphic events within the North Atlantic borderlands is often problematic because many of the rock units that record orogenesis of this age were strongly reworked at amphibolite facies during the Ordovician-Silurian Caledonian orogeny. The degree of Caledonian over-printing means that information on the timing and pressure-temperature conditions of pre-Caledonian orogenic events is typically only preserved in the cores of garnet porphyroblasts (Vance et al. 1998; Cutts et al. 2009a; Cutts et al. 2009b; Cutts et al. 2010). In Shetland (Fig 1), a sillimanite foliation entirely preserved within garnet porphyroblasts gave U-Pb monazite and zircon ages of c. 950-940 Ma, despite the presence of kyanite-bearing Caledonian fabrics (Cutts et al. 2009b). In this paper we present the results of an integrated geochronological and metamorphic study of garnet porphyroblasts from the Meadie Pelite within the Caledonides of northern mainland Scotland (Fig 2). These results further extend the geographic range of Renlandian orogenic events, with implications for the ages of, and correlations between, major lithostratigraphic successions.

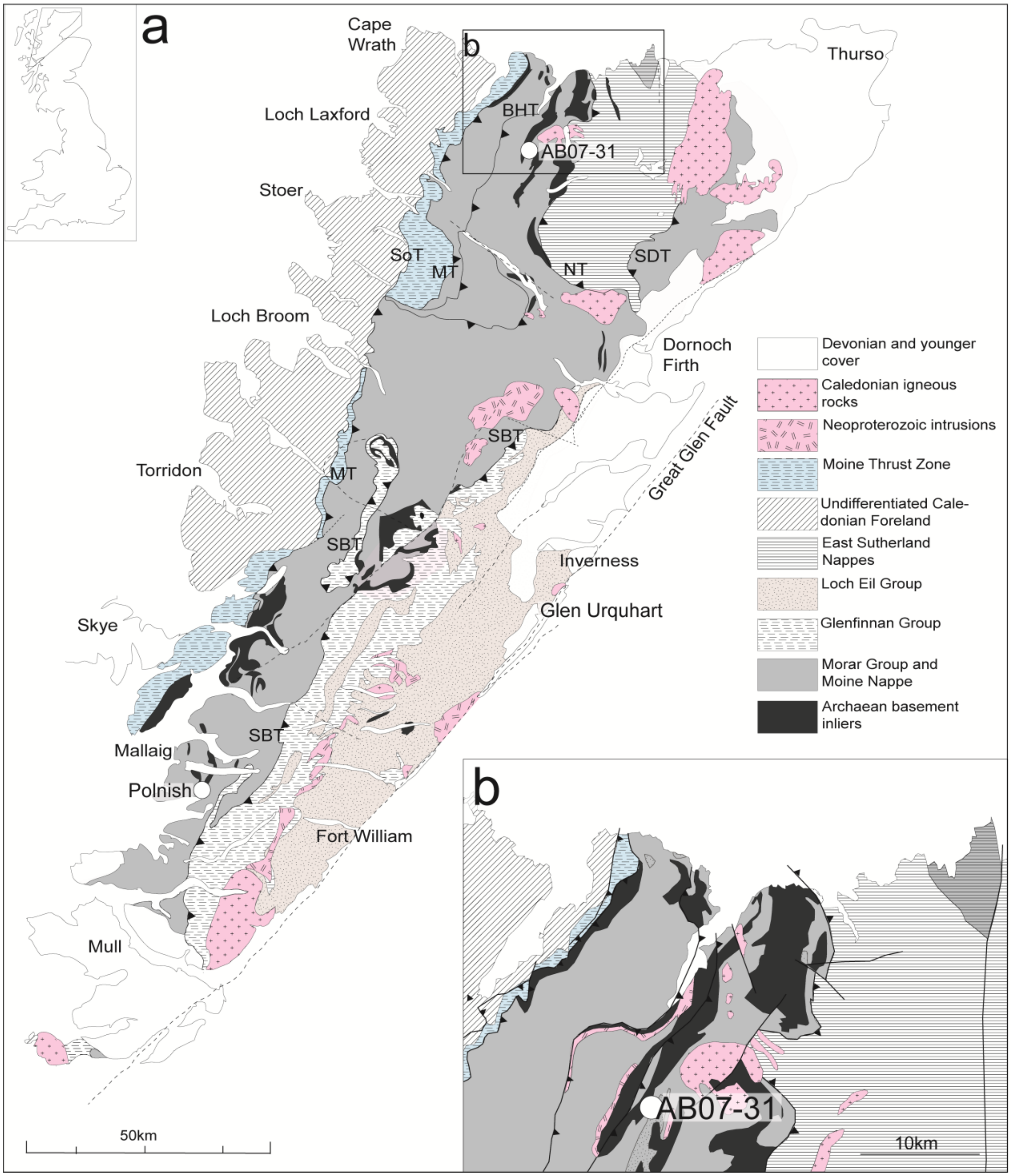

Fig. 2 a. Simplified geological map of Scotland after Bird et al. 2013.. The location of AB07-31 is shown in Fig. 2a and in Fig 2b. Abbreviations; SBT – Sgurr Beag Thrust; MT – Moine Thrust; SoT – Sole Thrust; NT – Naver Thrust; BHT – Ben Hope Thrust; SDT, Skinsdale Thrust.

2. Regional Geology

The Caledonian orogenic belt in northern Scotland is limited to the west by the Moine Thrust (Fig 2). The Hebridean foreland comprises the Archaean-Palaeoproterozoic Lewisian Gneiss Complex which is overlain unconformably by three sedimentary successions: a) the c. 1200 Ma Stoer Group, b) the c. 1000 Ma Sleat and Torridon groups, and c) the Cambrian to Ordovician Ardvreck and Durness groups (e.g. Park et al. 2002 and references therein; Stewart 2002; Wheeler et al. 2010; Krabbendam et al. 2008, 2017). In the hangingwall of the Moine Thrust, the metasedimentary rocks of the Moine Supergroup underlie large tracts of northern Scotland (Fig 2). Infolds and tectonic slices of Archaean orthogneisses have been broadly correlated with the Lewisian Gneiss Complex and are thought to represent the basement on which the Moine sediments were originally deposited (Ramsay 1958; Holdsworth 1989; Friend et al. 2008).

The Moine Supergroup comprises the Morar, Glenfinnan and Loch Eil groups (Fig 2; Strachan et al. 2002, 2010 and references therein). All three groups record evidence for 'Knoydartian' metamorphic events between 820 Ma and 725 Ma (Rogers et al. 1998; Vance et al. 1998; Tanner & Evans 2003 Cutts et al. 2009a, 2010; Cawood et al. 2015). The Morar Group was deposited after 980 ± 4 Ma (the age of the youngest detrital zircon; Peters 2001) whereas the Glenfinnan and Loch Eil groups contain detrital zircons as young as 885 ± 85 Ma (Cawood et al., 2004). Recent debate has centred on the stratigraphic relationship between the Morar Group and the Glenfinnan/Loch Eil groups. On Mull (Fig 2), the junction between the Morar and Glenfinnan groups has been interpreted as stratigraphic (Holdsworth et al. 1987). However, Krabbendam et al.

(2008) and Bonsor et al. (2012) favoured correlation of the Morar Group with the Torridon Group of the Hebridean foreland. The two successions were thought to have been deposited in the foreland basin to the c. 1.0 Ga Grenville orogen. If correct, this implies a depositional age close to c. 980 Ma for the Morar Group, which would therefore be distinctly older than the <885 Ma Glenfinnan and Loch Eil groups. Furthermore, the Morar Group would have been deposited prior to c. 940-925 Ma Renlandian metamorphism on Shetland (Cutts et al. 2009b; Cutts et al. 2011; Jahn et al. 2017), only 260 km north of mainland Scotland. If the Morar Group was affected by Renlandian orogenic activity, the Morar-Glenfinnan junction on Mull must hide a cryptic unconformity, and the term “Moine Supergroup” would be a misnomer. However, as yet no evidence has been forthcoming that would indicate that the Morar Group was affected by orogenesis of this age.

In Sutherland (northernmost mainland Scotland; Fig 2), the Morar Group is dominated by quartzo-feldspathic psammites with minor intercalations of pelitic schist (Moorhouse & Moorhouse 1988; Holdsworth 1989; Holdsworth et al. 2001). Inliers of Archaean basement mostly occur in the cores of large-scale anticlines. In central Sutherland (Fig 2), the eastern part of the Meadie basement inlier is separated from typical Morar Group psammites by the Meadie Schist Formation. The latter comprises a lower semi-pelite (the ‘Meadie Schist’) and an upper garnetiferous pelite, locally with kyanite and staurolite (the ‘Meadie Pelite’). Although Moorhouse & Moorhouse (1988) assigned the Meadie Schist Formation to the pre-Moine basement, the unit does not contain any tectonic structures or metamorphic assemblages that are unequivocally older than the adjacent Moine rocks, and has no features in common with any undisputed basement rocks in the area. Accordingly, the most recent interpretation of the area views the Meadie Schist Formation as a locally developed basal pelite of the Morar Group succession (British Geological Survey 2002).

3. Sample Description

Sample AB07-31 was obtained from the Meadie Pelite at NC 5231 4022 (Fig 2). The sample contains a well-developed muscovite-biotite foliation that is interpreted to be S2. The mica fabric is located within a quartz-plagioclase matrix and encloses garnet (1-20 mm), staurolite (up to 30 mm) and kyanite (<1mm; Fig. 3a, b). Kyanite wraps garnet and staurolite as an S2 fabric element (Fig. 3a). Garnet grains contain inclusions of quartz and ilmenite, which preserve an earlier fabric (S1, in some grains this fabric appears to be crenulated) within garnet cores while garnet rims are often seen to have fewer inclusions than the cores (Fig. 3a). Staurolite grains have been observed to grow between the cores and rims of garnet; however it is uncertain whether these are inclusions or have grown at the expense of garnet. Fine grained garnet with extensive inclusions that are often oriented parallel to the matrix foliation grow around large garnet grains. Fine-grained kyanite, which is not oriented with the matrix foliation, is also found around the edges of large garnet grains (Fig. 3a). Large staurolite grains contain inclusions of ilmenite and quartz that are oriented in a crenulation fabric (Fig. 3b). Larger staurolite grains are often surrounded by kyanite with kyanite also growing along cracks within the staurolite grains (Fig. 3b). Finer grained, euhedral staurolite grains are present in the matrix where they truncate kyanite and muscovite grains. Randomly orientated chlorite occurs on the rims of the garnet and in the matrix biotite (Fig. 3b).

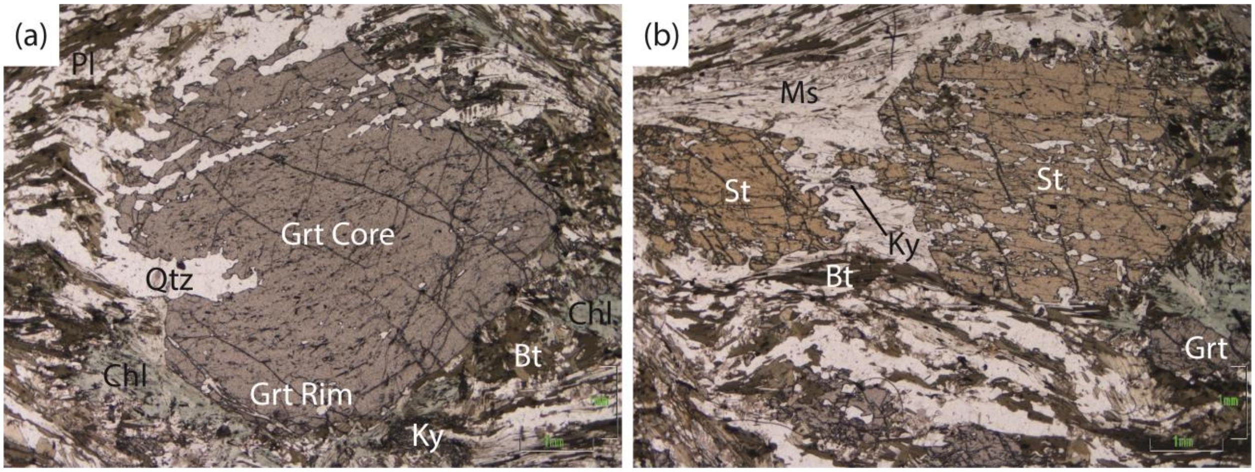

Fig. 3. Photomicrographs of sample AB07-31. A. Large garnet showing inclusions and core and rim. B. Staurolite, with small garnets

4. Analytical Methods

4.1 Major and Trace Element Mineral Chemistry

Compositional traverses of garnet grains from sample AB07-31 were obtained using a Cameca SX100 Electron Microprobe at the Open University. Quantitative analyses were run at an accelerating voltage of 15 kV and a beam current of 20 nA, with a beam diameter of 2-3 µm. Analyses were collected on wavelength dispersive spectrometers and all data is included in Supplementary File 1.

At Royal Holloway line traverses were carried out across the three garnets within a thick (60µm) thin-section of AB07-31. The instrumentation comprised a RESOlution L50 LPXPRO220 Excimer 193nm laser ablation system with a two-volume laser ablation cell that was coupled to an Agilent 7500 ICP-MS (Müller et al., 2009). SiO_2 contents obtained by electron microprobe at the Natural History Museum were used as an internal standard, and were found to be internally constant at 37.7 ± 0.21%. Analysing traverses of NIST SRM-612 glass standard at the beginning and end of each run allowed for external standardization. The spot size for data acquisition was 44 µm, the repetition rate was 15 Hz, the scan speed was 0.5 mm/min. All LA ICP-MS data is included in Supplementary File 2.

The X-ray fluorescence (XRF) analyses were also undertaken at Royal Holloway using the methods described by Thirlwall et al. (2000).

4.2 Garnet Geochronology

Core and rim material was separated during picking based on a purple core and an orange rim. To calculate the amount of spike necessary to be added to the garnet fractions the Lu, Hf, Sm and Nd concentrations were estimated from part of the pure garnet using the LA ICP-MS trace element data (Fig 4). XRF analysis of whole rock powders was used to establish concentrations of Nd, Y and Zr to calculate the mass of spike needed for the whole rock fractions.

For Lu–Hf and Sm–Nd analyses, the procedures for sample leaching, spiking and dissolution generally followed the guidelines described by Anczkiewicz & Thirlwall (2003) and Bird et al. (2013). Lu-Hf and Sm-Nd analyses were performed on a single total dissolution. The samples were first passed through AG50W-X8 cation resin to separate high field strength elements (HFSE), light rare earth elements (LREE) and heavy rare earth elements (HREE) fractions. The HFSE fraction required a second pass through these columns to minimise the HREE that may be in the fraction. The fractions were individually passed through Eichrom LN resin to separate respectively Hf, Sm and Nd, and Lu. Total procedure blanks were typically 24pg for Hf and 23pg for Nd. The lowest Hf mass used is 62.2ng from sample from AB07-31 WR and when the effect from the blank is calculated for it has no significant effect on the age obtained from the sample. This is also true for the sample with the lowest Nd mass is 64.1µg (AB07-31 Grt 1).

Analyses conducted using the GV IsoProbe MC-ICP-MS at RHUL, follow procedures of Thirlwall & Anczkiewicz (2004), except that static mode was used. Blank solutions were analysed before each sample to provide on-peak-zeros, and yield < 0.07mV ^{142}Nd and 0.08mV ^{180}Hf respectively, less than 10^{-3} x typical sample intensities. Drift commonly observed in static ratio analysis required frequent analysis of JMC475 Hf and Aldrich Nd standards. Hf data were collected on two separate days, when JMC 475 yielded average ^{176}Hf/^{177}Hf of 0.282189 ± 0.000009 and 0.282186 ± 0.000004 (2sd, N=6 and 5, respectively), and ^{180}Hf/^{177}Hf of 1.88664 ± 0.00006 and 1.88679 ± 0.00005. Nd data were collected on three separate days, and on these Aldrich Nd and Aldrich mixed Nd Ce solutions yielded ^{143}Nd/^{144}Nd of 0.511408 ± 0.000016, 0.511407 ± 0.000015 and 0.511410 ± 0.000007, (2sd, N=11, 16 and 9 respectively), after slope correction using the method of Thirlwall & Anczkiewicz (2004). Isochron ages and uncertainties were calculated using Isoplot version 4.15 (Ludwig 2003) and decay constants of 1.865 x 10^{-11} for ^{176}Lu (Scherer et al., 2001) and 6.54 x 10^{-12} for ^{147}Sm (Gupta & Macfarlane 1970).

4.3 Metamorphic modelling

A pressure-temperature (*P-T*) pseudosection was calculated for sample AB07-31 using the composition obtained via whole-rock XRF analysis. *P-T* pseudosections were calculated using THERMOCALC v.3.33 (June 2009 update of Powell & Holland 1988) with the internally consistent dataset of Holland & Powell (1998; dataset tcds55, November 2003 update). *P-T* pseudosections were calculated for the geologically realistic system MnNCKFMASH (MnO–Na_2O–CaO–K_2O–FeO–MgO–Al2O_3 –SiO_2–

H_2O). The modelling for this system uses the *a–x* relationships of White et al. (2007) for silicate melt; Tinkham et al. (2001) for garnet, cordierite, staurolite and alkali feldspar; Powell and Holland (1999) for biotite and orthopyroxene; a combination of Mahar et al. (1997) and White et al. (2000) for chloritoid; Coggon & Holland (2002) for muscovite and paragonite; and Holland & Powell (2003) for plagioclase.

The constraint on maximum H_2O content is taken as equivalent to the 'loss on ignition' from the XRF analyses. Compositional isopleths for garnet were calculated and have been plotted onto the peak field of the pseudosections to aid with interpretation of the *P–T* path.

5. Results

5.1 Major and trace element garnet chemistry

Based on the electron microprobe traverses (Fig. 4A), garnet grains appear to have two compositional zones. Grain cores (Z1) are relatively rich in inclusions that are oriented in an S1 fabric (Fig. 3C). Compositionally, XFe, Xgrs and Xsps are highest in the core and drop toward the edge of Z1 (0.91-0.83, 0.17-0.09 and 0.18-0.06 respectively, Fig. 4A). Xpyr and Xalm are lowest in the core and increase toward the edge of Z1 (0.06-0.14 and 0.59-0.70 respectively). On the edge of Z1 and Z2 there is a break in the compositional profiles of XFe, Xpyr and Xsps and Xgrs (Fig. 4A). Zone Z2 contains fewer inclusions than the garnet cores (the exception being large staurolite grains which are occasionally included in this zone), where present, the inclusions again define an S1 foliation. In Z2 XFe, Xgrs and Xsps drop towards the rim (0.83-0.81, 0.11-0.09 and 0.06-0.02 respectively) whereas Xpyr and Xalm rise towards the rim (0.14-0.17 and 0.70-0.73 respectively; Fig. 4A). There is no evidence of a change in composition on the very rim of the garnet. However, in thin section the edges of garnet grains are abundant in inclusions and in some places are quite broken up and replaced by chlorite. In these areas, the orientation of inclusions is generally continuous with the matrix foliation.

Trace and major element data was also collected from AB07-31 garnet. The garnet shows notable HREE zoning, with HREE increasing towards the core, represented by Lu in Fig. 4B. Sm and Nd do not show any obvious zoning (Fig. 4B and C), but do show several peaks that relate to LREE and MREE-rich inclusions, e.g. apatite. Hf is fairly homogeneous throughout the garnet with some small peaks, which are probably due to minor zircon inclusions (Fig. 4C).

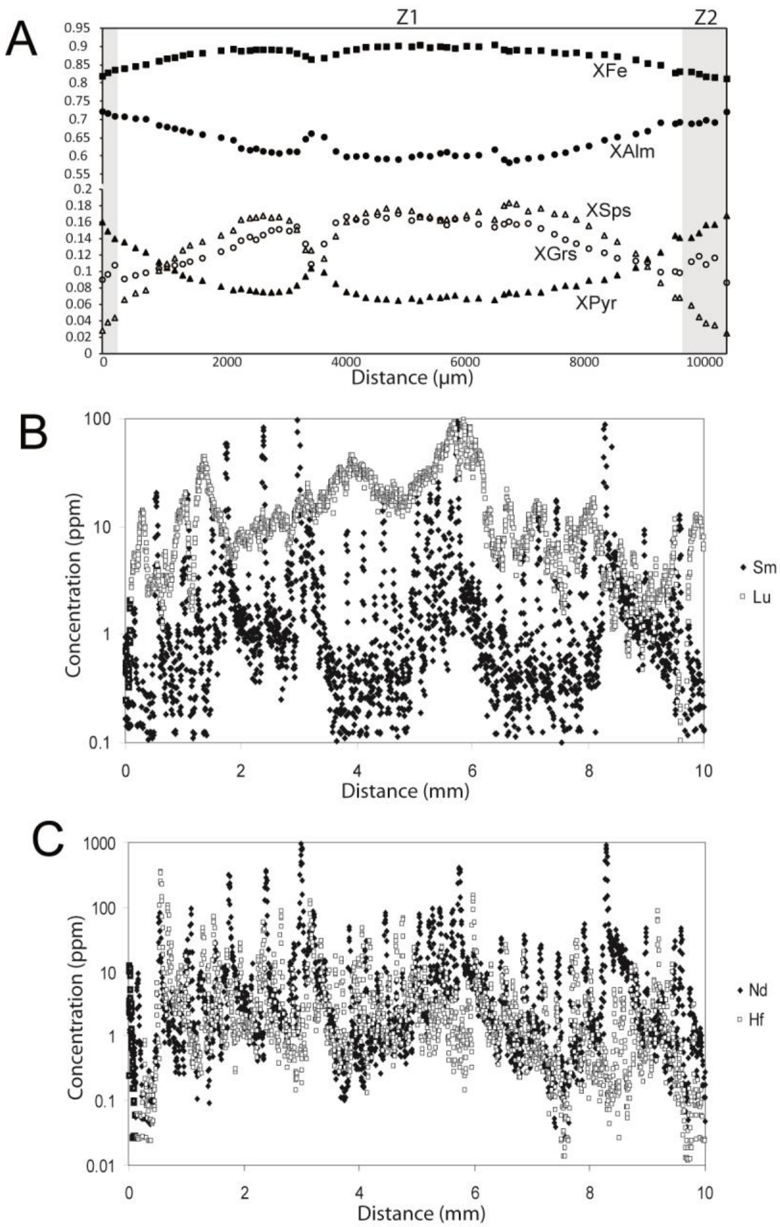

Fig. 4. A. Major element traverse for sample AB07-31. B. Sm and Lu LA ICPMS profiles for AB07-31. C. Hf and Nd LA ICPMS profiles for AB07-31.

5.2 Garnet geochronology

The dates reported in Table 1 are two-point dates based on a whole rock and garnet fraction. Three Lu-Hf dates from the garnet core (Z1) are in the range 947.0 – 951.8 Ma and consistent with one successful and slightly lower Lu-Hf rim date of 942.1 ± 4 Ma and also consistent with three low precision Sm-Nd dates (951 to 917 ± 34-32 Ma). The

Lu-Hf core dates are considered robust as they have reasonably high $^{176}Lu/^{177}Hf$ and $^{176}Hf/^{177}Hf$ ratios and are within uncertainty of each other, they can also be calculated as a 4-point isochron (Fig. 5A) using all three garnet cores and the whole-rock fraction to give an date of 949.6 ± 3 Ma (MSWD = 1.4). All the Lu-Hf data can be calculated as a 7-point isochron of 944.4 ± 7.0 (MSWD = 3.6), shown in Fig. 5B. Two further Lu-Hf rim dates are within uncertainty of the core dates, but have poor precision, with $^{176}Lu/^{177}Hf$ and $^{176}Hf/^{177}Hf$ ratios lower than those of the whole rock, in part due to inclusions rich in Hf, as the Hf concentrations are 75 and 6 ppm which the pure garnet is ~4 ppm (Table 1). Grt Core 1 gave a Sm-Nd date of 841 ± 9 Ma. Gt Core samples 2, 3 and 4 have large date errors due to low garnet $^{147}Sm/^{144}Nd$ ratios, but are higher than the date for Core 1, and within uncertainty of the Lu-Hf core dates suggesting that these ages may be meaningful. The Sm-Nd dates from the garnet core can be calculated as a 5-point isochron (Fig. 5C), which gives an age of 840 ± 29 Ma (MSWD = 14). Two Sm-Nd rim samples yield 772 ± 26 Ma and 701.7 ± 9.7 Ma, while another two yield dates that have been strongly influenced by the presence of inclusions, shown by the high (6-53 ppm) Nd concentrations, resulting in the garnets having similar $^{147}Sm/^{144}Nd$ to the whole rock.

	LA ICPMS concentration (ppm)		Isotope ratios and concentrations determined by isotope dilution (ppm)									
	Lu	Hf	Lu	Lu 2se	Hf	Hf 2se	176Lu/177Hf	2se	176Hf/177Hf	2se	Age	2se
AB07-31 Grt Core 1	52.7	0.1	10.956	0.005	3.963	0.001	0.391	0.001	0.289179	0.000009	947.0	4.2
AB07-31 Grt Core 2	52.7	0.1	13.145	0.021	4.483	0.003	0.415	0.001	0.289631	0.000025	951.8	5.5
AB07-31 Grt Core 3	52.7	0.1	13.230	0.016	4.354	0.002	0.430	0.001	0.289897	0.000017	951.1	4.6
AB07-31 Grt Rim 1	17.0	0.3	14.031	0.033	3.942	0.004	0.504	0.002	0.291146	0.000010	942.1	3.7
AB07-31 Grt Rim 2	17.0	0.3	20.077	0.006	75.131	0.074	0.038	0.000	0.282914	0.000040	913	44
AB07-31 Grt Rim 3	17.0	0.3	1.556	0.001	6.457	0.007	0.034	0.000	0.282845	0.000038	917	39
AB07-31 WR	0.7	4.4	0.729	0.001	1.200	0.001	0.086	0.000	0.283738	0.000009		
	Sm	Nd	Sm	2se Sm	Nd	2se Nd	147Sm/144Nd	2se	143/144	2se	Age	2se
AB07-31 Grt Core 1	0.3	0.1	1.883	0.001	2.457	0.001	0.464	0.000	0.513771	0.000016	841.3	8.6
AB07-31 Grt Core 2	0.3	0.1	1.030	0.001	3.401	0.001	0.183	0.000	0.512256	0.000009	951	34

AB07-31 Grt Core 3	0.3	0.1	1.040	0.000	3.439	0.001	0.183	0.000	0.512241	0.000007	917	32
AB07-31 Grt Core 4	0.3	0.1	1.001	0.000	3.269	0.001	0.185	0.000	0.512260	0.000008	929	33
AB07-31 Grt Rim 1	0.8	0.2	1.696	0.000	2.608	0.001	0.393	0.000	0.513136	0.000013	701.7	9.7
AB07-31 Grt Rim 2	0.8	0.7	0.848	0.000	2.372	0.001	0.216	0.000	0.512353	0.000012	772	26
AB07-31 Grt Rim 3	0.8	0.7	11.674	0.005	53.539	0.027	0.132	0.000	0.511946	0.000012	1134*	280
AB07-31 Grt Rim 4	0.8	0.7	1.180	0.000	5.646	0.005	0.126	0.000	0.511905	0.000010	1098*	740
AB07-31 WR	6.2	30.9	5.330	0.002	26.083	0.002	0.124	0.000	0.511895	0.000012		
AB07-31 WR	6.2	30.9	5.462	0.002	26.755	0.002	0.123	0.000	0.511884	0.000010		

Table 1, Lu-Hf and Sm-Nd geochronological data for sample AB07/31. The 2 σ uncertainty is less than 0.3% on 176Lu/177Hf, and assumed to be 0.3% in the calculations. The 2 σ uncertainty is less than 0.1% on 147Sm/144Nd, and assumed to be 0.1% in the calculations

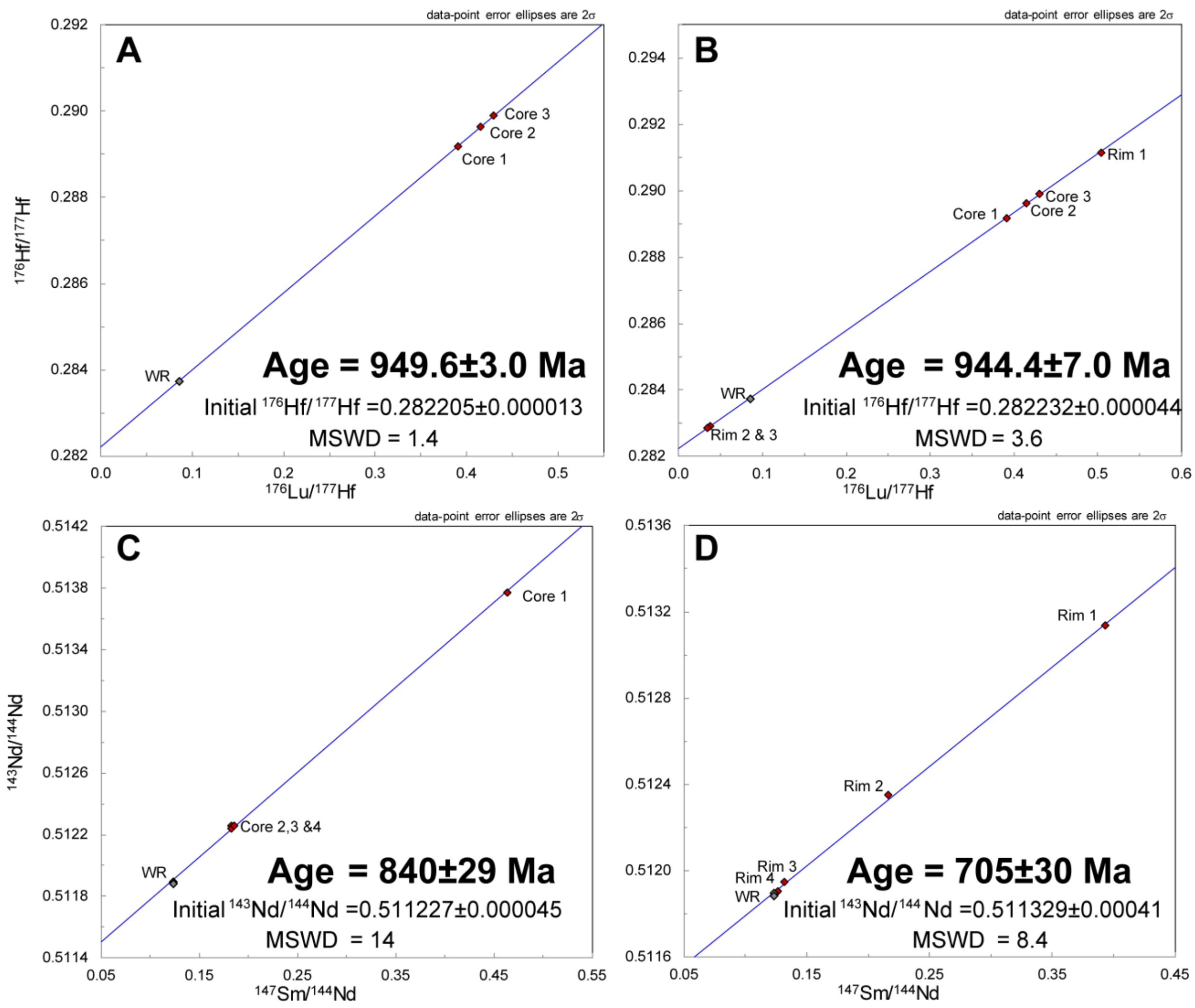

Fig. 5. Lu-Hf and Sm-Nd isochrons for AB07-31. A shows the Lu-Hf isochron from the garnet core; B shows the Lu-Hf isochron using the core and rim fractions; C shows the Sm-Nd from the garnet core; and D shows the Sm-Nd isochron from the garnet rim.

5.3 Metamorphic modelling

The whole rock bulk composition was used to create the *P-T* pseudosection, which shows the mineral relationships during the growth of Z1 garnet (Fig. 6). The *P-T* path is defined by the mineral assemblage evolution as well as the chemical zoning profiles of each garnet zone. In the *P-T* pseudosection, the garnet core composition overlaps in the field garnet + biotite + plagioclase + chlorite + muscovite + quartz which is consistent with the inclusion assemblage in the garnet grains. The change in composition of garnet in Z1 indicates an up-P and T evolution into the staurolite-bearing field. This is consistent with the observation of multiple generations of staurolite in the sample. Peak conditions are difficult to determine, as it is possible that Z1 garnet rims were retrogressed prior to Z2 growth. A conservative estimate for this event is 6-7 kbar and c. 600 °C as there is no evidence of kyanite growth prior to growth of the Z2 garnet (Fig. 6).

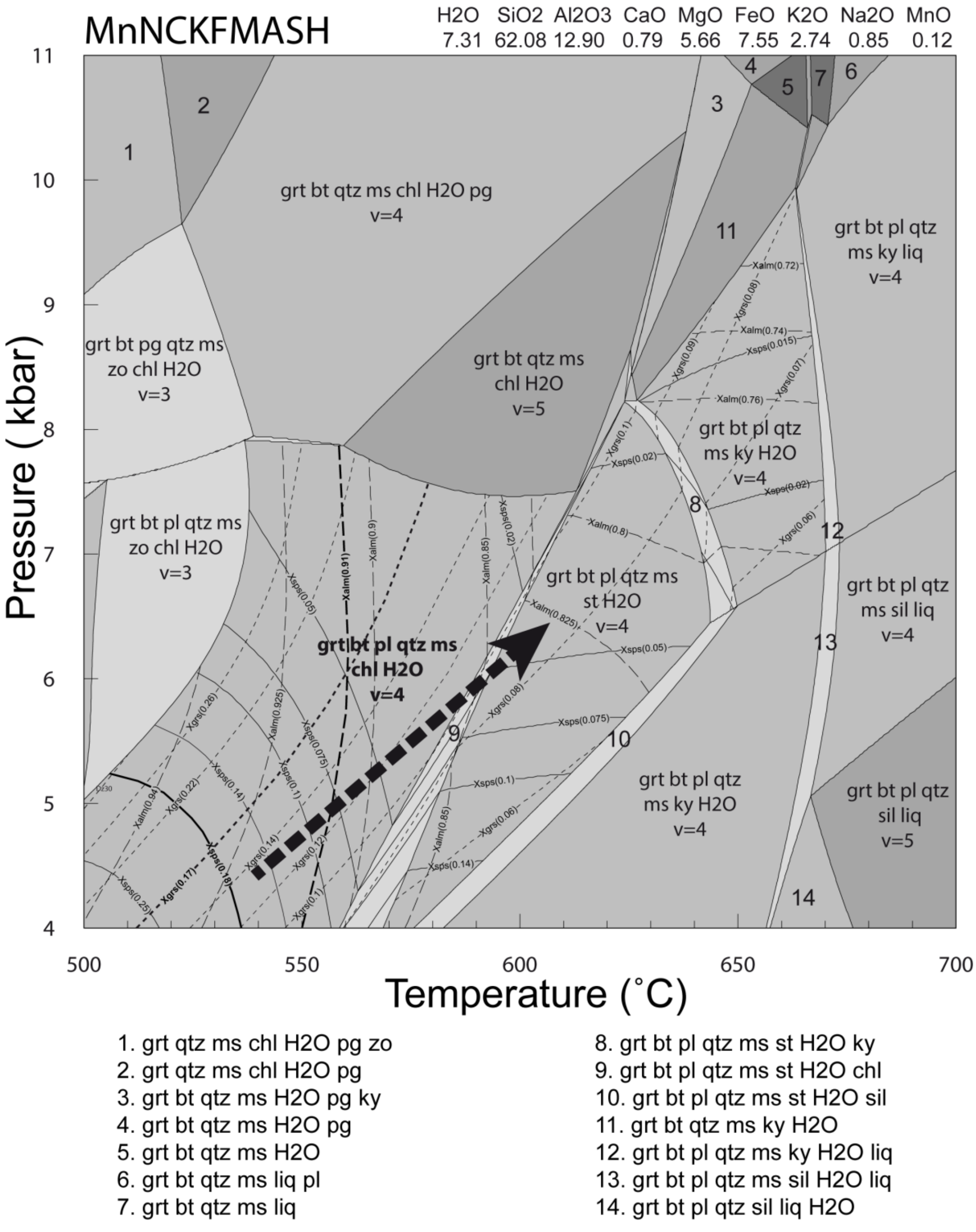

Fig. 6. The whole rock bulk composition was used to create a P-T pseudosection, for sample AB07-31. This diagram reflects mineral relationships during growth of Z1 garnet. The labelled, dashed lines indicate compositional isopleths for garnet. The bold ones indicate the composition of the garnet core. The large, dashed arrow indicates the P-T path for sample AB07-31 based on the compositional zoning in garnet.

6. Discussion and conclusions

6.1 Significance of age and P-T data

The LA ICP-MS gave a Hf concentration of ~1.7 ppm for pure garnet which is just less than half of the Hf concentration from isotope dilution in both of the garnet fractions. This suggests that there has been ~50% Hf contribution from zircon inclusions. The Nd concentration for pure garnet from LA ICP-MS was ~0.78 ppm, the Nd concentrations from ID ranged from 2.4 ppm to 3.4 ppm suggesting substantial input from Nd-rich inclusions. However, the two-point Sm-Nd dates from Gt core fractions 2, 3 and 4 are within uncertainty of the core Lu-Hf dates, suggesting that the inclusions have not significantly affected these dates, beyond reducing their precision. The ~100 Ma lower Sm-Nd date of Grt core 1 could represent physical mixing between the picked garnet core and rims as Sm-Nd rim dates are 200-180 Ma lower. Although, physical mixing should also affect the Lu-Hf dates, but it would have no observable effect as the Lu-Hf rim dates are nearly within error of the core dates. The lower Sm-Nd rim dates when compared with Lu-Hf may relate to differences in the closure temperatures between the two systems. Sm-Nd may have been partially reset by later Caledonian thermal events and not affect the Lu-Hf isotopic system, as Lu-Hf is thought to have a higher closure temperature than Sm-Nd (e.g. Anczkiewicz et al. 2007; Scherer et al., 2000; Smit et al., 2013).

The Electron Probe Micro Analysis (EPMA) data in combination with the Lu-Hf and Sm-Nd analyses suggests that the garnets have two growth zones (Fig. 4A). Based on the appearance of the garnet in thin section (broken up, thin rims with inclusions parallel to the matrix foliation as well as fine-grained matrix garnet), it is possible that there were three episodes of garnet growth. Potentially, the cores and rims (zones 1 and 2) are Neoproterozoic while the thin rim and fine garnet could feasibly be Caledonian in age, which would correlate with the findings of Cutts et al. (2010) and Bird et al. (2013) from elsewhere within the Moine Supergroup. The LA-ICP-MS data can provide more information on whether the garnet dates reflect prograde growth or cooling, as samples with Lu enrichment towards the garnet cores (e.g. Fig. 4B) are more likely to provide dates that reflect garnet growth, as HREE are highly compatible in garnets (e.g. Lapen et al. 2003; Skora et al. 2008; Bird et al. 2013). Since this is the case here (Fig. 4B), the Lu-Hf dates presented here should reflect the age of garnet growth.

In summary, the data shows prograde garnet growth at ~950 Ma, relating to metamorphic pressures and temperatures of at least 6-7 kbar and 600°C. Z2 garnet probably grew during the same metamorphic event as it also overprints the S1 foliation and gives a similar age. The break in composition of the major elements could be a result of a growth hiatus, possibly as a result of the growth of staurolite (which appears as inclusions in Z2), limiting the amount of Al available for growth garnet (or even as a result of the growth of Z1 garnet altering the bulk composition of the sample, e.g. Cutts et al. (2010)). Z2 garnet also seems to have fewer quartz inclusions (Fig. 3a and Supplementary File 2), Kelly et al. (2015) found that quartz was consumed across the staurolite-in isograd, suggesting that Z2 garnet grew in equilibrium with staurolite. Z2 achieved the highest-pressure conditions as matrix staurolite is partially replaced by kyanite (Figs. 3A, 6).

6.2. Implications for the status of the Moine Supergroup

Our findings potentially have significant implications for the age of the Morar Group and the status of the Moine Supergroup. If the Meadie Pelite is indeed part of the Morar Group as currently assumed, the latter must have been deposited between 980 ± 4 Ma (age of the youngest detrital zircon; Peters 2001) and c. 950-940 Ma (age of regional metamorphism reported here). Prior to the new ages reported here, the Morar Group was only constrained to have been deposited before 842 ± 20 Ma, the age of new zircon rims on detrital grains (Kirkland et al. 2008). The data from the Meadie Pelite implies that an orogenic unconformity must separate the Morar Group from the Glenfinnan and Loch Eil groups that were deposited after 883 ± 35 Ma (Cawood et al., 2004). As a 'supergroup' must comprise a number of groups that are linked by stratigraphic passage, the term 'Moine Supergroup' may therefore no longer be useful as it likely incorporates at least two unrelated sedimentary successions. Further isotopic and P-T data are necessary from Morar Group rocks higher in the succession in order to test this new view of Moine stratigraphy.

6.3 Correlations with other circum-North Atlantic successions

The data reported here provide the first evidence for c. 950-940 Ma Renlandian orogenic activity in mainland northern Scotland, significantly extending the geographic extent of this event southwards from Shetland. U-Pb zircon and monazite dates of c. 950-930 Ma obtained from the Westing and Yell Sound groups and from reworked Archaean basement in northeast Shetland and interpreted to date prograde amphibolite-facies metamorphism (Cutts et al. 2009b; Jahn et al. 2017), are close to the new dates reported here. Further north along the palaeo-Laurentian margin of E Greenland, Svalbard and Ellesmere Island (Pearya, Fig 1) there is abundant evidence for similar-aged tectonothermal activity (Figs 1 & 7; Cawood et al. 2010, 2015 and references therein). Evidence for amphibolite facies metamorphism and accompanying felsic magmatism at c. 950-910 Ma is recorded in the Krummedal Succession (E Greenland), the Krossfjorden Group (western Svalbard), the Brennevinsfjorden Group and Helvetesflya Formation (eastern Svalbard) and Pearya ‘Succession I’ (Pearya) (see references for Fig 7). The Sværholt Succession of northern Norway (Figs 1 & 7) is generally believed to be broadly time-equivalent, although deformation and metamorphism occurred slightly earlier at c. 980 Ma. All of these successions contain c. 1100-1030 Ma populations of detrital zircons that are interpreted to have been sourced from the Grenville orogen (e.g. Cawood et al. 2007; Kirkland et al. 2008; Rainbird et al. 2001, 2012). The temporal constraints provided by detrital zircon studies and dating of metamorphism and/or intrusive magmatism therefore imply that all these successions are broadly time-equivalent, although it is likely that they were deposited in separate basins. On the Scottish Hebridean foreland (Figs 1 & 7), the un-metamorphosed Torridon and Sleat groups are thought to form part of the same tectonostratigraphic package (Krabbendam et al. 2017 and references therein).

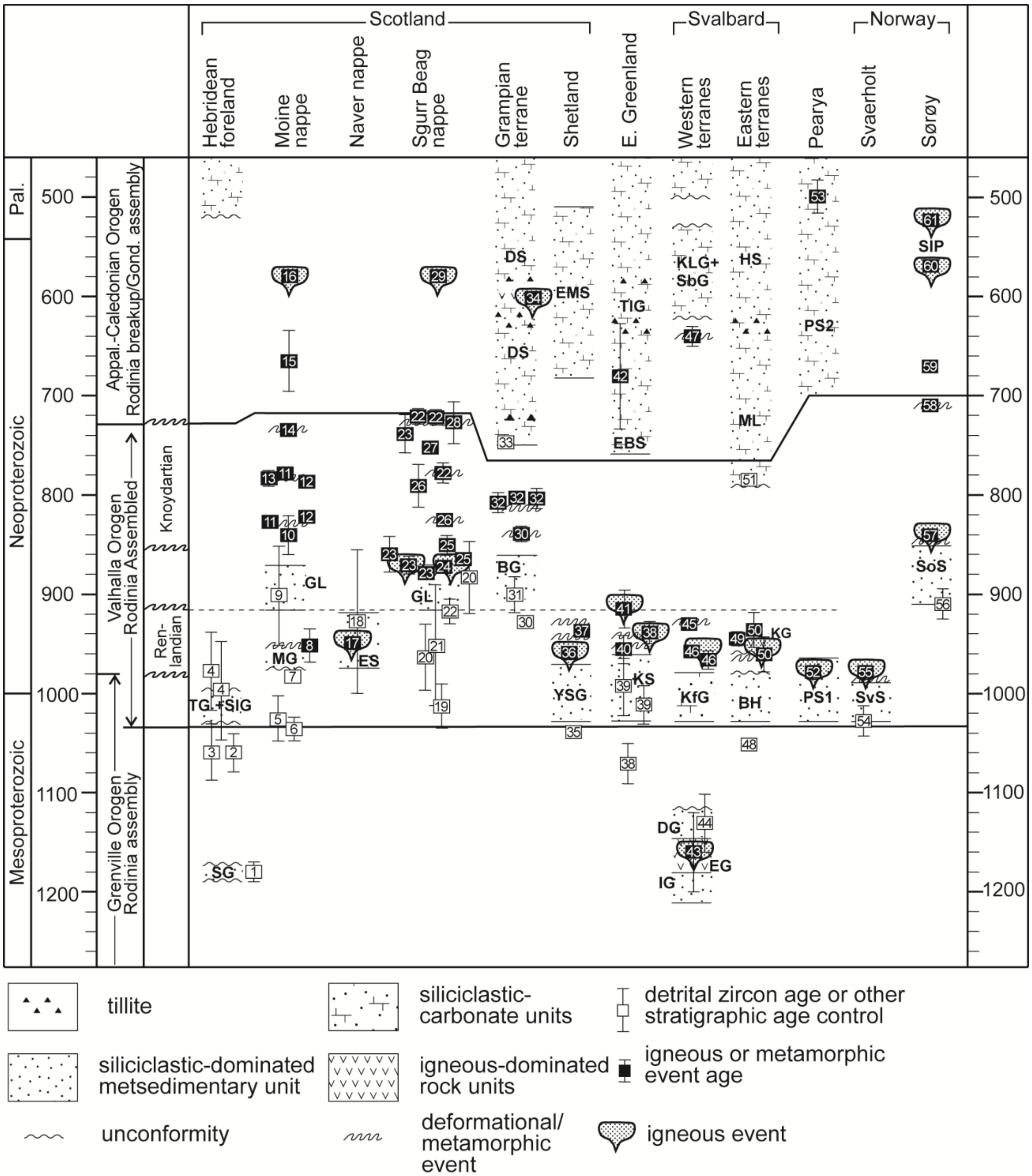

Figure 7. Age range of principal late Mesoproterozoic to Palaeozoic metasedimentary units and of tectonothermal events within regions affected by the Valhalla Orogen, from the North Atlantic borderlands. See Supplementary File 3 for the extended figure caption. Numbers on data points refer to the following sources: **1** - Parnell et al. (2011); **2** – Rainbird et al. (2001); **3** – Krabbendam et al. (2017); **4** - Turnbull et al. (1996); **5** – Kirkland et al. (2008); **6** – Friend et al. (2003); **7** – Peters (2001); **8** – this paper; **9** – Cawood et al. (2015); **10** – Kirkland et al. (2008); **11** – Rogers et al. (1998); **12** – Vance et al. (1998); **13** – Cawood et al. (2015); **14** – Tanner and Evans (2003); **15** – Storey et al. (2004); **16** – Oliver et al. (2008); **17** – Kinny and Strachan (unpublished data); **18** – Friend et al. (2003); **19** – Kirkland et al. (2008); **20** – Cawood et al. (2004); **21** – Friend et al. (2003); **22** – Cutts et al. (2010); **23** – Cawood et al. (2015); **24** –(Friend et al., 1997), (Millar, 1999), (Rogers et al., 2001); **25** – Cawood et al. (2015); **26** – Cawood et al. (2015); **27** – Cawood et al. (2015); **28** – van Breemen et al. (1974); **29** – Kinny et al. (2003); **30** – Highton et al. (1999); **31** – Cawood et al. (2003); **32** – Noble et al. (1996); **33** –(Piasecki and van Breemen, 1983); **34** – Halliday et al. (1989) and Dempster et al. (2002); **35** – Cutts et al. (2009); **36** – Kinny and Strachan (unpublished data); **37** – Cutts et al. (2009 and Jahn et al. (2017); **38** – Watt et al. (2000); **39** – Kalsbeek et al. (2000); **40** – Strachan et al. (1995); **41** – Leslie and Nutman (2003); **42** – Jensen (1993); **43** – Balashov et al. (1996); **44** – Pettersson et al. (2009);

__45__ – Balashov et al. (1995); __46__ – Pettersson et al. (2009); __47__ – Majka et al. (2008); __48__ – A.N. Larionov, unpub. data in Johansson et al. (2005); __49__ – Johansson et al. (2000); __50__ –Gee et al., (1995); see also Johansson et al., (2004); Johansson et al., (2000). __51__ – Knoll (1982); __52__ – Malone et al. (2017); __53__ – Trettin et al. (1982); __54__ – Kirkland et al. (2007); __55__ – Kirkland et al. (2006); __56__ – Kirkland et al. (2007); __57__ – Kirkland et al. (2006); __58__ – Kirkland et al. (2006); __59__ – Kirkland et al. (2007); __60__ – Roberts et al. (2006); __61__ – Pedersen et al. (1989).

Abbreviations: BD – Badenoch Group; BH – Brennevinsfjorden Group and Helvetesflya Formation; DG – Deilegga Group; DS – Dalradian Supergroup; EBS – Eleonore Bay Supergroup; EG – Eimfjellet Group; EMS – East Mainland Succession; ES – East Sutherland Moine succession; GL – Glenfinnan and Loch Eil groups; HS – Hinlopenstretet Supergroup; IG – Isbjörnhamma Group; KfG – Krossfjorden Group; KG – Kapp Hansteen Group; KLG – Kapp Lyell Group; KS – Krummedal succession; MG – Morar Group; ML – Murchisonfjorden and Lomfjorden successions; PS1 – Pearya Succession I; PS2 – Pearya Succession II; SbG – Sofiebogen Group; SG – Stoer Group; SIP – Seiland Igneous Province; SlG – Sleat Group; SoS – Sørøy succession, Kalak Nappe Complex; SvS – Svaerholt succession, Kalak Nappe Complex; TG – Torridon Group; TlG – Tillite Group; YSD – Yell Sound Division – Westing Group

In the context of the model of Cawood et al. (2010) for the Valhalla orogen (Fig 1), potential tectonic drivers for Renlandian deformation and metamorphism are flat-slab subduction and /or terrane accretion. No allochthonous terranes have yet been identified but if present may be submerged on the rifted margins of the Arctic shelf. It is important to emphasise, however, that the conclusions of the present study do not preclude the interpretation that Renlandian events result from Laurentia-Baltica collision within a northern arm of the Grenville orogen as advocated by Park (1992), Lorenz et al. (2012) and Gee et al. (2015). Irrespective of which model is correct, post-920 Ma successor basins in Scotland (Glenfinnan, Loch Eil and Badenoch groups) and northern Baltica (Sørøy succession) likely resulted from steepening and/or retreat of subduction zones around this sector of Rodinia prior to renewed Knoydartian accretionary orogenesis at 820-725 Ma (Cawood et al. 2004, 2010, 2015).

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