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A new stratigraphic framework for the early Neoproterozoic successions of Scotland

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Abstract

The circum-North Atlantic region archives three major late-Mesoproterozoic to Neoproterozoic tectonic episodes, the Grenville-Sveconorwegian and Renlandian orogenies followed by rifting and formation of the Iapetus Ocean, and each is bracketed by sedimentary successions that define three megasequences. In this context, we summarise sedimentological and geochronological data and propose a new stratigraphic framework for the iconic Torridonian-Moine-Dalradian successions and related units in Scotland. The Iona, Sleat, Torridon and Morar groups of the Scottish mainland and Inner Hebrides, and the Westing, Sand Voe and Yell Sound groups in Shetland, form the newly named Wester Ross Supergroup. They were deposited c. 1000–950 Ma within a foreland basin to the Grenville Orogen and, collectively, are in Megasequence 1. Some of these units record Renlandian orogenesis at c. 960-920 Ma. The newly named Loch Ness Supergroup consists of the Glenfinnan, Loch Eil and Badenoch groups of the Scottish mainland, deposited c. 900–870 Ma and are assigned to Megasequence 2. These units record Knoydartian orogenesis c. 820-725 Ma. The regionally extensive Dalradian Supergroup belongs to Megasequence 3; it was deposited c. <725-500 Ma and records the opening of the Iapetus Ocean, ultimately leading to deposition of the passive margin Cambrian-Ordovician Ardvreck and Durness groups.

The North Atlantic region contains a number of Neoproterozoic (meta)sedimentary successions, each several to many kilometres thick, that record the amalgamation and erosional denudation of
the Rodinia supercontinent and its subsequent break-up (e.g. Kirkland et al. 2007; 2008a, b; Cawood et al. 2007; 2010; Krabbendam et al. 2017). The oldest successions contain detrital zircons with U-Pb ages of 1100–1000 Ma, evidence that they were derived from the Grenville-Sveconorwegian orogen, itself a consequence of collision between Laurentia, Baltica and Amazonia at c. 1000 Ma (Fig. 1). The successions are commonly highly deformed by Neoproterozoic (Renlandian, Knoydartian) and early Palaeozoic (Caledonian) orogenic events making correlations and inferences regarding palaeoenvironments difficult. However, integration of geochronological and sedimentological datasets allows linking of these successions not only across the Scottish Highlands but also the circum-North Atlantic region.

Researchers working in the circum-North Atlantic region have defined three ‘Megasequences’ (Fig. 2; Kirkland et al. 2008a, b; Cawood et al. 2007; 2010; Agyei-Dwarko et al. 2012; Olierook et al. 2020). Megasequence 1 comprises strata deposited c. 1000–950 Ma that, in places, are deformed and metamorphosed by the c. 960–920 Ma Renlandian orogeny (e.g. Watt & Thrane 2001; Dhuime et al. 2007; Pettersson et al. 2009a, b), an early phase of the accretionary Valhalla Orogen (Cawood et al. 2010). Megasequence 2 consists of rocks c. 900–870 Ma in age and Megasequence 3 spans from c. 725 Ma through to the Cambrian-Ordovician development of the Iapetus Ocean (Olierook et al. 2020). The Neoproterozoic successions in Scotland have been provisionally placed into this three-fold subdivision (Cawood et al. 2007; Kirkland et al. 2008a; Olierook et al. 2020). In the most recent iteration of this scheme (Olierook et al. 2020), this results in grouping Scottish units assigned historically to different tectonostratigraphic packages and basin settings. Problems with the present framework were also noted earlier (e.g. Cawood et al. 2007; Cutts et al. 2009; Bird et al. 2018) and, consequently, a new stratigraphic framework is required. Here we propose a revised stratigraphy of the Scottish successions, compatible with, and integrating readily into, the recently refined understanding of the Neoproterozoic tectonic evolution of the North Atlantic region.

Geological overview

The Neoproterozoic rocks of the Scottish Highlands have been traditionally consigned to one of three iconic successions: the Torridonian, Moine and Dalradian supergroups (Gibbons & Harris 1994; Trewin et al. 2002; Mendum et al. 2009). The Torridonian contains the sedimentary rocks resting unconformably on Archaean-Palaeoproterozoic Lewisian basement west of the Caledonian Moine thrust zone, whereas the Moine comprises the amphibolite-facies metasedimentary rocks in the hanging wall of that thrust. Southeast of those successions, and on the opposite side of the Great
Glen strike-slip fault zone (Fig. 3), are the metasedimentary rocks of the Dalradian Supergroup. Our focus here is on the Torridonian and Moine successions, both of which have played central roles in ideas regarding the geological evolution of the Scottish Highlands and the North Atlantic region in general.

Some early workers in the Scottish Highlands suggested that parts of the Torridonian and Moine were correlative (e.g. Peach & Horne 1930; Kennedy 1951; Sutton & Watson 1964) but the consensus view formulated in the latter half of the 20th Century rejected that idea and instead inferred they were deposited in spatially and temporally distinct rift basins (e.g. Williams 1969; Stewart 1982; Soper et al. 1998; Stewart 2002; Strachan et al. 2002; Cawood et al. 2004). However, some workers questioned the rift basin models (e.g. Nicholson 1993) and in the last two decades sedimentological studies (Bonsor & Prave 2008; Krabbendam et al. 2008; Bonsor et al. 2010, 2011), combined with isotopic dating of detrital mineral suites (Rainbird et al. 2001; Kinnaird et al. 2007; Cawood et al. 2004, 2015; Kirkland et al. 2008a; MacAteer et al. 2014; Krabbendam et al. 2017; Lebeau et al. 2020) and dating of metamorphic and igneous events (e.g. Cutts et al. 2009, 2010; Cawood et al. 2015; Bird et al. 2018), have added substantially to understanding the age and basin setting of these successions. Below we provide a synthesis and summary of existing and new data that underpin our revision of the Neoproterozoic stratigraphy of the Scottish Highlands.

**Basement**

In many places the Neoproterozoic successions rest on basement rocks and basal unconformities are well exposed, albeit strongly deformed east of the Moine Thrust. In the Caledonian foreland (footwall of the Moine Thrust), the basement comprises mostly Archaean meta-igneous rocks of the Lewisian Gneiss Complex (e.g. Kinny & Friend 1997; Friend & Kinny 2001; Kinny et al. 2005; Wheeler et al. 2010; Fischer et al. 2021) but Palaeoproterozoic meta-igneous and -sedimentary rocks are present locally, such as the Loch Maree Group, South Harris Complex, Laxfordian granitoids (e.g. Park et al. 2002; Mason et al. 2004; Kinny et al. 2005; Goodenough et al. 2013) and, on Islay and extending to the north of Ireland, the c. 1800-1750 Ma Rhinns Complex (Marcantonio et al. 1988; Muir et al. 1992; Daly et al. 1991; Daly 1996). East of the Moine Thrust (Fig. 3), basement rocks occur as inliers in the cores of major folds and along ductile thrust faults (Ramsay 1958; Tanner 1970; Rathbone & Harris 1979; Strachan & Holdsworth 1988) and those have yielded 2900-2700 Ma and 1800-1710 Ma protolith ages (Friend et al. 2008; Strachan et al. 2020b). Several inliers also exhibit tectonothermal events that overlap with Grenville orogenesis, for example 1082 ± 22 Ma and 1010 ± 13 Ma eclogite-facies metamorphism and 994 ± 8 Ma exhumation in the Eastern Glenelg Inlier (Sanders et al. 1984; Storey et al. 2005; Brewer et al. 2003), c. 1008 Ma isotopic disturbance in
the Swordly Inlier (Strachan et al. 2020b) and c. 1050 Ma reworking of Archaean basement in Shetland (Walker et al. 2021).

**Torridonian and the Moine Supergroup**

The Torridonian consists of the Stoer, Sleat and Torridon groups (Stewart 2002). The Stoer and Torridon groups occur west of the Moine Thrust, are only weakly deformed and have been the foci of detailed sedimentological studies as exemplars of pre-land-plant fluvial systems preserved as several-kilometre-thick successions of mostly trough and planar cross-bedded feldspathic sandstone (e.g. Selley 1969; Stewart 1982; 1988; 2002; Nicholson 1993; Owen & Santos 2014; Ielpi & Ghinassi 2015; McMahon & Davies 2020). They also contain well-preserved, organic-walled microfossils postulated to be one of the earliest non-marine eukaryotic biotas (Strother et al. 2011; Battison & Brasier 2012, cf. Stüeken et al. 2017). However, the Stoer Group is late Mesoproterozoic in age (Parnell et al. 2011), thus predates the Neoproterozoic Megasequence framework of the North Atlantic region and is not considered further herein.

Within the Moine Thrust zone are the lower greenschist-facies Sleat and Tarskavaig groups and, east of the Moine Thrust, the amphibolite-facies Moine Supergroup. The latter has been divided into the Morar, Glenfinnan and Loch Eil Groups (Johnstone et al. 1969; Holdsworth et al. 1994) and records partial melting and deformation events at 950–940 Ma (Renlandian orogeny; Bird et al. 2018), 820–725 Ma (Knoydartian orogeny; Tanner & Evans 2003; Cutts et al. 2010; Cawood et al. 2015) and 470–425 Ma (Caledonian orogeny; Bird et al. 2013; Mako et al. 2021; Strachan et al. 2020a). The Moine rocks are rather monotonous successions of psammite, semipelite and pelite that, together with strong deformation and high-grade metamorphism, hampers sedimentological studies and correlations. Nevertheless, in low-strain zones detailed sedimentological analyses have been possible (Strachan 1986; Glendinning 1988; Strachan et al. 1988; Bonsor & Prave 2008); and have shown that the Morar and Torridon groups share similar facies characteristics and palaeoenvironmental settings (see below; Krabbendam et al. 2008; Bonsor et al. 2010, 2012). A schematic restoration of Caledonian nappes (Fig. 4) provides relative structural relationships. True displacement is not shown because the Moine Thrust alone likely had >100 km of movement (Elliott & Johnson 1980; Strachan et al. 2002; Krabbendam et al. 2008) and intra-nappe deformation (which may be > 50 % shortening) is also omitted. For simplicity all displacement is inferred to be to the WNW, even though displacement vectors between nappes east of the Moine thrust can vary substantially (e.g. Kelley & Powell 1985; Roberts et al. 1987; Strachan & Holdsworth 1988; Holdsworth 1989; Krabbendam et al. 2011, Mazza et al. 2018).
Sleat-Torridon-Morar groups

**Sleat Group.** The Sleat Group is named for the eponymous peninsula on Skye (Fig. 3) and occurs in a restricted belt of exposures extending 15 km north of there on the adjacent mainland. A further 10 km north, along Loch Torridon, Sleat Group rocks are absent and the Torridon Group rests unconformably on Archaean Lewisian gneiss. The Sleat rocks comprise a c. 3.5 km thick sequence of mostly fine to medium grey sandstone with intervals of interbedded grey shale. Sedimentary features are varied and include dm-scale trough cross-bedding, desiccation cracks, cm-scale ripple lamination and locally flaser bedding. As summarised in Stewart (2002), most workers interpreted these rocks as recording non-marine deposition, but Krabbendam *et al.* (2017) suggested a tidally influenced shallow marine setting for some units. The Sleat Group rests unconformably (albeit poorly exposed) on Lewisian gneiss. The contact between the Sleat Group and overlying Torridon Group is considered by some workers to be transitional (e.g. Stewart 2002) whereas others interpret it as a regional-scale unconformity (e.g. Kinnaird *et al.* 2007). The Sleat-Torridon contact certainly defines major facies change from fine-grained sandstone-shale of the upper Sleat Group (Kinloch Formation) to coarse arkosic sandstone of the lower Torridon Group (Applecross Formation). Detrital zircon age spectra across the Sleat-Torridon boundary are similar (see below; Krabbendam *et al.* 2017), thus both units appear to share the same provenance. Consequently, given current datasets, the most parsimonious interpretation of the Sleat-Torridon contact is that it is a significant sequence boundary of as yet unknown duration.

**Torridon-Morar groups: northern areas.** It is now recognised that most of the Torridon and Morar groups are correlative (Fig. 5), lateral components of braided fluvial to shallow-marine systems within a foreland basin to the Grenville Orogen (e.g. Nicholson 1993; Rainbird *et al.* 2001; Bonsor & Prave 2008; Krabbendam *et al.* 2008; 2017; Bonsor *et al.* 2010, 2012). The Applecross–Aultbea formations of the Torridon Group and Altnaharra Formation of the Morar Group are each 3-5 km thick, exhibit regionally uniform lithofacies patterns marked by fine to coarse (meta)sandstone with local pebble lags and minor red-grey shale/pelitic layers that become more common at higher stratigraphic levels. Ubiquitous dm-to-m scale trough cross-beds and channels yield broadly unimodal sediment dispersal patterns towards the NNE to SE (Selley 1969; Nicholson 1993; Stewart 2002; Owen and Santos 2014; Krabbendam *et al.* 2008; Bonsor *et al.* 2010). Both groups have similar detrital mineral age spectra (see below). Further, both unconformably overlie basement rocks (Holdsworth *et al.* 1994; Friend *et al.* 2008; Stewart 2002; Strachan *et al.* 2020b) with local basal conglomerate and shale/pelite facies (e.g. Diabaig Formation of Torridon Group; Strathan Conglomerate and Meadie Schist of Morar Group). Units higher in the stratigraphy, such as the
Glascarnoch-Vaich Pelite-Crom Psammite-Diebidale Pelite formations above the Moine Thrust (Fig. 5) and the Cailleach Head Formation on the Caledonian foreland, define an overall transgressive sedimentation phase, from non-marine to marine facies, above the more proximal braided fluvial units described above (Bonsor et al. 2010, 2012; Krabbendam et al. 2011; 2017).

In northernmost Scotland, rocks in the hanging wall of the Moine Thrust are unquestionably Morar Group (Holdsworth et al. 1994) but affinities of rocks in the structurally higher Naver, Swordly and Skinsdale nappes (Fig. 6) are less certain due to poor exposure and extensive gneissic and migmatitic reworking (Moorhouse & Moorhouse 1988; Strachan & Holdsworth 1988; Holdsworth 1989; Kocks et al. 2006; Strachan et al. 2020a). Tentative correlations have been made (Fig. 6) and, based on lithological and geochemical compatibility, rocks in the Naver nappe are assigned to the Morar Group (Moorhouse & Moorhouse 1988; Strachan & Holdsworth 1988). This correlation is supported by single spot U-Pb ages of c. 950–900 Ma on monazites contained within garnet porphyroblasts (Mako et al. 2021) that show that rocks of the Naver nappe were affected by Renlandian metamorphism. The Swordly Thrust was correlated with the Sgurr Beag Thrust by Holdsworth et al. (1994) and in this scenario the Swordly nappe carries rocks provisionally assigned to the Glenfinnan and Loch Eil groups (Fig. 6). This is plausible on lithological grounds but a lack of age constraints on these units means that confirming or rejecting this correlation awaits future dating. Alternatively, the Skinsdale Thrust is the northern continuation of the Sgurr Beag Thrust (Kocks et al. 2006). The Skinsdale nappe preserves a right-way-up succession of units of likely Loch Eil Group affinity (Strachan 1988).

**Torridon-Morar groups: southern areas.** The Torridon Group rocks along their entire 200-km-long outcrop belt exhibit similarity in lithofacies and stratigraphic consistency, making correlations from north to south straightforward (Fig. 5). In contrast, the complex structure in the Knoydart-Kintail-Morar areas (Fig. 3; May et al. 1993; Krabbendam et al. 2014) complicates Morar Group correlations, particularly in the lower part of the Morar Group. This is indicated by the plethora of stratigraphic names that reflect variations in proportions and thicknesses of psammite and pelite (Fig. 5; Ramsay & Spring 1962; Sutton & Watson 1964; Krabbendam et al. 2014). However, the base of the Vaich Pelite in northern parts of the outcrop belt is defined by a transgressive surface (e.g. Bonsor et al. 2010, 2012) similar to the base of the Morar Schist in southern parts of the belt. We interpret this surface as recording the same marine flooding event. Formation-scale sedimentation phases also provide a correlation tool and suggest that the braided fluvial-shallow marine-braided fluvial trinity of the Altnaharra Psammite–Vaich Pelite-Crom Psammite formations can be matched unit-by-unit to the Lower Morar Psammite-Morar Schist-Upper Morar Psammite formations. Thus, the Upper
Morar Psammite and Crom Psammite formations are plausible basin-scale correlatives: both occupy a stratigraphic position above a likely basin-wide marine unit, and both are typified by trough cross-bedded metre-scale lens/channel-shaped bodies of feldspathic sandstone interpreted as braided fluvial deposits (Bonsor & Prave 2008; Bonsor et al. 2012) with associated facies changes (e.g. Glendinning 1988).

**Glenfinnan-Loch Eil-Badenoch groups**

**Glenfinnan Group.** The Glenfinnan Group comprises amphibolite-facies pelitic and semipelitic schists and migmatites, in places in basal contact with Archaean-Palaeoproterozoic basement inliers (e.g. Scardroy Inlier). All units are strongly deformed and metamorphosed hence sedimentological investigations are not possible. Everywhere across mainland Scotland the contact between the Glenfinnan Group and the Morar Group is tectonic, defined by the Sgurr Beag Thrust (Tanner, 1970; Rathbone & Harris 1979; Kelley & Powell 1985; Barr et al. 1986; Roberts et al. 1987).

In contrast, on the isle of Mull the Morar-Glenfinnan boundary has been interpreted as being stratigraphically conformable and placed at the transition from the Upper Shiaba Psammite Formation to the overlying Laggan Mor Formation (Fig. 7; Holdsworth et al. 1987). This interpretation was crucial for ideas that the Moine rocks, from Morar through Glenfinnan to Loch Eil groups, are stratigraphically continuous and define a supergroup, interpreted to be deposited in a series of sequential rift basins (e.g. Roberts et al. 1987; Soper et al. 1998; Holdsworth et al. 1994). However, re-evaluation of the Mull succession has shown that the key boundary is between the non-migmatitic quartzite-pelitic schists of the Laggan Mor Formation and migmatitic rocks of the Scoor Pelitic Gneiss Formation (Fig. 8). The interval leading up to that boundary is marked a c. 200-300m wide zone of variably but commonly highly strained platy quartzite, psammite and pelite, culminating in a zone of extremely platy mylonites with paper-thin ‘tramline’ lithons, with the Scoor Pelitic Gneiss juxtaposed on top. In view of this evidence for a ductile shear zone, we suggest that the Morar and Glenfinnan groups are everywhere structurally separate, that no stratigraphic continuity exists across the contact and that previous ideas about basin settings and tectonic evolution relying on stratigraphic continuity within the Moine Supergroup are incorrect.

**Loch Eil Group.** This group is dominated by fine- to medium-grained psammite with laterally restricted quartzite units, all of which exhibit sedimentary structures indicative of shallow-marine deposition (e.g. wave ripples, variably scaled ripple cross lamination, compound cross bedding) with an overall northward sediment transport direction (Strachan 1986; Strachan et al. 1988). The psammite-quartzite facies motif has resulted in a suite of stratigraphic names (see Fig. 7), but the
main outcrop of the Loch Eil Group forms a large syncline such that, along its limbs, the Loch Eil units pass transitionally downward into interbedded psammite-semipelite units assigned to the Glenfinnan Group. In this context, it is reasonable to interpret the Glenfinnan-Loch Eil groups as having stratigraphic continuity and coherence.

**Badenoch Group.** The Badenoch Group (Leslie *et al.* 2013; also known as the Central Highland Division or sub-Grampian Basement; Piasecki & Temperley 1988; Robertson & Smith 1999; Cawood *et al.* 2003) occurs in the Grampian Highlands southeast of the Great Glen Fault (Fig. 3) as a series of inliers structurally below the Grampian Group, the basal unit of the Dalradian Supergroup. Two units are formally recognised, the Dava and Glen Banchor subgroups, although their relative stratigraphic position is uncertain (Leslie *et al.* 2013; BGS Sheet 74W British Geological Survey 2004b). The rocks are strongly deformed and commonly migmatitic and do not preserve sedimentary features. They have been considered correlative with the Moine Supergroup and separated from the overlying Dalradian rocks via a cryptic and commonly highly tectonised unconformity (Piasecki 1980; Piasecki & Temperley 1988), an interpretation that has proved controversial (e.g. compare different viewpoints of Highton *et al.* 1999; Phillips *et al.* 1999; Robertson & Smith 1999; Oliver 2002). As discussed below, detrital zircon age data and dating of metamorphic events have resolved this issue.

**Age constraints and linkages to North Atlantic Megasequences**

Although precise depositional ages remain elusive for the Scottish Neoproterozoic successions, the creation of extensive detrital mineral U-Pb age distributions, combined with accurate dating of tectono-thermal events over the last 20 years, now provide reasonable minima-maxima age brackets on sedimentation and basin evolution for the Torridonian-Moine-Dalradian successions. For detrital mineral datasets, best practice is to use the youngest peak on a kernel density estimation (KDE) plot and analyse large numbers of grains (n>100-300) to minimise missing the youngest detrital grains (Vermeesch 2012; Pullen *et al.* 2014). For example, the youngest age obtained by Kinnaird *et al.* (1997) from an analysis of 30 detrital zircon grains from the upper Sleat Group was c. 1265 Ma whereas for the same stratigraphic level Krabbendam *et al.* (2017) obtained a peak between 1060–1000 Ma analysing 150 grains thereby lowering the maximum depositional age by c. 250 Ma. For the synthesis below, we incorporate all published U-Pb geochronological data, regardless of vintage, but rely on those that follow best practice to assess the Torridonian-Moine-Dalradian successions within the temporal constraints established for the North Atlantic Megasequence framework.

**Sleat-Torridon-Morar groups**
The detrital zircon age spectra of these groups (Fig. 9) show a paucity of Archaean zircons and sharp and narrow peaks at either c. 1650 Ma or c. 1750 Ma, with various subsidiary peaks between 1500–1200 Ma. The youngest detrital zircon and rutile ages (Fig. 10) for these rocks are 1070–1000 Ma (Rainbird et al. 2001; Friend et al. 2003; Kirkland et al. 2008a; Cutts et al. 2009; Cawood et al. 2015; Krabbendam et al. 2017) and diagenetic ages of 994 ± 48 Ma and 977 ± 39 Ma (Rb-Sr whole rock) have been determined for the Torridon Group (Turnbull et al. 1996). These ages and age spectra match well Megasequence 1 units in Greenland and Svalbard (Figure 2), which also have a scarcity of Archaean zircons and pronounced Palaeoproterozoic clusters particularly around 1650 Ma (Olierook et al. 2020). Renlandian metamorphism and magmatism at 960–920 Ma are common in rocks placed in Megasequence 1 and this event is now identified in Scotland by high-grade metamorphism at 950–940 Ma (Lu-Hf and Sm-Nd on garnet) from the Meadie Schist Formation near the stratigraphic base of the Morar Group (Bird et al. 2018). Taken together, these age constraints restrict deposition of the Sleat-Torridon-Morar rocks to 1000–950 Ma and place them firmly within Megasequence 1 (e.g. Olierook et al. 2020).

**Glenfinnan-Loch Eil-Badenoch Groups**

The age spectra of these groups (Fig. 9) also show a general absence of Archaean detrital zircons and dominant peaks at c. 1750 and 1650 Ma but other Mesoproterozoic peaks are more pronounced than those for the Sleat-Torridon-Morar rocks and some units have 1100–1000 Ma peaks. This pattern is comparable to Megasequence 2 detrital age spectra derived from Greenland, Svalbard and Norway (see Olierook et al. 2020). Youngest detrital zircons for Glenfinnan-Loch Eil-Badenoch groups (Fig. 10) fall between c. 1000–900 Ma (Cawood et al. 2003; 2015; Friend et al. 2003; Kirkland et al. 2008a; Cutts et al. 2010; Spencer et al. 2015) with some in the Glenfinnan and Badenoch groups younger than the 960–920 Ma Renlandian orogeny thereby confirming that these rocks were deposited after that orogenic event. Minimum depositional ages are also provided by the West Highland Granite Gneiss and Glen Doe metagabbro that intruded Glenfinnan Group rocks at c. 870 Ma (Friend et al. 1997; Millar 1999; Rogers et al. 2001; Cawood et al. 2015). Further, the Badenoch Group was affected by Knoydartian metamorphism at c. 840 Ma (Highton et al. 1999) and its youngest detrital zircon is 900 ± 17 Ma (Cawood et al. 2003), confirming Piasecki’s (1980) and Piasecki & Temperley’s (1988) interpretation of an early Neoproterozoic age for the Badenoch Group. Combined, these data place deposition of Glenfinnan-Loch Eil-Badenoch successions to between c. 900–870 Ma, younger than the temporal window of Megasequence 1 but within that of Megasequence 2 (Fig. 10).

**Dalradian Supergroup - Ardvreck-Durness Groups**
We mention briefly these successions in that they comprise the third and youngest component of the Megasequence trinity (Fig. 2; see Olierook et al. 2020). Discussing their stratigraphic framework and depositional setting is beyond the scope of this paper but we highlight that they archive a variety of non-marine and shallow- to deep-marine environments within Cryogenian-Ediacaran tectonic phases that lead to rifting and formation of the Iapetus Ocean and its Cambrian-early Ordovician passive margin (Anderton 1982; Stephenson et al. 2013). The precise timing of initiation of sedimentation in the Dalradian remains debated but was likely younger than c. 725 Ma, i.e. younger than the Knoydartian orogenic episode. A c. 590 Ma volcanic unit near the upper part of the Dalradian and Cambrian and Ordovician fossils in the top part of the Dalradian Supergroup indicates that sedimentation continued through the Ediacaran Period into the lower Ordovician (Halliday et al. 1989; Tanner 1995; Tanner & Sutherland 2007; Cawood et al. 2012). The Great Glen and Moine Thrust faults separate the Cryogenian-Cambrian Dalradian and Cambro-Ordovician Ardvreck-Durness outcrop belts thus, even though they are nowhere in contact with one another, their age constraints place them collectively within Megasequence 3. The Colonsay Group, previously correlated with the Torridonian, is now generally seen to be correlated with the lower Dalradian (McAtteer et al. 2010).

A Revised Highlands Stratigraphy: Wester Ross and Loch Ness Supergroups

It is now clear that the tectonostratigraphic models that guided much of the thinking regarding basin evolution of the Torridonian and Moine successions of northern Scotland require revision. Firstly, major parts of the Torridon and Morar groups differ only in terms of metamorphic grade and represent the preserved components of a once extensive foreland basin sourced from the Grenville orogen (Krabbendam et al. 2008; 2017). Secondly, the Torridon-Morar rocks were deposited during 1000–950 Ma, syn-to post-Grenville orogenesis, whereas the Glenfinnan-Loch Eil rocks are substantially younger, c. 900–870 Ma, and postdate the Renlandian orogeny (Fig. 10). Thus, the concept of a ‘Torridonian succession’ as distinct from a ‘Moine succession’, and the stratigraphic continuity of the latter, are no longer viable. Consequently, we propose two new stratigraphic divisions, the Wester Ross and Loch Ness supergroups (Fig. 11), to incorporate this new understanding and establish stratigraphic consistency for the Neoproterozoic rocks of the Scottish Highlands. The names were chosen to reflect the two regions in the Scottish Highlands that encompass the hallmark areas of exposure of the rocks contained within those supergroups.
Wester Ross and Loch Ness Supergroups

There are four key reasons for reorganising the stratigraphy of the Moine and Torridonian rocks into the Wester Ross and Loch Ness Supergroups. Firstly, the similar sedimentological characteristics and depositional settings of the Torridon and Morar groups, as well as their near identical detrital mineral U-Pb age spectra, suggest that they can be readily correlated across the Moine Thrust. This implies that the combined Torridon and Morar groups were deposited across a very wide area (considering the ≥ 100 km displacement along the thrust, e.g. Elliot and Johnson 1980), which is compatible with the significant thicknesses of both sequences as well as with the large fluvial systems that the sedimentology suggests (e.g. Nicholson 1993). Thus, the thrust is not a terrane boundary but merely the metamorphic front of the Caledonian orogen, with displacement that was less than the original size of the Torridon-Morar basin. Secondly, existing age constraints place deposition of the Sleat, Torridon and Morar groups to between 1000–950 Ma. In contrast, it is now known that the other two units of the previous Moine Supergroup, the Glenfinnan and Loch Eil groups, as well as the Badenoch Group, contain detrital zircons younger than 950 Ma and post-date the 960–920 Ma Renlandian event. Hence their deposition is separated from the Sleat-Torridon-Morar triplet by many tens of millions of years and an intervening orogeny. Thirdly, whilst stratigraphic continuity between the Morar and Glenfinnan groups was previously highlighted to occur on the Ross of Mull, new field evidence presented here shows that a shear zone separates the two groups there. Consequently, nowhere do they show either stratigraphic continuity or coherence. Lastly, the combined suite of sedimentological and geochronological data indicate that the Torridon and Morar groups are correlative with Megasequence 1 whilst the Glenfinnan and Loch Eil groups, together with Badenoch Group in the Grampian Highlands, are correlative with Megasequence 2. This rationalises the post-Grenville and post-Renlandian sedimentary successions across the circum-North Atlantic region (Fig. 10), a framework that can guide future studies on the tectonostratigraphic evolution of the Scottish Highlands.

Other units within a Wester Ross-Loch Ness Supergroup framework

Iona Group. The Iona Group is a 700 m thick sedimentary succession that is present on the island of Iona and occurs in the footwall of the southern Moine Thrust (Fig. 3). It is divided into a lower unit (200 m thick) of epidotised cobble-boulder breccia and arkosic sandstone resting unconformably on Lewisian gneiss and an upper unit (500 m thick) of thin- to medium-bedded fine to coarse sandstone and dark grey shale (Stewart 2002; McAteer et al. 2014). The succession is deformed by a mylonitic fault zone at the stratigraphic level of the contact between the lower and upper units and no top is
exposed. However, the detrital zircon age distribution (Fig. 8) for the upper unit has a unimodal peak at c. 1800-1770 Ma, a few Archaean grains and a youngest grain at 1490 ± 15 Ma (McAteer et al. 2014), which is a similar age spectrum to the Loch na Dal Formation of the Sleat Group (Fig. 8). Thus, the similarities in detrital zircon geochronology and structural position relative to the Moine Thrust system permit placing the Iona Group as part of the basal Wester Ross Supergroup, and plausibly a lateral correlative of the Sleat Group (Fig. 5).

**Tarskavaig Group.** The Tarskavaig Group is a poorly studied sequence of deformed greenschist facies psammite, semipelite and pelite (Cheeney and Matthews 1965) restricted in occurrence to the southeast margin of the Sleat Peninsula on the Isle of Skye (Fig. 3). Its contact with the underlying Lewisian gneiss is strongly sheared but local quartz-pebble conglomerates suggest a deformed unconformity (Cheeney and Matthews 1965). No sedimentology has been attempted and no detrital mineral age data are available for comparison to other units in the Highlands. However, structural restoration of the Tarskavaig nappe places it in the footwall of the southern Moine Thrust nappe thus, pending further detailed study, we tentatively view it as part of the basal Wester Ross Supergroup (Fig. 5).

**Shetland: Sand Voe, Yell Sound and Westing groups.** Some 200 km NNE of mainland Scotland, the early Neoproterozoic rocks of Shetland comprise three geographically and tectonically separate units (see inset Fig. 3). The Sand Voe Group, an 800 m thick succession of mainly feldspathic psammite overlain by a 300 m thick pelite (Flinn 1988), rests on strongly reworked Neoarchaean basement with a contact that is thought to be a basement-cover unconformity (Pringle 1970; Kinny et al. 2019). There are no robust depositional age constraints, but it resembles, and has been tentatively correlated with, the Morar Group (Flinn 1988). The Yell Sound Group, locally in contact with crystalline basement, comprises psammitic gneiss with subordinate semipelitic and pelitic gneiss and quartzite (Flinn 1988) in which no sedimentary structures are preserved. Its depositional age is between c. 1019 Ma, the youngest detrital zircon U-Pb age, and c. 944-931 Ma, the age of high-grade metamorphism (Jahn et al. 2017). The Westing Group comprises pelitic gneiss with subordinate marble that overlies Neoarchaean basement (Flinn 2014). Its depositional age is constrained to between 1031 ± 5 Ma, the U-Pb age of the youngest detrital zircon, and the 925 ± 10 Ma age of high-grade metamorphism (Cutts et al. 2009). Given these age constraints, we place these groups as part of the Wester Ross Supergroup (Fig 10).

**Wester Ross and Loch Ness Supergroups in a Grenville-Renlandian setting**
There is now compelling evidence that the Wester Ross Supergroup represents a foreland basin to the Grenville Orogen (Rainbird et al. 2001; Bonsor & Prave 2008; Krabbendam et al. 2008, 2017). The detrital zircon U-Pb age spectra of the units now assigned to the Western Ross Supergroup, typified by a scarcity of Archaean zircons and pronounced Palaeoproterozoic clusters, suggests that the most likely source is the Grenville Orogen (Rainbird et al. 2001; Krabbendam et al. 2008; 2017; Olierook et al. 2020), which contains extensive areas of Palaeoproterozoic granitoid rocks (e.g. Rivers 1997). Alternating 1650 and 1750 Ma clusters can be explained by intra-basinal source switching between the Trans Labrador batholith in Canada for the former cluster, and Rhinnian-age rocks in the Irish-Scottish sector for the latter cluster (Krabbendam et al. 2017). The Grenville orogen was of comparable spatial and temporal scale to the Himalayan orogen (e.g. Hynes & Rivers, 2010), which offers a useful analogue. The proximal portions of the orogen-parallel Ganges-Brahmaputra basins would be analogous to the Wester Ross Supergroup in Scotland whereas their deltas and associated shelf-slope-fan systems (e.g. Bengal fan) would be approximate analogues for the more distal Megasequence 1 units in Greenland, Svalbard and Norway, as well as the more marine-influenced portions of the Wester Ross Supergroup. For example, the Krummedal and Krossfjorden sequences in Greenland and Svalbard are dominated by pelitic/semipelitic rocks deposited on continental basement (e.g. Higgins 1988; Strachan et al. 1995; Pettersson et al. 2009a; Higgins & Leslie 2008) and are reasonably inferred to be distal correlatives of the Torridon-Morar groups. A caveat to this scenario is that the postulated Asgard Sea fringing the Grenville Orogen was formed on continental crust and thus likely shallower than the present-day Indian Ocean. Consequently, the accommodation space for the volume of sediment shed off the Grenville Orogen would have required significant wider lateral dispersion to compensate for a probable reduced vertical subsidence component.

Because many of the rocks comprising the Loch Ness Supergroup are strongly deformed and metamorphosed, far less can be said about its depositional framework and associated basin setting. However, the overall facies motif is one of psammite-pelite-quartzite lithologies interbedded on metre and decametre scales. Such patterns are characteristic of shallow-marine to marine shelf depositional settings and the few sedimentological datasets available for the Loch Ness Supergroup rocks support this (e.g. Strachan 1986). Additional constraints on basin setting interpretations are that: (i) they were deposited subsequent to the Renlandian orogeny, hence any inferences regarding basin scenarios must be compatible with those associated with denudation of orogenic belts; and (ii) a bimodal suite of granite and mafic intrusions, with the latter exhibiting MORB-like geochemistry, intruded the lower part of the Loch Eil Group, suggesting an episode of extensional tectonism (Millar 1999). A speculative scenario to consider would be a foreland setting evolving into a rift-related
(back-arc spreading?) setting in the hinterland of the Renlandian Orogen, which would satisfy most of the above constraints. The detrital age spectra for the Loch Ness Supergroup units (and their equivalent Megasequence 2 units across the circum-North Atlantic region) show detrital zircons of Renlandian age, suggesting that the Renlandian Orogen formed at least partly the source. However, the main peaks of the spectra are like those of the Wester Ross Supergroup. Either the two supergroups had the same provenance, which is perhaps unlikely given the very different basin settings, or alternatively a significant component of the Loch Ness Supergroup detritus was reworked from the older Wester Ross Supergroup rocks. This latter possibility is plausible given the extensive distribution of Megasequence 1 rocks (see Rainbird et al. 1992; 2017 for their widespread distribution on Laurentia) that would have represented a supracrustal cover that was at least partially uplifted and eroded during the Renlandian Orogeny.

Conclusions

The emerging understanding of the Neoproterozoic geology of the circum-North Atlantic shows that region-wide sedimentation episodes fit into three temporal clusters or Megasequences (Olierook et al. 2020) and that those record the region’s tectonostratigraphic evolution from Grenville-Sveconorwegian foreland basin to rift-drift passive margin sedimentation in the Iapetus Ocean. U-Pb ages from detrital mineral datasets, radiometric dating of metamorphic and igneous events, as well as recent sedimentological studies show that the Neoproterozoic rocks of the Scottish Highlands can be assigned to the Megasequences as follows:

(i) Sleat-Torridon-Morar groups into Megasequence 1 (1000–960 Ma);

(ii) Glenfinnan-Loch Eil-Badenoch groups into Megasequence 2 (900–850 Ma);

(iii) Dalradian Supergroup (c. 725–500 Ma) within Megasequence 3.

The boundaries between these packages are marked by orogenic unconformities related to the 960–920 Ma Renlandian and 840–725 Ma Knoydartian orogenies. Consequently, the iconic subdivision into Torridonian and Moine requires revision. Thus, to create geological continuity across Scotland and the North Atlantic region, we define two new stratigraphic entities: the Wester Ross and Loch Ness supergroups. The Wester Ross Supergroup was deposited between c. 1000–960 Ma and includes the Sleat, Torridon and Morar groups, and likely the Iona, Tarskavaig (Skye), and Sand Voe, Yell Sound and Westing (Shetland) groups. Sediment was derived from the eroding Grenville orogen and deposited in a foreland-basin setting. Wester Ross Supergroup rocks have been affected by
Renlandian metamorphic and igneous events, so that deposition must predate that orogeny. The Loch Ness Supergroup was deposited between c. 900–870 Ma and includes the Glenfinnan-Loch Eil-Badenoch groups. These rocks record a suite of marine environments in likely foreland and perhaps extensional basin settings. Contacts between the Wester Ross and Loch Ness Supergroups are consistently marked by high-strain shear zones and there is no evidence for stratigraphic continuity between them. The long-standing terms ‘Torridonian’ and ‘Moine’ retain historical significance but should be avoided in future studies investigating the tectonostratigraphic evolution of the Scottish Highlands.

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References


Supergroup): the formation of the Ardgour granite gneiss, north-west Scotland. 


**Figure Captions**

**Fig. 1.** Geological setting of the North Atlantic region at c. 1000 ma (simplified after Krabbendam et al. 2017 and Olierook et al. 2020). Relative positions of Baltica, Laurentia and Amazonia after Li et al. (2008). Note that some or all of the successions in Norway may have been deposited on Laurentia and were later thrust onto Baltica during the Caledonian orogeny.

**Fig. 2.** Summary diagram of Neoproterozoic Megasequences for the North Atlantic region (simplified after Olierook et al. 2020).

**Fig. 3.** Geological map of Northern Highlands and Shetland (same scale) simplified after British Geological Survey (2007). In Shetland: YS = Yell Sound; WE = Westing Group; SV = Sand Voe Group.

**Fig. 4.** Schematic structural reconstruction of the Northern Highlands (modified after Winchester 1988). Two possible positions of the Morar-Glenelg Window, and hence the Grenville front, are shown. No absolute displacement constraints are intended, scale is only applicable for the size of the nappes and does not depict absolute transport distance, nor the internal deformation of the nappes.

**Fig. 5.** Stratigraphic correlation chart of the Torridon-Morar groups – Wester Ross Supergroup. References to columns: **Iona:** Stewart (2002); McAteer et al. (2014); **Tarskavaig:** Cheeney & Matthews (1965); **Sleat:** Stewart (1969, 2002). **Assynt & Torridon:** Stewart (1969, 2002); **Ross of Mull:** Holdsworth et al. (1987) and this paper. **Morar:** Johnstone et al. (1969); Powell (1974); **Knoydart:** Ramsay & Spring (1962); Krabbendam et al. (2014); **Southern Kintail:** Tanner (1965); Krabbendam et al. (2014, 2018); **Northern Kintail:** May et al. (1993). **Central Ross-shire:** Bonsor et al. (2010, 2012); **Tongue:** Strachan & Holdsworth (1988). Alternative or older names in italics.

**Fig. 6.** Tectonostratigraphic correlation of Morar, Glenfinnan and Loch Eil units in Sutherland (compiled after Strachan & Holdsworth 1988; Strachan 1988; Holdsworth et al. 1994).

**Fig. 7.** Stratigraphic correlation charts of the Glenfinnan-Loch Eil-Badenoch groups - Loch Ness Supergroup. References to columns: **Mull:** Holdsworth et al. (1987); **Glenfinnan:** Johnstone et al. (1969); Strachan (1985); **Glen Dessary / Loch Quoich:** Roberts et al. (1984, 1987); **Loch Eil:** Strachan (1985); **East Loch Quoich:** Roberts & Harris (1983); **Invermoriston:** Strachan et al. (1988); BGS Sheet 73W and 83W (British Geological Survey 1993, 2002); **Kildonan – Scaraben:** Strachan (1988); **Central Highlands:** Leslie et al. (2013); BGS Sheet 74W (British Geological Survey 2004b).
**Fig. 8.** Summary of observations on stratigraphy, sedimentology and deformation, and revised tectonostratigraphy of Moine rocks, Ross of Mull.

**Fig. 9.** Detrital zircon age spectra of rock units assigned to Megasequence 1 (left column) and Megasequence 2 (right column). Colour bars indicate Laurentia craton provenance age ranges (see Rivers 1997; Krabbendam et al. 2017). MKR – Makkovik-Ketlidian-Rhinnian terranes; Nags – Nagsoquidian; YZ – youngest zircon.


**Fig. 11.** Revised stratigraphic framework for the Neoproterozoic successions of the Scottish Highlands. The historical terms ‘Torridonian’ and ‘Moine’ are no longer viable within the emerging understanding of the Neoproterozoic evolution of the North Atlantic region. Two new stratigraphic divisions are erected to retain geological compatibility across the Highlands and North Atlantic: Wester Ross and Loch Ness Supergroups.
Figure 2

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Megasequence 1: Hagen Fjord Gr, Títte Gr, Andres Land Gr, Ymer Ør Gr, Lyell Land Gr, Detlefsen SG, Ermfjellet Gr, Rivieradal Gr, Loch Eil Gr, Gleenfinnan Gr, Badenoch Gr, Sárv Succ, Sárey succession, Vadsø Gr

Megasequence 2: Rørvikdal Gr, Nátorstfjord Gr, Rørvikdal Gr, Loch Eil Gr, Gleenfinnan Gr, Badenoch Gr, Sárv Succ, Sárey succession, Vadsø Gr

Megasequence 3: Kromfjorden Gr / Sinaenburgfjorden Cx / Isbjørnhamma Gr / Helvetestfjord, Krummedal succ / Smallerford succ, Torriden Gr, Sletvatn Gr, Yell Sound / Westing Gr, Hegmo Succ, Sveamodd Succeed
Figure 4

[Map of geological formations with key]

- Neoproterozoic granitoids, c. 600 Ma
- Neoproterozoic mafic igneous, c. 870 Ma
- West Highland granite gneiss, c. 870 Ma

[Legend explaining geological formations and colors used in the map]
Figure 6

Morar - Glenfinnan - Loch Eil group subdivision, Sutherland
Figure 8

### Unit | Lithology | Deformation | Interpretation
--- | --- | --- | ---
Scoor Pelitic Gneiss | Migmatitic, semi-pelitic gneiss, qtz-fsp-qtz. Visible bands of alternation of qtz-fsp-rich vs. mica bands. All minerals are coarse. No sedimentary structures preserved. | Strong and high-grade. Three deformation phases seen: qtz-fsp segregations parallel to S1; F2 small-scale folding, vergent to west, on an east-vergent F3 limb. | High-grade metamorphic gneisses, migmatitic, semi-pelitic in composition.

#### Tectonic contact - shear zone

### Laggar Mor Fm - Highly sheared

- Alternation of fine-grained psammitic and pelitic. Psammitic/pelitic layers are sharply defined.
- Extremely attenuated bedding; strongly transposed. Blades are ‘paper thin’ (1-5 mm) towards mylonite fabric. Pelitic layers are schistose with minor grain coarsening. Bedding, S1 and S2 completely parallel. Strong L2 mylonite lineation oblique to L3 crenulation lineation.
- Non-migmatitic; high-strain zone with internally different stratologies on either side. Refolded in F3 set.

### Morar Group (the paper) | Atnial Group = Glennfinnian Group (McKerren et al., 1987)

- Rhythmic alternation of psammitic/pelitic beds. Psammitic beds 3-10 cm thick, felsite beds 15-19 cm thick. Most beds have sharp tops and bases; some contain coarsening-up cycles are developed. Virgin quartzite layers c. 40 cm thick.
- Foliation is schistose rather than granosic. ‘Wavy’ F2 folding poorly developed, but pronounced L3 crenulation lineation occurs on pelitic bedding planes. Small angle between S1 and S0 seen (c. 5°), suggesting westerly vergence. High shear strain.
- Overall thinning upwards sequence defined by increasing proportion of pelitic beds. Overall increase in shear strain towards top.

### Laggar Mor Fm - Centre

- Alternation of quartzite/pelite layers with sharp bases and tops. Quartzite layers 10-80 cm thick with internal laminations. Pelite layers 5-40 cm thick, internally laminated (but with S0/S1). Large variation in bed thicknesses.
- Beds are well defined, S1 parallel to sub-parallel to bedding. Strain is considerable. Sedimentary structures largely obscured.

### Laggar Mor Fm - Base

- Mainly psammitic beds (feldspathic), with minor pelitic beds. Bed thickness 5-20 cm, with internal laminae. Poorly preserved trough cross-beds (young to west).
- Strong flattening and sedimentary structures commonly obscured. Beds appear moderately strongly attenuated.

### Upper Shaba Psammitite Fm - Top

- Thick bedded (20-60 cm) feldspathic psammitite with abundant planar and trough cross-bedding (young to west), heavy mineral bands.
- Some flattening but sedimentary structures well preserved.

### Shaba Gr = Morar Gr

- Likely fluvial or tidal channels. Very similar to Morar Group elsewhere.