Research article

JGS
Journal of the Geological Society

https://doi.org/10.1144/jgs2021-054 | Vol. 179 | 2022 | jgs2021-054

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 summarize sedimentological and geochronological data and propose a new stratigraphic framework for the iconic Torridonian–Moine 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.

Received 14 May 2021; **revised** 19 August 2021; **accepted** 23 August 2021

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. Cawood *et al.* 2007, 2010; Kirkland *et al.* 2007, 2008*a*, *b*; 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 Paleozoic (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; Cawood *et al.* 2007, 2010; Kirkland *et al.* 2008*a*, *b*; 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 and Thrane 2001; Dhuime *et al.* 2007; Pettersson *et al.* 2009*a*, *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.* 2008*a*; 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 tectono-stratigraphic 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 and Harris 1994; Trewin 2002; Mendum *et al.* 2009). The Torridonian contains the sedimentary rocks resting unconformably on Archean–Paleoproterozoic Lewisian basement west of the Caledonian Moine Thrust zone, whereas the Moine comprises the amphibolite-facies metasedimentary rocks in the hangingwall of that thrust. SE 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 and Horne 1930; Kennedy 1951; Sutton and Watson 1964) but the consensus view formulated in the latter half of the twentieth century rejected that idea and instead inferred they were deposited in spatially and temporally distinct rift basins (e.g. Williams 1969; Stewart 1982, 2002; Soper *et al.* 1998; 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 and Prave 2008; Krabbendam *et al.* 2008; Bonsor *et al.* 2010,

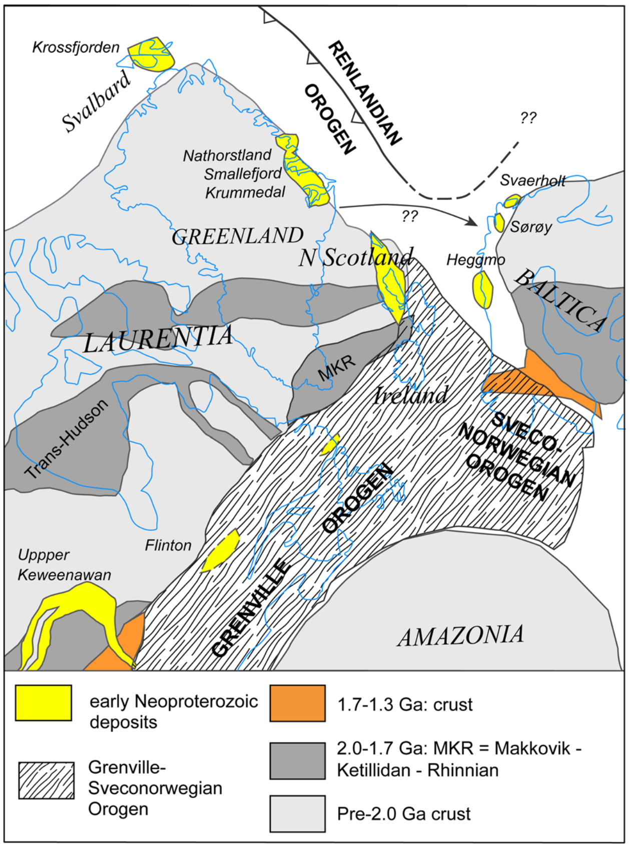

Fig. 1. Geological setting of the North Atlantic region at *c.* 1000 Ma (simplified after Krabbendam *et al.* 2017; Olierook *et al.* 2020). Relative positions of Baltica, Laurentia and Amazonia after Li *et al.* (2008). Note that some or all of the successions in Norway may have been deposited on Laurentia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

2012), combined with isotopic dating of detrital mineral suites (Rainbird *et al.* 2001; Cawood *et al.* 2004, 2015; Kinnaird *et al.* 2007; Kirkland *et al.* 2008*a*; McAteer *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 Archean meta-igneous rocks of the Lewisian Gneiss Complex (e.g. Kinny and Friend 1997; Friend and Kinny 2001; Kinny *et al.* 2005; Wheeler *et al.* 2010; Fischer *et al.* 2021) but Paleoproterozoic 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 1957; Tanner 1970; Rathbone and Harris 1979; Strachan and Holdsworth 1988) and those have yielded 2900–2700 Ma and 1800–1710 Ma protolith ages (Friend *et al.* 2008; Strachan *et al.* 2020*b*). 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; Brewer *et al.* 2003; Storey *et al.* 2005), *c.* 1008 Ma isotopic disturbance in the Swordly Inlier (Strachan

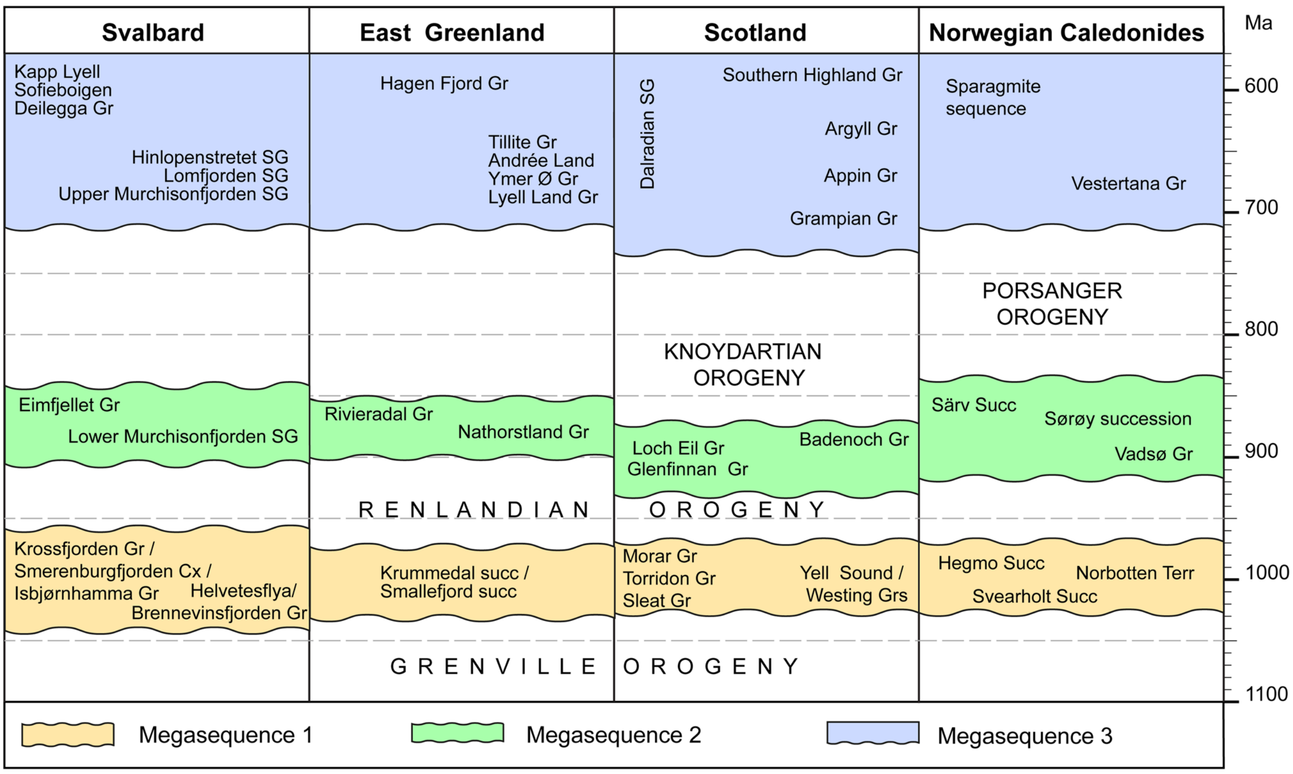

Fig. 2. Summary diagram of Neoproterozoic megasequences for the North Atlantic region (simplified after Olierook *et al.* 2020).

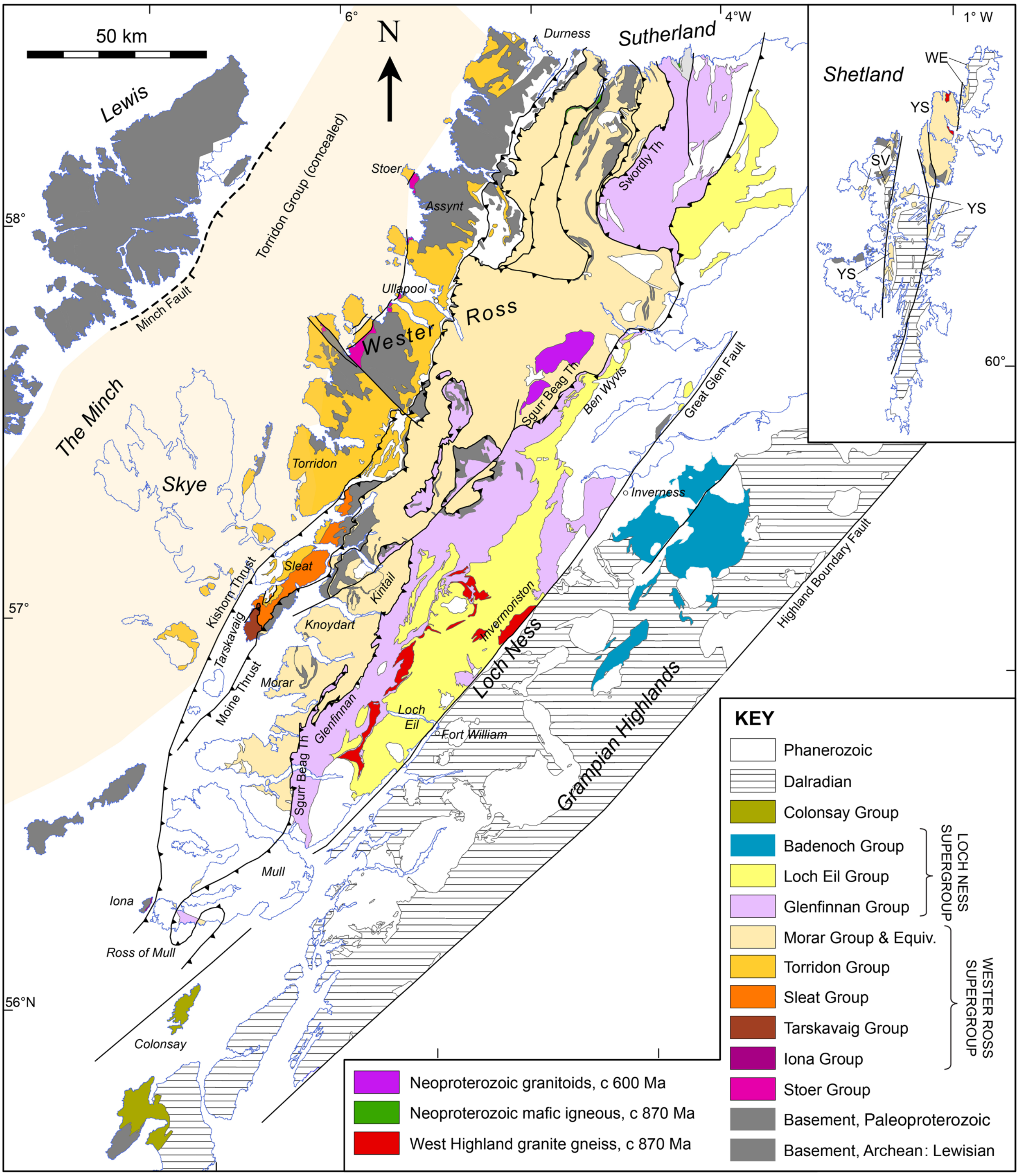

Fig. 3. Geological map of Northern Highlands and Shetland (same scale) simplified after British Geological Survey (2007). In Shetland: SV, Sand Voe Group; WE, Westing Group; YS, Yell Sound.

et al. 2020*b*) and *c.* 1050 Ma reworking of Archean 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 and Santos 2014; Ielpi and Ghinassi 2015; McMahon and 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 and Brasier 2012, cf. Stüeken *et al.* 2017). However, the Stoer Group is late Mesoproterozoic in age (Parnell *et al.* 2011), thus predating 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; Rogers *et al.* 1998; Tanner and Evans 2003; Cutts *et al.* 2010; Cawood *et al.* 2015) and 470–425 Ma (Caledonian orogeny; Bird *et al.* 2013 ; Strachan *et al.* 2020*a*; Mako *et al.* 2021). The Moine rocks are rather monotonous successions of psammite, semipelite and pelite that, together with strong deformation and high-grade metamorphism, hamper sedimentological studies and correlations. Nevertheless, in low-strain zones detailed sedimentological analyses have been possible (Strachan 1986; Glendinning 1988; Strachan *et al.* 1988; Bonsor and 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 and 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 and Powell 1985; Roberts *et al.* 1987; Strachan and 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 Archean 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 decimetre-scale trough

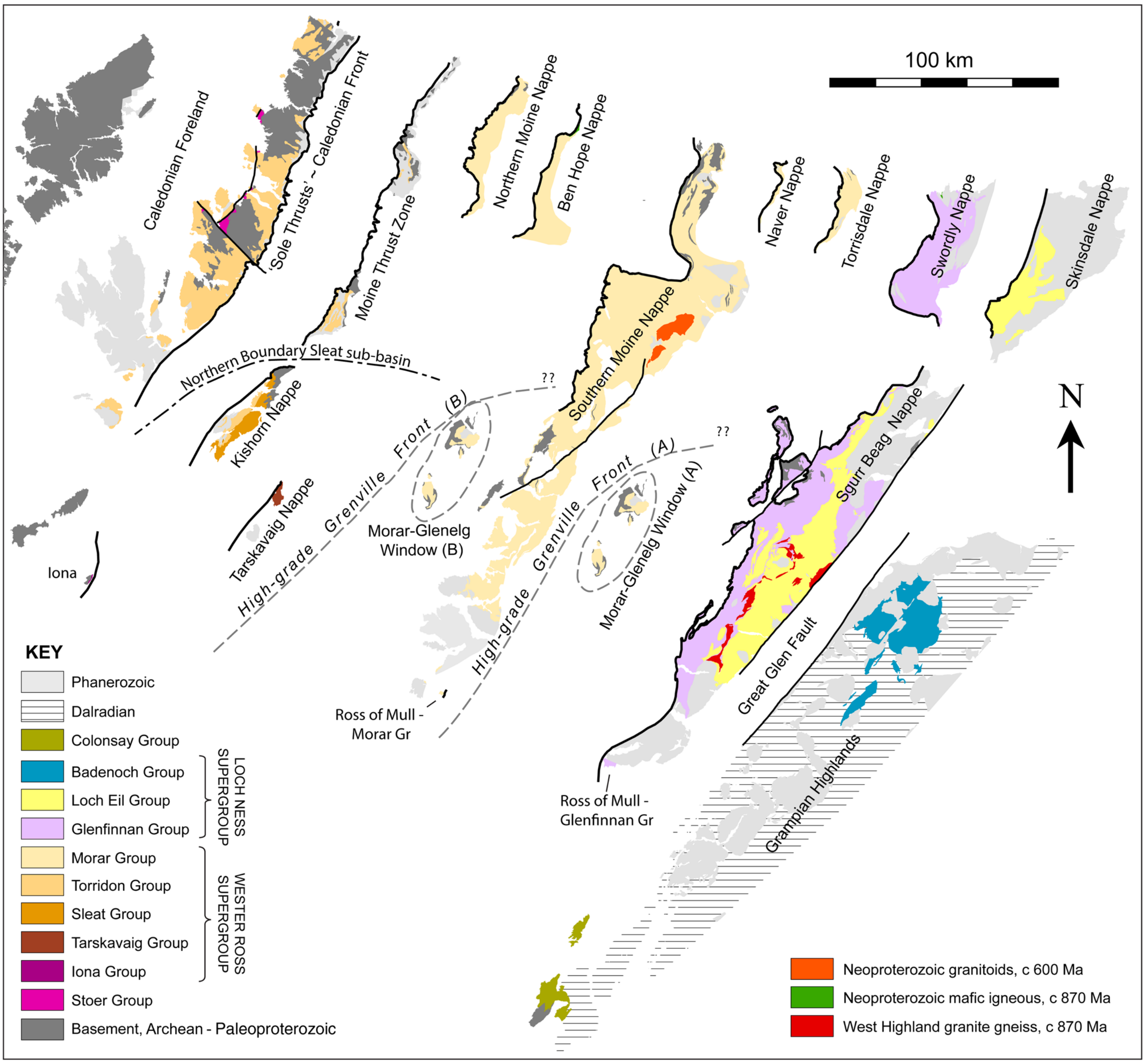

Fig. 4. Schematic structural reconstruction of the Northern Highlands (modified after Winchester 1988). Two possible positions of the Morar–Glenelg Window, and hence the Grenville front, are shown. No absolute displacement constraints are intended, scale is only applicable for the size of the nappes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

cross-bedding, desiccation cracks, centimetre-scale ripple lamination and locally flaser bedding. As summarized 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 a 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 recognized that most of the Torridon and Morar groups are correlative (Fig. 5), lateral components of braided fluvial to shallow-

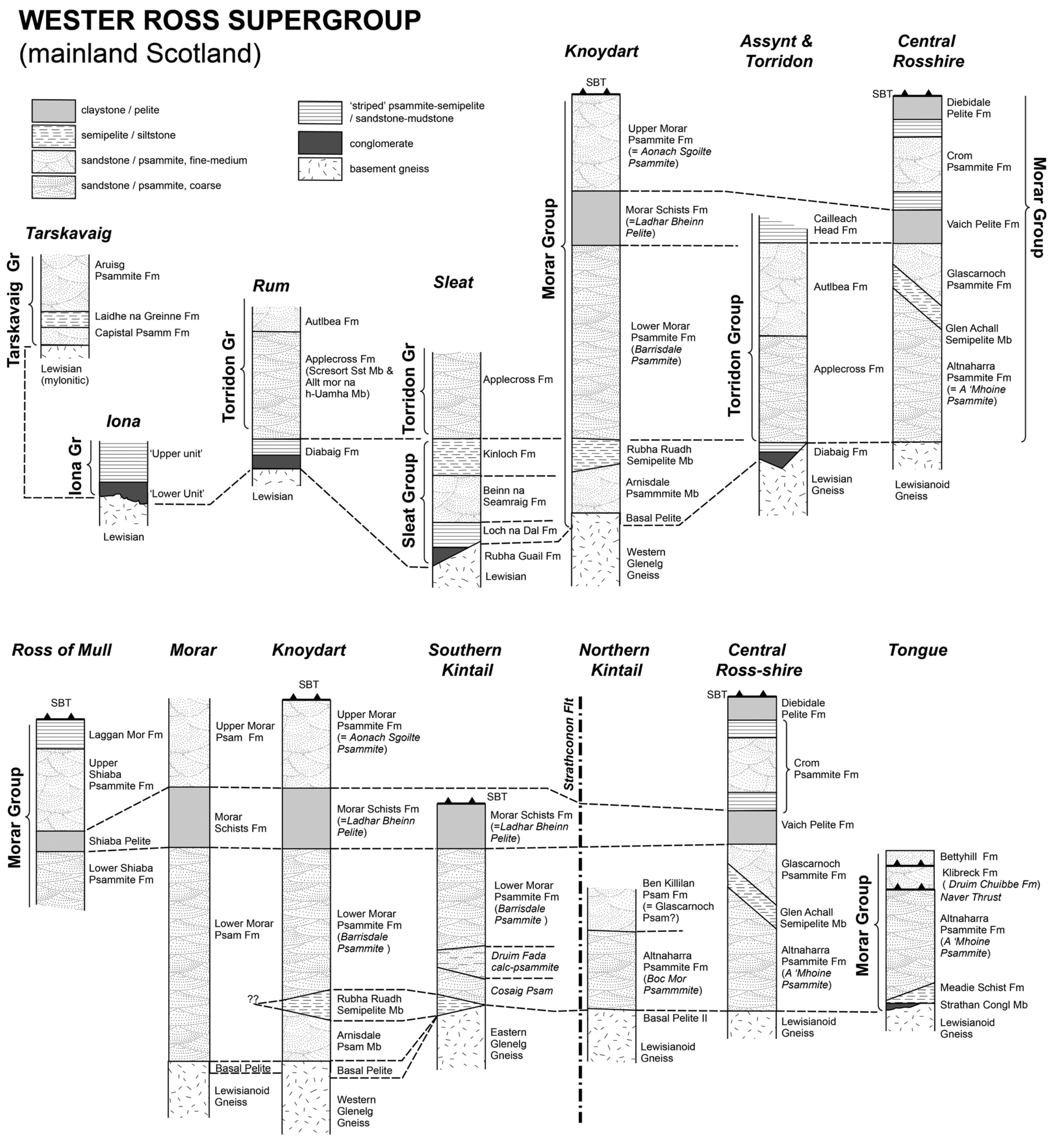

Fig. 5. Stratigraphic correlation chart of the Torridon–Morar groups – Wester Ross Supergroup. References to columns: *Tarskavaig*: Cheeney and Matthews (1965); *Iona*: Stewart (2002); McAteer *et al.* (2014); *Rum*: Stewart (2002); *Sleat*: Stewart (1969, 2002). *Assynt & Torridon*: Stewart (1969, 2002); *Ross of Mull*: Holdsworth *et al.* (1987) and this paper. *Morar*: Johnstone *et al.* (1969); Powell (1974); *Knoydart*: Ramsay and 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 and Holdsworth (1988). Alternative or older names in italics.

marine systems within a foreland basin to the Grenville Orogen (e.g. Nicholson 1993; Rainbird *et al.* 2001; Bonsor and 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 decimetre- to metre-scale trough cross-beds and channels yield broadly unimodal sediment dispersal patterns towards the NNE to SE (Selley 1969; Nicholson 1993; Stewart 2002; Krabbendam *et al.* 2008; Bonsor *et al.* 2010; Owen and Santos 2014). Both groups have similar detrital mineral age spectra (see below). Further, both unconformably overlie basement rocks (Holdsworth *et al.* 1994; Stewart 2002; Friend *et al.* 2008; Strachan *et al.* 2020*b*) 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 hangingwall 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 and Moorhouse 1988; Strachan and Holdsworth 1988; Holdsworth 1989; Kocks *et al.* 2006; Strachan *et al.* 2020*a*). 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 and Moorhouse 1988; Strachan and 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 exhibit similarity in lithofacies and stratigraphic consistency, along their entire 200 km-long outcrop belt 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 and Spring 1962; Sutton and Watson 1964;

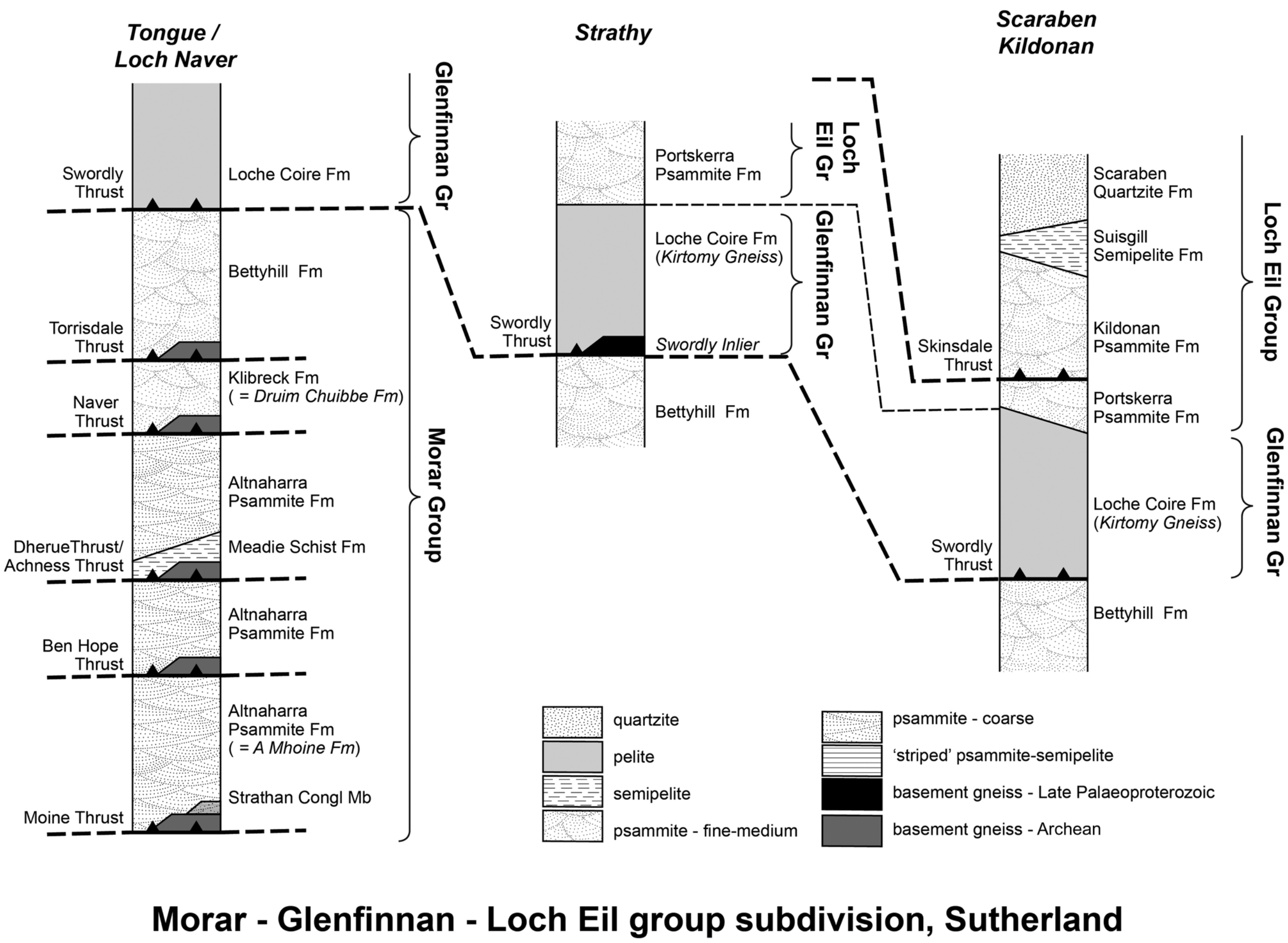

Fig. 6. Tectonostratigraphic correlation of Morar, Glenfinnan and Loch Eil units in Sutherland (compiled after Strachan 1988; Strachan and Holdsworth 1988; Holdsworth *et al.* 1994).

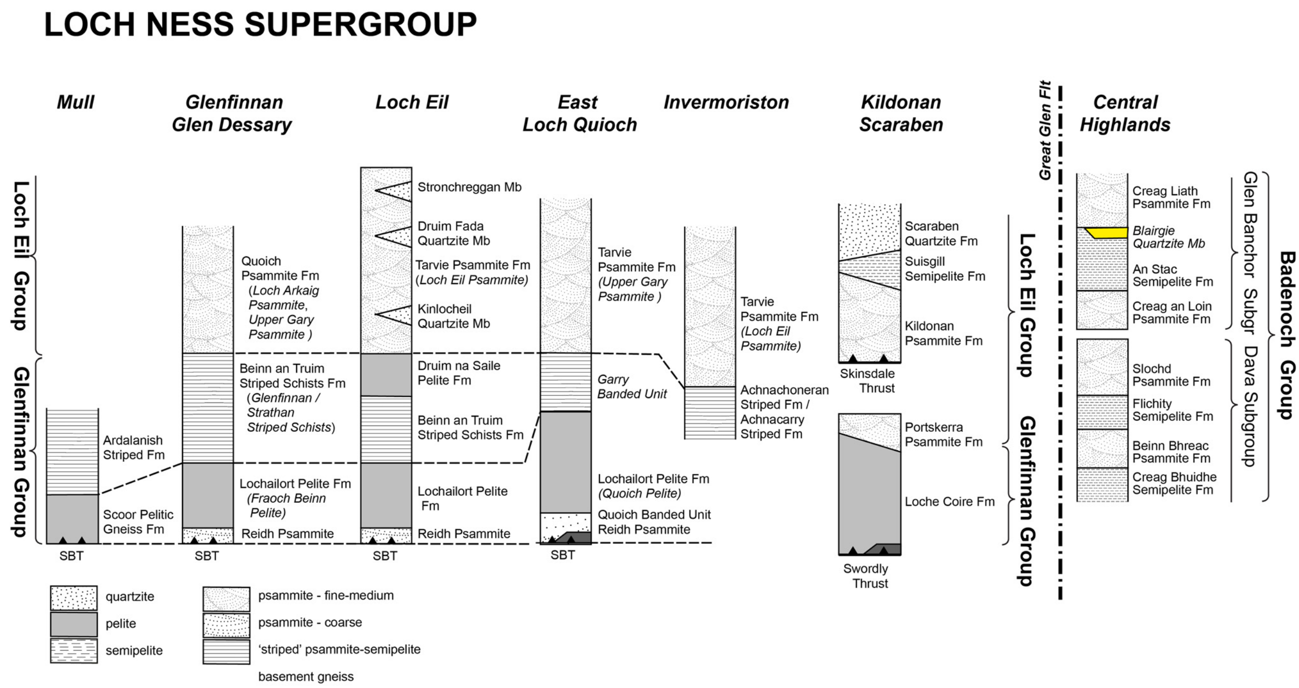

Fig. 7. Stratigraphic correlation charts of the Glenfinnan–Loch Eil–Badenoch groups – Loch Ness Supergroup. References to columns: *Mull:* Holdsworth *et al.* (1987); *Glenfinnan*: Johnstone *et al.* (1969); Strachan (1985); *Glen Dessary/Loch Quoich:* Roberts *et al.* (1984, 1987); *Loch Eil*: Strachan (1985); *East Loch Quoich*: Roberts and 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 2004).

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 Schists Formation 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 Schists–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 and 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 Archean–Paleoproterozoic 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 and Harris 1979; Kelley and 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 (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; Holdsworth *et al.* 1994; Soper *et al.* 1998). 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.* 200–300 m 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 and Temperley 1988; Robertson and Smith 1999; Cawood *et al.* 2003) occurs in the Grampian Highlands SE of the Great Glen Fault

Typical migmatitic Scoor Pelitic Gneiss

High strain zone: mylonitic Laggan Mor Fm below Scoor Peltic Gneiss

Transitional contact between Upper Shiaba and Laggan Mor formations

Cross bedding in Upper Shiaba Psammite Formation.

		Unit	Lithology	Deformation	Interpretation
GLENFINNAN GROUP		**Scoor Pelitic Gneiss**	Migmatitic, semipelitic gneiss, qtz-fsp-bt-grt. Wispy and altered banding of alteration 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 gneiss, migmatitic; semipelitic in composition
		tectonic contact - shear zone			
MORAR GROUP (this paper)	*Assapol Group = Glenfinnan Group (Holdsworth et al. 1987)*	**Laggan Mor Fm - Highly sheared**	Alternation of fine-grained psammite and pelite. Psammite/pelite layers are sharply defined.	Extremely attenuated bedding; strongly tramlined. Beds 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 mineral lineation oblique to L3 crenulation lineation.	Non-migmatitic. High-strain zone with profoundly different lithologies on either side. Refolded in F3 synform
		Laggan Mor Fm Top; medium sheared	Rhythmic alternation of psammite/pelite beds. Psammite beds 3-10 cm thick, pelite beds 10-15 cm thick. Most beds have sharp tops and bases, but in some places coarsening-up cycles are developed. Minor quartzite layers c. 40 cm thick.	Foliation is schistose rather than gneissose. '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 fining upwards sequence defined by increasing proportion of pelitic beds. Overall increase in shear strain towards top.
		Laggan 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	
		Laggan Mor Fm Base	Mainly psammite beds (feldspathic), with minor pelite beds. Bed thickness 5-20 cm, with internal laminae. Poorly preserved trough cross-beds (youngs to west)	Strong flattening and sedimentary structures commonly obscured. Beds appear moderately strongly attenuated.	Transitional contact with underlying psammite unit.
	Shiaba Gr = Morar Gr	**Upper Shiaba Psammite Fm Top**	Thick bedded (20-60 cm) feldspathic psammite with abundant planar and trough cross-bedding (youngs to west); heavy mineral bands.	Some flattening but sedimentary structures well preserved.	Likely fluvial or tidal channels. Very similar to Morar Group elsewhere.

Fig. 8. Summary of observations on stratigraphy, sedimentology and deformation, and revised tectonostratigraphy of Moine rocks, Ross of Mull. SO, bedding; S1, S2, S3; L2, L3 and F2, F3 refer to foliations, lineations and folds of successive deformation phases.

(Fig. 3) as a series of inliers structurally below the Grampian Group, the basal unit of the Dalradian Supergroup. Two units are formally recognized, the Dava and Glen Banchor subgroups, although their relative stratigraphic position is uncertain (Leslie *et al.* 2013; BGS Sheet 74W, British Geological Survey 2004). 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 tectonized unconformity (Piasecki 1980; Piasecki and Temperley 1988), an interpretation that has proved controversial (e.g. compare different viewpoints of Highton *et al.* 1999; Phillips *et al.* 1999; Robertson and 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 datasets, combined with accurate dating of tectonothermal 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 minimize missing the youngest detrital grains (Vermeesch 2012; Pullen *et al.* 2014). For example, the youngest age obtained by Kinnaird *et al.* (2007) 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 and 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 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 Archean 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.* 2008*a*; 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 (Fig. 2), which also have a scarcity of Archean zircons and pronounced Paleoproterozoic 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 Archean 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 and 900 Ma (Cawood *et al.* 2003, 2015; Friend *et al.* 2003; Kirkland *et al.* 2008*a*; 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 the interpretation of Piasecki (1980) and Piasecki and Temperley (1988) of an early Neoproterozoic age for the Badenoch Group. Combined, these data place deposition of Glenfinnan–Loch Eil–Badenoch successions to between *c.* 900 and 870 Ma; this is 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 and 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 so that even though they are nowhere in contact with one another, their age constraints place them collectively within Megasequence 3. The Colonsay Group, previously corelated with the Torridonian, is now generally seen to be correlated with the lower Dalradian (McAteer *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 post-date 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 reorganizing 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

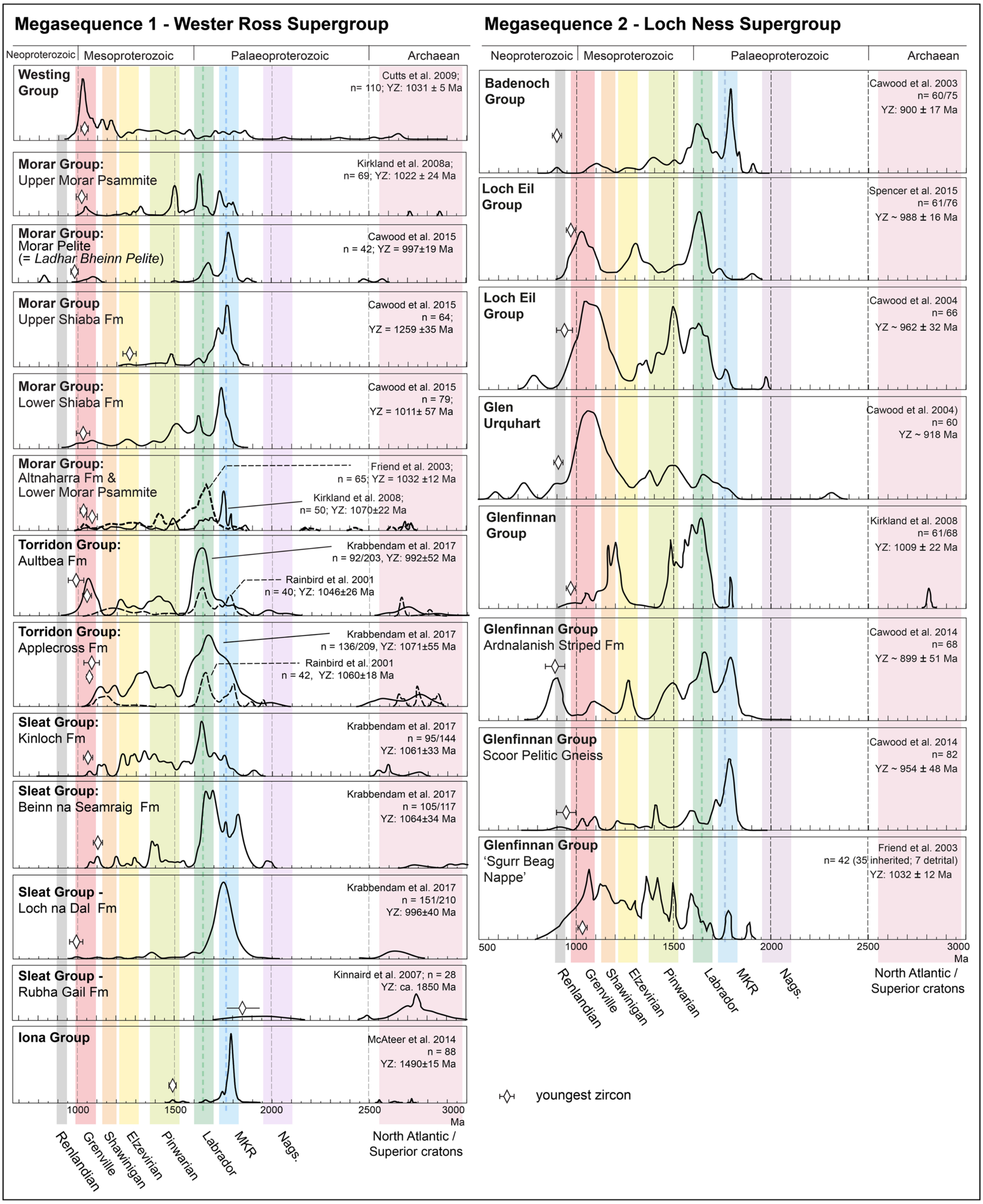

Fig. 9. Detrital zircon age spectra of rock units assigned to Megasequence 1 (left column) and Megasequence 2 (right column). Colour bars indicate Laurentia craton provenance age ranges (see Rivers 1997; Krabbendam *et al.* 2017). MKR, Makkovik–Ketlidian–Rhinnian terranes; Nags, Nagsoquidian; YZ, youngest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

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. Elliott 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 and 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

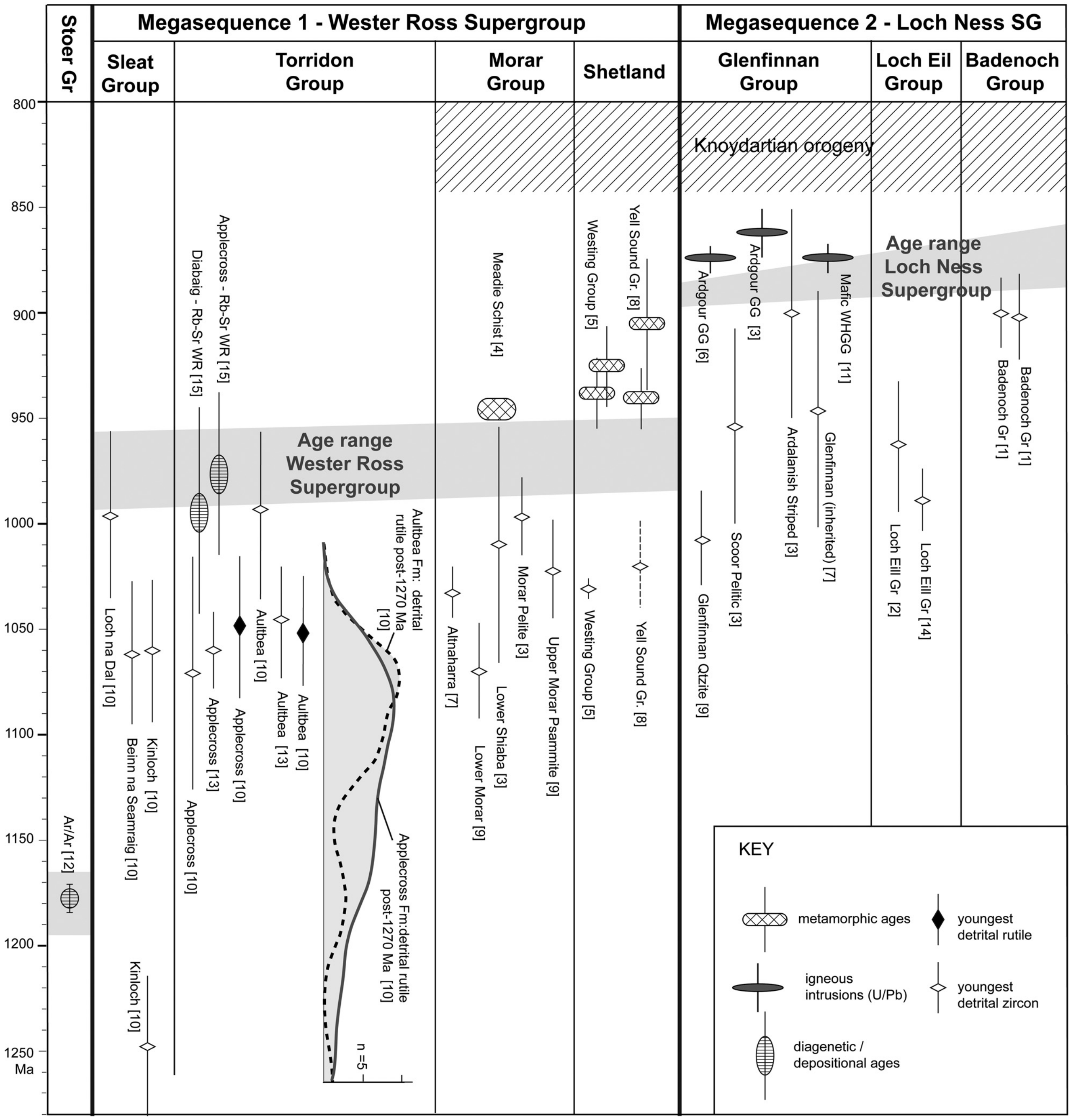

Fig. 10. Overview of radiometric age constraints in Northern Scotland, provided by youngest detrital zircon and rutile ages, metamorphic and intrusive ages and depositional/diagenetic ages. Data after: [1], [2], [3] Cawood *et al.* (2003, 2004, 2015); [4] Bird *et al.* (2018); [5] Cutts *et al.* (2009); [6], [7] Friend *et al.* (1997, 2003); [8] Jahn *et al.* (2017); [9] Kirkland *et al.* (2008*a*); [10] Krabbendam *et al.* (2017); [11] Millar (1999); [12] Parnell *et al.* (2011); [13] Rainbird *et al.* (2001); [14] Spencer *et al.* (2015); [15] Turnbull *et al.* (1996).

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 rationalizes 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 epidotized cobble-boulder breccia and arkosic

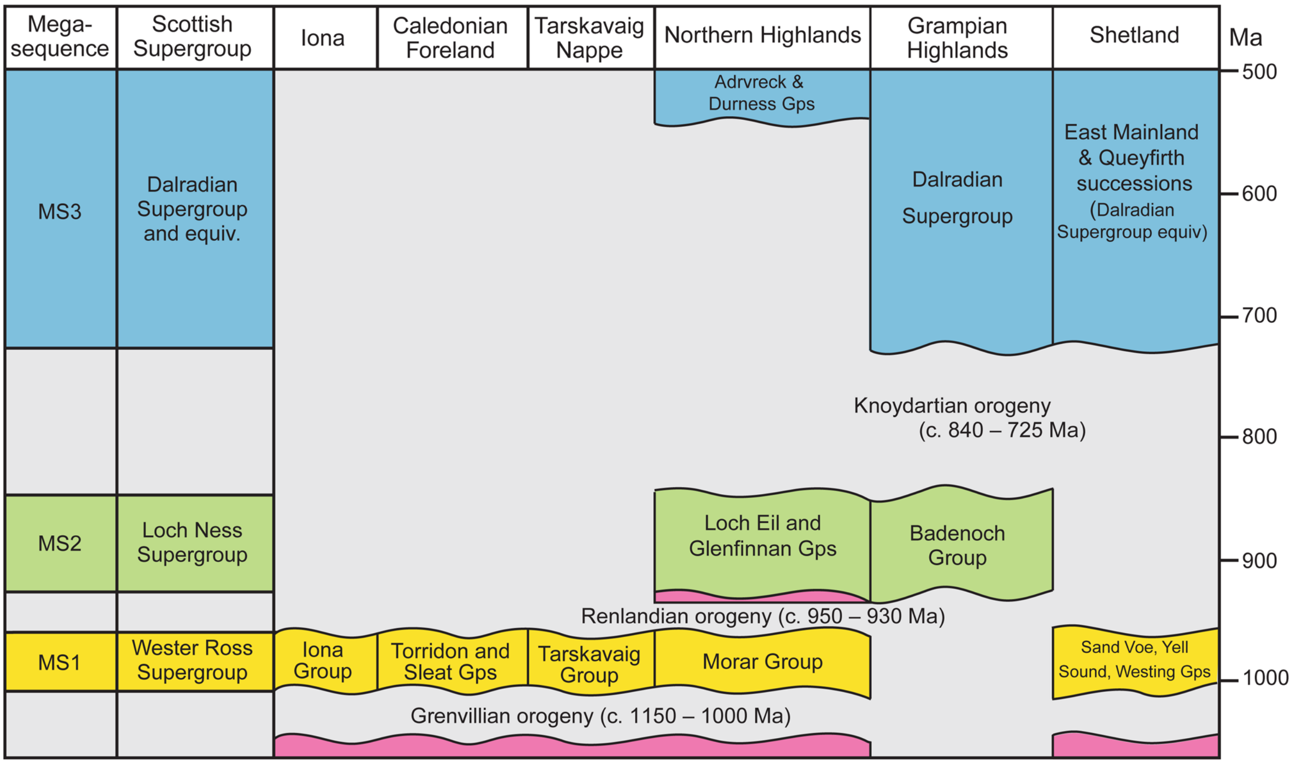

Fig. 11. Revised stratigraphic framework for the Neoproterozoic successions of the Scottish Highlands. The historical terms 'Torridonian' and 'Moine' are no longer viable within the emerging understanding of the Neoproterozoic evolution of the North Atlantic region. Two new stratigraphic divisions are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

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 Archean 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 SE 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 Neoarchean 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 Neoarchean 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 and 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 Archean zircons and pronounced Paleoproterozoic 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 Paleoproterozoic 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 and 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. 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; Higgins and Leslie 2008; Pettersson *et al.* 2009*a*) 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:

(a) Sleat–Torridon–Morar groups into Megasequence 1 (1000–960 Ma);
(b) Glenfinnan–Loch Eil–Badenoch groups into Megasequence 2 (900–850 Ma);
(c) 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 and 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 and 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.

Acknowledgements Helen Fallas is thanked for reviewing an early version of the manuscript. Reviewers Peter Cawood and Rick Law are thanked for reviews. MK publishes with permission of the Executive Director of BGS.

Author contributions **MK**: conceptualization (lead), formal analysis (equal), investigation (equal), writing – original draft (lead), writing – review & editing (equal); **RS**: conceptualization (equal), formal analysis (equal), investigation (equal), writing – review & editing (equal); **TP**: conceptualization (supporting), formal analysis (equal), investigation (equal), writing – original draft (supporting), writing – review & editing (equal)

Funding This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Data availability All data generated or analysed during this study are included in this published article.

Scientific editing by Martin Whitehouse

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