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Research Paper

Eclogites and basement terrane tectonics in the northern arm of the Grenville orogen, NW Scotland

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ABSTRACT

The presence of eclogites within continental crust is a key indicator of collisional orogenesis. Eclogites within the Eastern Glenelg basement inlier of the Northern Highland Terrane (NHT) have been redated in order to provide more accurate constraints on the timing of collision within the northern arm of the Grenville Orogen. The eclogites yield dates of ca. 1200 Ma which are interpreted to record the onset of continent–continent interaction, and the NHT as a whole is thought to represent the lower plate in successive 1200–1000 Ma collision events. The Eastern Glenelg basement inlier is viewed as a fragment of the leading edge of the NHT continental basement that was partially subducted along a suture and then exhumed back up the subduction channel. Differences in ages of igneous protoliths and intrusive histories, and metamorphic events (this paper) between the NHT basement and the Laurentian foreland, suggests that they were separate crustal blocks until after ca. 1600 Ma. We therefore suggest that: (1) the NHT represents a fragment of Archean–Paleoproterozoic crust that was reworked within the ca. 1.7–1.6 Ga Labradorian-Gothian belt, although whether it was derived from Laurentia or Baltica is uncertain, and (2) amalgamation of the NHT with the Laurentian foreland did not occur until the terminal stages of the Grenville collision at ca. 1000 Ma.

1. Introduction

The presence of eclogites within continental crust is a key indicator of collisional orogenesis (e.g. Brown, 2007). This is because they typically represent a low thermal gradient (<350 °C GPa^{-1}), which is essential for high pressure/medium–low temperature metamorphism. Such thermal gradients are far lower than the geotherm expected within normal thickness continental crust, and imply orogenesis and often in particular deep subduction (e.g. Brown, 2007). Eclogites have therefore been used worldwide to assist in the delineation of collisional sutures (e.g. Trans-Hudson orogen, Weller and St-Onge, 2017; Himalaya, O'Brien, 2018), and can therefore be used to unravel the complex collages of accreted terranes that make up substantial parts of many orogens. Key issues include whether or not accreted terranes can be linked to the foreland of an orogen or are instead allochthonous and derived from a colliding craton or intervening ocean. Tectonic analysis of deeply eroded Precambrian gneiss complexes is particularly difficult as faunal controls are absent and palaeomagnetic constraints are often poor. As an example, there has been much debate concerning the assembly of Rodinia and specifically the tectonic setting of the ca. 1.0 Ga Grenville and Sveconorwegian orogens. In one interpretation, they are different parts of the same collisional belt that resulted from the collision of Laurentia, Amazonia and Baltica (Fig. 1D; Cawood and Pisarevsky, 2017; Bingen et al., 2021). Alternatively, following its rifting from Laurentia at or after ca. 1265 Ma (Fig. 1C), Baltica always remained outboard and separate from the Amazonia-Laurentia collision, and the Sveconorwegian orogeny was accretionary in nature (Slagstad et al., 2013, 2019; Slagstad and Kirkland, 2017). In this paper we present new isotopic ages from reworked basement gneiss complexes in NW Scotland and consider the implications for Mesoproterozoic tectonics in this sector of Rodinia.

The Northern Highland Terrane (NHT) of the Ordovician to Early Devonian Caledonide orogen in NW Scotland (Fig. 2 inset) is dominated by the Neoproterozoic Wester Ross and Loch Ness supergroups (formerly the Moine Supergroup (Krabbendam et al.,

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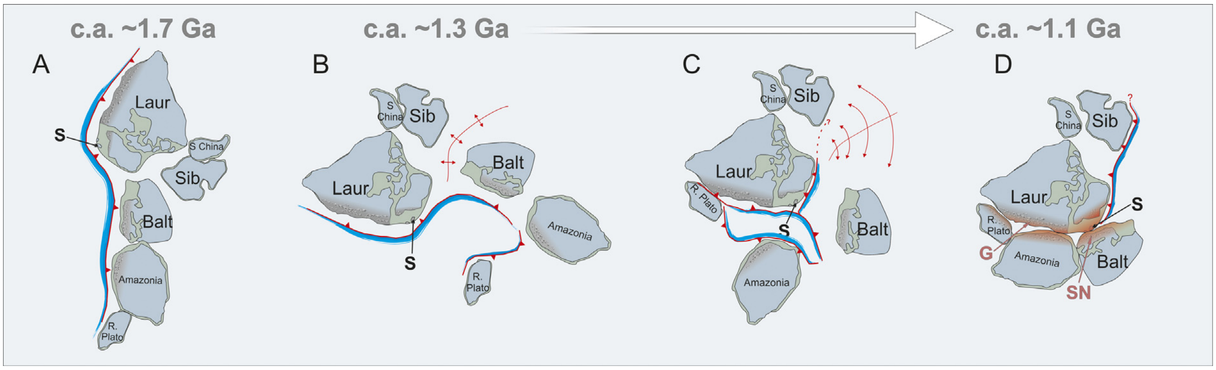

Fig. 1. Schematic plate reconstruction of the amalgamation of Rodina from 1.7 Ga to 1.1 Ga based on the reconstructions of Li et al. (2008), Cawood and Pisarevsky (2017) and Martin et al. (2020). Laur = laurentia, S = Scotland, S China = South China Craton, Sib = Siberian cranon, Balt = Baltica, R. Plata = Rio de la Plata craton, G = Grenville orogeny, SN = Sveno-norweigian Orogeny. Dark blue with red trim = subduction (red teeth indicate hanging-wall side), double ended red arrows = ocean spreading, red/orange shading = ~1.1 Ga orogenesis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

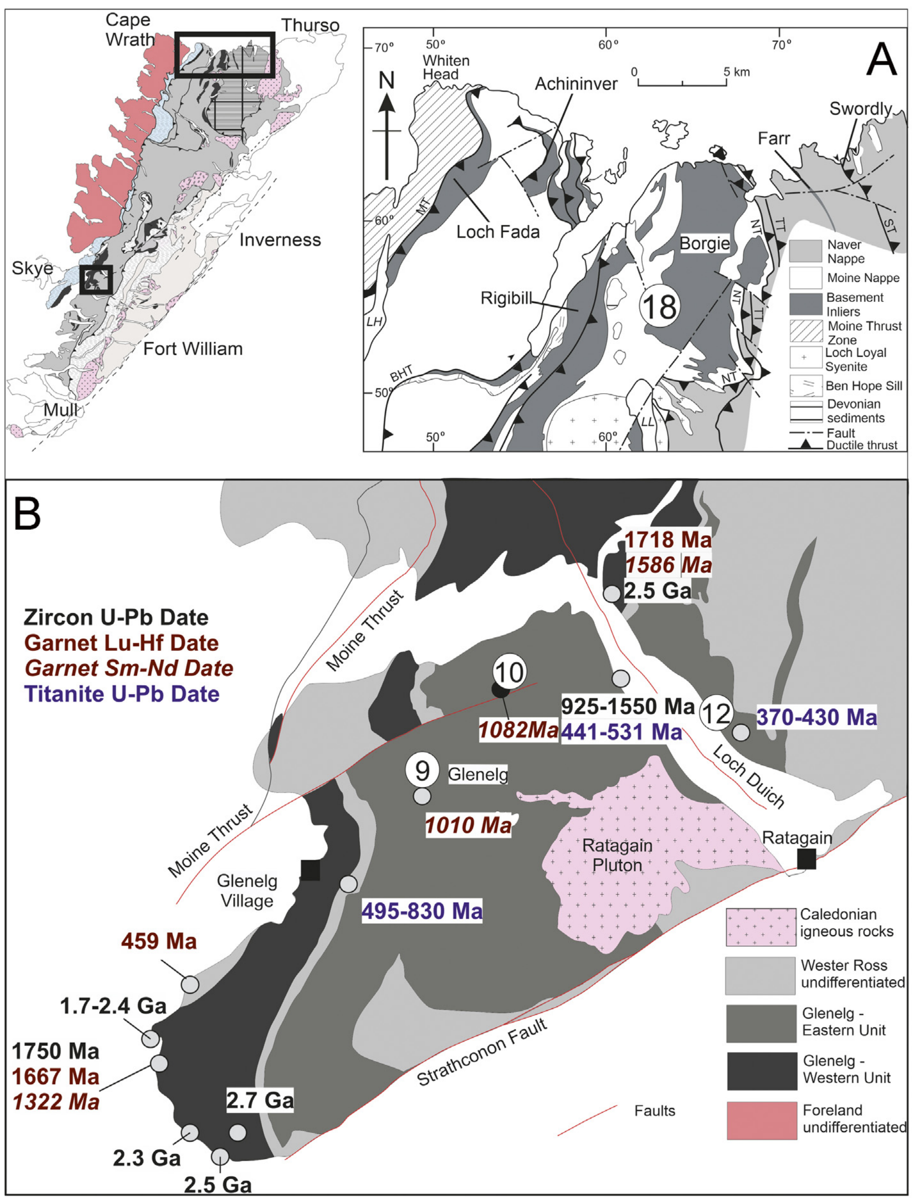

Fig. 2. Simplified map of the northern Highlands, Scotland and study areas. (A) Shows the geology of northern Sutherland and the location of the Borgie and other inliers mentioned within the text. BHT – Ben Hope Thrust, LL – Loch Loyal, MT – Moine Thrust, NT – Naver Thrust, ST – Swordly Thrust, TT – Torrisdale Thrust. (B) Shows the geology of the Glenelg region and the locations of samples with published data (Storey et al., 2004, 2010; Storey, 2008) and locations of the samples within this study.

2021), and inliers of largely orthogneissic basement that have been correlated with the Archean–Paleoproterozoic Lewisian Gneiss Complex of the Laurentian foreland to the west (Fig. 2A and B; Friend et al., 2008). This correlation is largely based on the lithological similarities between the mainly TTG orthogneisses of the Lewisian Gneiss Complex and the Inliers, and comparable Neoarchean and Paleoproterozoic U-Pb zircon protolith ages (Fig. 3). Alternatively, it has been suggested that the basement inliers represent a fragment of Baltican basement that was transferred to the Scottish margin of Laurentia following Grenville-aged collision and subsequent Ediacaran rifting of Rodinia to form the Iapetus Ocean (Strachan et al., 2020b). Further support for the latter hypothesis is provided by a multidimensional scaling analysis of published U-Pb zircon data, including some from Scandinavia, and which shows that there are generally two groups of Inliers, one group with a more Laurentian (Lewisian Gneiss Complex) affinity and one with potentially more of a Baltican affinity (Fig. 3).

Eclogites that have yielded Sm-Nd mineral-whole rock isochrons of ca. 1.1–1.0 Ga occur within the Eastern Glenelg basement inlier along the western margin of the Scottish Caledonides (Fig. 2B; Sanders et al., 1984) and provide evidence for high-pressure Grenville metamorphism in this segment of Rodinia,

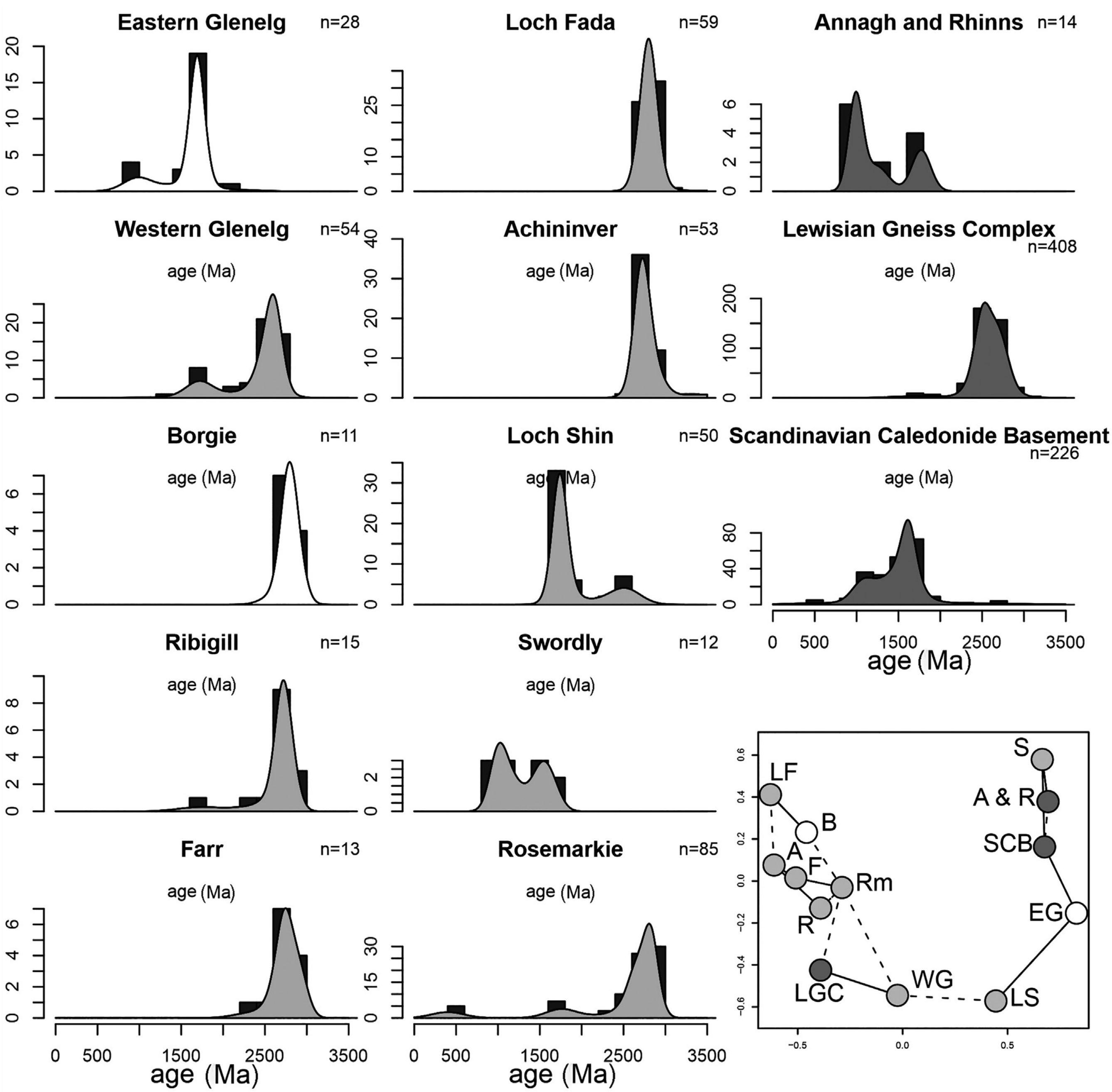

Fig. 3. Zircon U-Pb dates for the inliers from Brewer et al., 2003; Friend et al., 2008; Mendum and Noble, 2010; Storey et al., 2010; Strachan et al., 2020b. The dates from the Lewisian Gneiss Complex are only from mainland Scotland and are from Corfu et al., 1994; Love et al., 2004; Davies and Heaman, 2014; Crowley et al., 2015; Baker et al., 2019; Fischer et al., 2021. Irish dates are from Daly, 1991, 1996. Scandinavian dates are from Bergh et al., 2015; Slagstad and Kirkland, 2017. Only dates less than 15% discordant have been included. A MDS for these regions using these zircon U-Pb dates is also included: LF – Loch Fada; B – Borgie; A – Achiniver; F – Farr; Rm – Rosemarkie; R – Ribigill; LGC – Lewisian Gneiss Complex; WG – Western Glenelg; LS – Loch Shin; EG – Eastern Glenelg; SCB – Scandinavian Caledonide Basement; A & R – Annagh and Rhinns; S – Swordly. All plots were made using IsoplotR (Vermeesch, 2018).

although its wider significance has remained uncertain. The Eastern Glenelg eclogites occur close to the Caledonian Moine Thrust, which defines the easterly-dipping boundary between the Laurentian foreland and the NHT and has been interpreted as a reworked Grenville front (Fig. 2B; Sanders et al., 1984), which has recently been suggested to represent continent–continent collision, in contrast to the Valhalla and Sveconorwegian orogens which represent accretionary margins (Spencer et al., 2019). Here, we report the results of isotopic dating from the Eastern Glenelg inlier and also, for the purposes of comparison, from the Borgie inlier further north (Fig. 2A) that establish that (1) the NHT basement was affected by a high-grade metamorphic event at ca. 1680–1630 Ma, which is largely absent on the Laurentian foreland, (2) eclogite-facies metamorphism occurred at ca. 1180 Ma, at least ca. 100 myr older than thought previously. We propose a tectonic model for the amalgamation of basement terranes and eclogite formation in this sector of the North Atlantic, within a northern arm of the Grenville belt.

2. Geological setting of the eastern Glenelg eclogites and the NHT basement

The Neoarchean and Paleoproterozoic basement inliers within the NHT are dominated by tonalitic to dioritic hornblende gneisses with minor supracrustal layers, and occur either as fold cores or thrust slices (Friend et al., 2008; Strachan et al., 2010, 2020a, 2020b). The inliers have been strongly reworked at amphibolite facies during Neoproterozoic and Ordovician–Silurian (Caledonian) orogenic events, but in areas of low tectonic strain and minimal retrogression preserve evidence of older and higher grades of metamorphism. The eastern Glenelg inlier incorporates units of garnet-kyanite pelite that are often closely associated with mafic and felsic rocks that contain pods and lenses of eclogite. Ultrabasic rocks are also present as olivine websterites +/- garnet. The pelites and the eclogite protoliths likely formed part of a supracrustal sequence that accumulated at ca. 2000 Ma on pre-existing orthogneisses of probable Neoarchean protolith age (Storey et al., 2010; Supplementary Data 2). The eclogites are typically composed of garnet + omphacite + rutile + quartz (Sanders, 1989). Pressure–temperature estimations obtained from various lithologies, including the eclogites, indicate peak metamorphic conditions of $\sim$20 kbar and 730–750 °C, consistent with burial to depths of ca. 70 km (Storey, 2008). Two samples of eclogite yielded Sm-Nd garnet-clinopyroxene-whole rock isochron ages of 1082 ± 24 Ma and 1010 ± 13 Ma (Sanders et al., 1984). For the purposes of comparison to the Eastern Glenelg Inlier, we also consider the Neoarchean Borgie basement inlier (Fig. 2A) that occupies a similar structural setting 150 km further north (Fig. 2A). The inlier is exposed in the core of a composite antiform (Strachan et al., 2020a) and consists mainly of layered felsic to intermediate, amphibolite facies orthogneisses (Friend et al., 2008). Mafic and ultramafic pods and sheets contain relic garnet-clinopyroxene metamorphic assemblages indicative of upper amphibolite to granulite facies metamorphism (Holdsworth et al., 2001).

3. Sample descriptions

Three samples were collected from the supracrustal sequence within the Eastern Unit of the Glenelg-Attadale inlier, one from a garnet-kyanite-phengitic white mica metapelite and two from eclogitic pods. The garnet-kyanite-phengitic metapelite (AB07-12, NG 9049 2330, Fig. 2) shows a strong schistosity (Rawson et al., 2001) and is associated with marble, that is interfolded with orthogneisses. It contains mauve coloured garnet porphyroblasts up to 5 mm in size, biotite, plagioclase, quartz, white mica, chlorite, rutile, sillimanite and kyanite (the kyanite is not seen in hand specimen). The white mica in this sample has been studied by Rawson et al. (2001) who found it to be phengitic in composition indicating that they may be relicts of the eclogite facies. The biotite, white mica and quartz define the schistose fabric which is wrapping the garnets. Kyanite is not common and is always associated with biotite. The garnets have inclusions of quartz, mica, opaque minerals and quite large rounded zircons (70 μm). Sillimanite (fibrolite) is present in very small needles which cluster at the rims of plagioclase grains.

The eclogites (AB07-09, NG 8411 2142; AB07-10, NG 8603 2343; Fig. 2) were collected from mafic pods cut by a network of quartzo-feldspathic veins ("streaks") that range in size from millimetre to tens of centimetre scale. According to Sanders (1989), the quartzo-feldspathic veins formed during eclogite facies metamorphism. There are also hydrated layers of amphibolitised material cutting through the eclogite pods. The rocks are strongly tectonised with a prominent foliation and associated mineral lineation. In thin section, AB07-09 has a coarse granoblastic polygonal texture (up to 4 mm). It comprises garnet, omphacite, rutile and quartz, with veins/streaks which contain quartz, plagioclase and kyanite. The kyanite sometimes forms asymmetric fish. Garnets are up to 4 mm in size, extremely plentiful and show some alteration to amphibole around the rims. Inclusions, where present, consist of rutile, omphacite, quartz, zircon and opaque mineral, which sometimes define linear trails. Omphacite grains occur with symplectites of diopside and plagioclase and are replaced around their rims by hornblende. Rutile has been replaced round the rims by ilmenite. The veins of amphibolitisation are much greener as more hornblende occurs and more symplectites are also present. AB07-10 is very similar to AB07-09 but is more retrogressed, in places, rutile intergrowths and inclusions have almost entirely been replaced by framboidal rims of titanite. The matrix is dominated by symplectitic intergrowths which are probably of diopside, plagioclase and quartz, and a blue-green amphibole is replacing the omphacite.

A sample from the Borgie Inlier garnet-clinopyroxene orthogneiss (AB07-18, NC 6344 5576) was obtained from a massive cm-scale mafic pod within the Borgie Inlier. The sample is structureless and dominated by garnet and clinopyroxene, which have undergone minor replacement by retrogressive hornblende. The garnets are euhedral to subhedral in shape, up to 3 mm in size, often with some amphibole around the edges and along fractures, they contain inclusions of clinopyroxene, rutile and opaques. The amphibole typically is replacing the clinopyroxene around grain rims and sometimes along cleavage planes. The plagioclase has inclusions of clinopyroxene.

4. Analytical methods

Trace element maps of garnets were obtained from all samples by laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) at the University of Hull, using the same methods as Bird et al. (2013). Based on the zoning patterns shown by the LA-ICPMS data, all of the Lu-Hf and Sm-Nd ages should be meaningful (Fig. 4). The Lu shows some zoning in AB07-09 and AB07-10 (Fig. 4A and E), suggesting that the Lu-Hf dates are likely to relate to garnet growth and close to peak metamorphism. AB07-12 and AB07-18 do not show zoning which means the dates obtained are less likely to relate to peak metamorphism. As AB07-18 records granulite facies metamorphism (Moorhouse, 1976; Holdsworth et al., 2001), this likely relates to the high temperature nature of this sample, and thus the date probably represents post-peak metamorphism but could still be close to peak. AB07-12 is from a sample which is likely not to have recorded such high

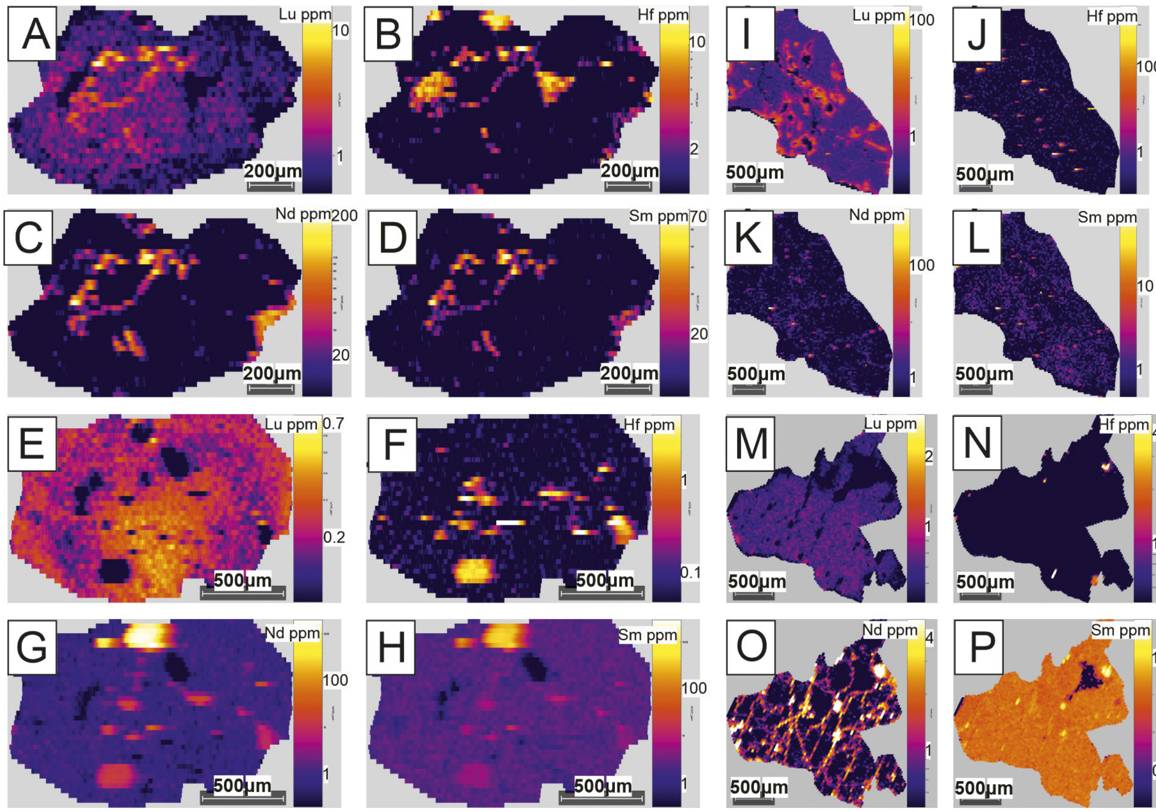

Fig. 4. LA ICPMS elemental maps of garnets from all samples. (A–D) are from AB07-09; (E–H) are from AB07-10; (I–L) are from AB07-12 and (M–P) are from AB07-18.

temperatures, suggesting that this date might relate to later diffusion/cooling during exhumation or resetting during later metamorphic events. In all cases, apart from AB07-18, the Sm and Nd maps show less zoning than the Lu maps, suggesting that the Sm-Nd ages are more likely than the Lu-Hf ages to reflect cooling or resetting. U-Pb zircon and Rb-Sr white mica and biotite ages were obtained from the metapelite sample for comparative purposes with the Lu-Hf and Sm-Nd data. Full details of samples, analytical procedures and all maps produced are provided in Supplementary Data 1 and all isotopic and geochemical results are in Supplementary Data 2.

5. Results

Samples from the Eastern Glenelg pelite (sample AB07-12) scatter around a Lu-Hf garnet-whole rock errorchron date of 1089 ± 76 Ma, (MSWD = 680, Fig. 5A). The four two-point Lu-Hf garnet-whole rock ages range from 1039 to 1162 Ma, and have a strong positive correlation with Lu/Hf ratio and Lu content, and a negative correlation with Hf (r^2 = 0.9985). Measured Hf contents in the dissolved garnet fractions range from 1 to 1.6 ppm, substantially higher than the 0.1 ppm measured in the garnet by LA-ICP-MS, suggesting that Hf-bearing inclusions such as zircon were dissolved. Combining garnet fractions 3 and 4 along with the fused whole rock gives a 3-point Lu-Hf isochron date of 1039.6 ± 3.7 M a (MSWD = 0.1, Fig. 5A). Sm-Nd garnet and whole rock data lie around an errorchron corresponding to an age of 913 ± 19 Ma, while low Sm/Nd garnet fractions 3 and 4 yield higher two-point garnet-WR dates of 941 ± 6 Ma and 948 ± 7 Ma respectively, and lie on a three-point isochron of 943 ± 11.4 Ma (MSWD = 4.1). Model Nd and Hf dates are around 1.9–2.0 Ga. This sample also provides a range of zircon U-Pb concordia age of 1648.8 ± 5.5 Ma (MSWD = 9.1, n = 24, all grains less than 15% discordant, Fig. 5C). However, the analyses plot along concordia from 1821 ± 21 Ma to 1651 ± 93 Ma, which suggests some open system behaviour, perhaps due to later metamorphism. These zircons would have had $^{176}Hf/^{177}Hf$ of ~0.28160 if they grew from the whole rock at 1650 Ma, not low enough to account for the low Lu-Hf ages of garnet fractions B, C and D if they had been present as inclusions in the garnet. Only zircon inclusions with $^{176}Hf/^{177}Hf$ < ~0.2810 could account for the low Lu-Hf ages, and these would have to be Archean, for which there is little evidence in the zircon population. The sample also gives a two-point Rb-Sr white mica-whole rock date of 1042 ± 13 Ma and a biotite-WR date of 418.7 ± 1.3 Ma (Fig. 5D), using an ^{87}Rb decay constant of 1.3972 ± 0.0045 × 10^{-11}-yr^{-1} (Villa et al., 2015).

The Borgie garnet-clinopyroxene orthogneiss sample (AB07-18) yielded a four-point Lu-Hf garnet-whole rock-fused whole rock age of 1634 ± 9 Ma (MSWD = 0.6) (Fig. 5A), and a three-point Sm-Nd garnet-whole rock date of 1462 ± 3.0 Ma, MSWD = 3.8 (Fig. 5B). The Lu-Hf isochron age is close to the Lu-Hf model age for the sample and slightly younger than the Nd model age (1.9 Ga).

Samples from eclogite AB07-09 scatter around a six-point Lu-Hf garnet-whole rock errorchron date of 1173 ± 37 Ma (MSWD = 230, Fig. 5A), and around a Sm-Nd errorchron date of 988 ± 26 Ma (MSWD = 59). Individual garnet-WR two-point Lu-Hf ages are higher at higher $^{176}Lu/^{177}Hf$ and higher Lu, from 1138 ± 5 Ma to 1218 ± 4 Ma, but unlike AB07-12, do not correspond to Hf content, which is much lower in this sample (0.19–0.28 ppm), suggesting minimal dissolution of Hf-bearing inclusions. Individual Sm-Nd two-point ages range from 949 ± 8 Ma to 988 ± 4 Ma, and have a strong positive correlation with $^{147}Sm/^{144}Nd$ and a strong negative correlation with Nd content. The garnet fraction that yielded the 988 Ma age has Sm and Nd contents of 2.4 and 1.9 ppm respectively, very comparable to those measured by LA-ICP-MS (2.3 ± 1.1 ppm and 1.4 ± 0.8 ppm respectively, 2sd, N = 280), those with lower ages have significantly greater Nd (3.8 ppm) suggesting

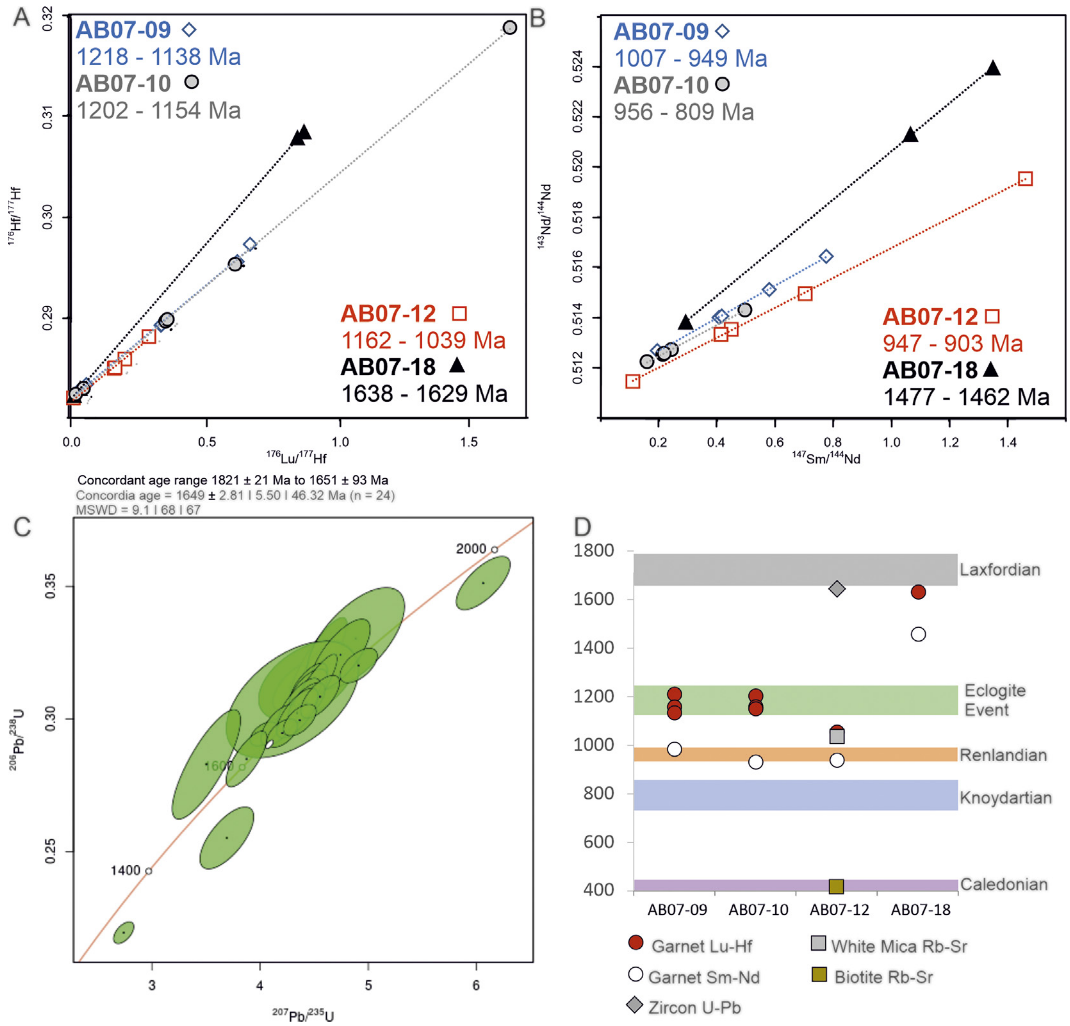

Fig. 5. (A) garnet Lu-Hf data; (B) garnet Sm-Nd data; (C) zircon U-Pb dates; (D) summary plot relating new dates to known orogenic episode.

contamination with other phases. The garnets from this sample lie on a 4-point isochron of 1007 ± 14.2 (MSWD = 9.6). The Hf model age for AB07-09 is around 1.4 Ga.

Samples from eclogite AB07-10 scatter around a six-point Lu-Hf garnet-whole rock errorchron of 1170 ± 21 Ma (MSWD = 92, Fig. 5A), and a Sm-Nd garnet-whole rock errorchron of 945 ± 31 Ma (MSWD = 44, Fig. 5B). Garnet fractions 2, 3 and 4 lie on a 1159.0 ± 5.3 Ma Lu-Hf isochron with the fused WR (MSWD = 4.4), but fraction 1 has a higher two-point age (1202 ± 5 Ma) coupled with much higher Lu/Hf, Lu and lower Hf, similar to AB07-09. For both eclogites, measured ID Hf concentrations in garnets are little higher than in situ Hf contents, suggesting that zircons have little influence on the observed Lu-Hf ages. Since Lu contents measured by LA-ICP-MS peak in the garnet cores, it is likely that the older two-point ages for AB07-09 and AB07-10 sample most closely constrain core growth, and these are very similar between the two eclogites, at 1202 ± 5 Ma and 1218 ± 4 Ma.

6. Discussion

6.1. Significance of the new isotopic ages

The Lu-Hf garnet and U-Pb zircon ages of 1635 Ma obtained from the Borgie inlier and the Eastern Glenelg pelite broadly compare to Lu-Hf garnet ages obtained from an eclogite (1667 ± 6 Ma) and a high-pressure granulite (1718 ± 6 Ma) within the Western Glenelg Inlier (Storey et al., 2010). Friend et al. (2008) also reported a U-Pb zircon lower intercept age of ca. 1600 Ma from the Borgie inlier, which was interpreted to represent a significant isotopic disturbance with further ~ 1750–1600 Ma dates recorded in the Rigibill, Loch Shin, Rosemarkie, Farr and Swordly inliers (Fig. 3). Together, the data suggest that a ca. 1700–1600 Ma high-grade metamorphic event that at least locally attained eclogite-facies is a defining feature of the NHT basement. In contrast, within the Lewisian Gneiss Complex of the Laurentian foreland the youngest high-grade (=granulite facies) metamorphic event occurred at ca. 1870 Ma (Baba, 1998; Fig. 5D), with subsequent events at ca. 1750–1650 Ma restricted to amphibolite-facies reworking and minor magmatism and anatexis (Kinny et al., 2005; Wheeler et al., 2010). Whether the ca. 1460 Ma Sm-Nd age obtained from the Borgie inlier reflects cooling or a younger metamorphic event is uncertain.

The new Lu-Hf garnet ages of ca. 1202 Ma and ca. 1218 Ma obtained from the Eastern Glenelg eclogites are ca. 100 Ma older than the published Sm-Nd ages of ca. 1010–1080 Ma (Sanders et al., 1984). Individual garnet-WR two-point Lu-Hf ages are higher at higher $^{176}Lu/^{177}Hf$ and higher Lu, and do not correspond to Hf content, which is much low in AB07-09 and AB07-10 (0.19–0.28 ppm), suggesting minimal dissolution of Hf-bearing inclusions. This correlation likely indicates mixing between unidentified growth zones, implying core growth at >1218 Ma (see Supplementary Data 2 for elemental garnet maps), suggesting that if there is mixing present between different growth zones, these zones are close together in age and are therefore likely to have grown throughout the same orogenic event. This is consistent with the LA-ICP-MS traverse across garnet from these rocks, which have two Lu concentration peaks at around 1.2 and 0.8 ppm, comparable to the maximum 1.22 and 2.14 ppm and minimum 0.65 and 1.26 ppm Lu measured on the dissolved garnet fractions. Lu-Hf dating is considered to be the more reliable technique for recording peak metamorphism, as it is believed to have a higher closure temperature (e.g. Scherer et al., 2000; Anczkiewicz et al., 2007), and thus the new ages are thought to more closely date eclogite-facies metamorphism. In addition, the LA ICPMS trace element garnet maps show that Lu concentrations are higher within the garnet cores for AB07-09 and AB07-12, whereas Sm and Nd are more homogenous throughout the garnets as a whole (Supplementary Data 1). The LA ICPMS trace element maps from AB07-12 suggest that dates from this sample are unlikely to reflect peak metamorphism, as Lu is concentrated around fractures and the HREE concentrations are not enriched in the core. The Lu-Hf date from the Eastern Unit metapelite (1039 Ma) is younger than the eclogite dates, perhaps reflecting a bigger influence from dissolved Hf-rich phases, or effects from later metamorphism/HREE-rich fluid migration. The new Sm-Nd garnet and Rb-Sr white mica ages range from ca. 1042 Ma to 943 Ma and could result from two separate metamorphic events (Fig. 5D), or could represent cooling. The two older ages of ca. 1042 Ma (AB07-12, Rb-Sr white mica) and ca. 988 Ma (AB07-09, Sm-Nd garnet) are plausibly related to terminal Grenville metamorphism as they are similar to the U-Pb zircon age of 995 ± 8 Ma reported from the Eastern Glenelg eclogites and attributed to amphibolite facies retrogression (Brewer et al., 2003). The younger Sm-Nd garnet ages of ca. 935 Ma (AB07-10) and ca. 943 Ma (AB07-12) are closer to the age of the oldest metamorphic event known to affect the Moine metasedimentary cover of the NHT at ca. 950–940 Ma, which has been assigned to the onset of Valhalla accretionary orogenesis around the Laurentian margin of Rodinia (Cawood et al., 2010, 2014; Bird et al., 2018; Fig. 5D).

6.2. A new tectonic model for eclogites and basement terrane amalgamation in NW Scotland

The new 1700–1600 Ma dates from Borgie and Glenelg agree with the published literature that a widespread 1700–1600 Ma event is recorded within many of the Northern Highland Terrane inliers. Fig. 3 shows that the inliers can be split into two groups, one group similar to the Lewisian Gneiss Complex and another where ages record a 1700–1600 Ma peak and share similarities with the Scandinavian Caledonide Basement. This 1700–1600 Ma event has been suggested by Storey et al. (2010) to record a major continental-continental collision or subduction (Fig. 6A). The new data recorded here only adds to this hypothesis, and suggests that this 1700–1600 Ma event may be more widespread.

Published ca. 1080–1010 Ma Sm-Nd ages for the Eastern Glenelg eclogites were initially interpreted to show that they formed during the Grenville orogeny (Sanders et al., 1984). However, since the publication of these ages there have been major advances in the understanding of this orogen in its type area of NE Canada, which is now known to comprise a number of autochthonous and allochthonous tectonic units and to have evolved over 265 myr (Rivers, 2008 and references therein). The outboard late Mesoproterozoic (<300 Ma) arc terranes of the Composite Arc and the Frontenac-Adirondack belts record, respectively accretionary orogenic events at 1245–1225 Ma (Elzevirian) and 1190–1140 Ma (Shawinigan), as Amazonia moves north as seen in Fig. 1C, prior to their accretion to Laurentia at the start of the main 1090–1020 Ma (Ottawan) and 1010–980 Ma (Rigolet) collisional phases of the orogeny (Rivers, 2008; Fig. 1D). The new ages obtained for the Eastern Glenelg eclogites are thus over 100 myr older than the onset of the main Grenville continental collision. They are temporally coincident with the Shawinigan orogenic event but the geological context is very different as in Scotland the eclogites are not associated with the accretion of juvenile arc material. In summary, there are no straightforward correlations between the Grenville belt in its type area and the Eastern Glenelg eclogites.

Any alternative tectonic model needs to account for: (1) the formation and location of the eclogites at ca. 1200 Ma, and (2) the differences in metamorphic history between the NHT inliers and the Laurentian foreland. A possible solution is found in tectonic models that propose a ca. 90° rotation of Baltica relative to Laurentia between ca. 1265 and 1000 Ma (Cawood and Pisarevsky, 2006). Prior to ca. 1265 Ma, present-day west Norway faced south (present-day coordinates) and an open ocean (Fig. 6B), but by ca. 1000 Ma it was juxtaposed against the sector of the Laurentian margin that contained Rockall Bank and the Laurentian foreland (Figs. 1 and 6C, D). One effect of this rotation was to open a new oceanic tract, the Asgard Sea, along the edge of Rodinia (Fig. 6C; Cawood et al., 2010). Further inboard, the rotation can only have been accomplished by a corresponding loss of oceanic lithosphere between Laurentia and Baltica as the latter rotated (Fig. 6C and D). Whether this was achieved by oroclinal bending of the subduction zone developed along the southern Laurentia-Baltica margin or the development of new subduction zones is uncertain, but the net effect was likely to 'sweep up' a series of marginal basins, magmatic arcs and microcontinental fragments as the two cratons converged, ultimately to collide by ca. 1000 Ma (Fig. 6C and D). We interpret the Eastern Glenelg eclogites to record the onset of convergence and the NHT as a whole to represent the upper plate in successive 1200–1000 Ma collision events. The Eastern Glenelg basement inlier is viewed as a fragment of the leading edge of the NHT basement that was subducted along a suture and then exhumed back up due to a process like gravitational collapse (Fig. 6D). Differences in the ages of igneous protoliths and intrusive histories (Storey et al., 2010; Strachan et al., 2020b), and metamorphic events (this paper) between the NHT basement and the Laurentian foreland, suggests that they were separate crustal blocks until after ca. 1600 Ma. We therefore suggest that: (1) the NHT represents a fragment of Archean–Paleoproterozoic crust that was reworked within the ca. 1600–1700 Ma Labradorian-Gothian belt, although whether it was derived from Laurentia or Baltica (Strachan et al., 2020a) is uncertain (Fig. 3), and (2) amalgamation of the NHT with the Laurentian foreland did not occur until the terminal stages of the Grenville collision at ca. 1000 Ma.

The ca. 1100–1000 Ma suture between the Laurentian foreland and the NHT is presumably located some distance (ca. 100 km?) further east in the footwall of the Caledonian Moine Thrust. None the less, various geological features of the foreland could be interpreted as 'far-field' responses to Grenville terrane amalgamation. These include: (1) the ca. 1180 Ma Stoer Group (Parnell et al., 2011; Fig. 6C) which has been interpreted as a rift basin deposit (Stewart, 2002) but nothing precludes it representing the fill of a foreland basin, and (2) Rb-Sr biotite ages of ca. 1150 Ma in the northern Outer Hebrides (Cliff et al., 1998), and $^{40}Ar/^{39}Ar$ ages obtained from pseudotachylyte veins in the Outer Hebrides (ca. 1200–1300 Ma), on the Scottish mainland (ca. 910–1019 Ma; Sherlock et al., 2008, 2009) and the Western Gneiss Complex Meso-Neoproterozoic garnet bearing assemblages (March et al., 2022; Tamblyn et al., 2022).

Most reconstructions of the Grenville-Sveconorwegian orogen extrapolate the northern 'front' of the orogen eastwards from Canada to lie just north of the Annagh Gneiss Complex of NW

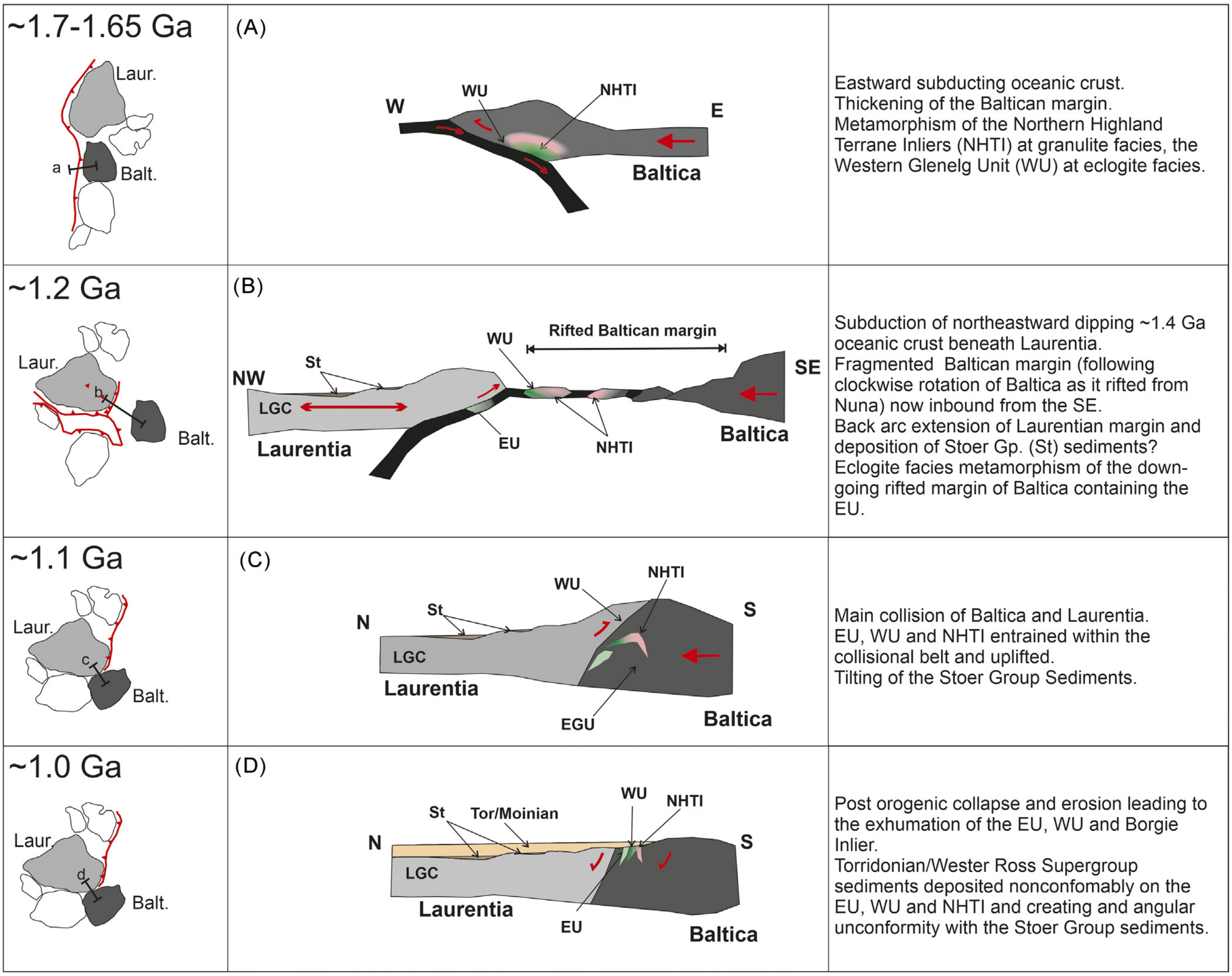

Fig. 6. Schematic models displaying the tectonic development of the northern Highland Basement Inliers (NHTI) from 1.7 to 1.0 Ga.

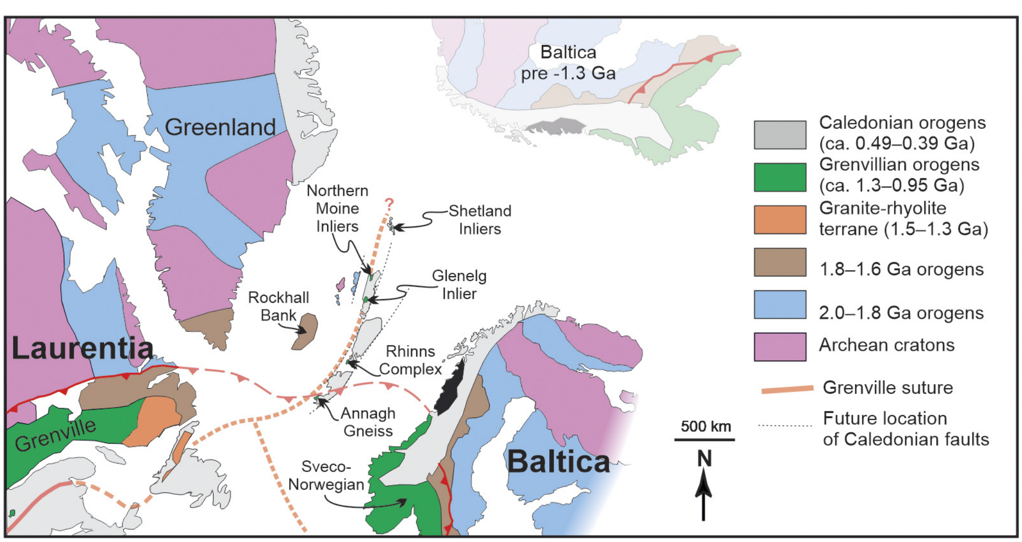

Fig. 7. Distribution of orogenic events on the north Atlantic region as distributed at the end of the Grenville orogeny (modified from Cawood et al., 2010) with the position of Baltic prior to the Grenville orogeny also shown (semi-transparent). Location of NHT inliers indicates the revised northern extent of Grenville orogenesis.

Ireland, and thence further east to link with its continuation in west Norway (Fig. 7; e.g. Buchan et al., 2000). This does not explain the 1200–1000 Ma events in NW Scotland, which was probably located ca. 500–700 km further north once late Caledonian strike-slip displacement along the Great Glen Fault is restored (Fig. 7). Our proposed tectonic model resolves this issue by explaining these events as the result of Laurentia-Baltica collision and hence provides evidence for the putative northern arm of the Grenville orogen favoured by Gee et al. (2015). Grenville-aged metamorphism at ca. 1050 Ma has been recorded in the Shetland Islands (Walker and Bird, 2020) although there is no reason to suppose that this small part of the orogen extended any further north.

CRediT authorship contribution statement

A. Bird: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Writing – original draft, Writing – review & editing. **M. Thirlwall:** Conceptualization, Data curation, Investigation, Methodology, Supervision, Writing – review & editing. **R.A. Strachan:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing – review & editing. **I.L. Millar:** Data curation, Formal analysis, Writing – review & editing. **E.D. Dempsey:** Visualization, Writing – review & editing. **K. Hardman:** Data curation, Formal analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gsf.2023.101668.

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