A Baltic heritage in Scotland: basement terrane transfer during the Grenvillian orogeny

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ABSTRACT

Archean basement inliers within the Northern Highland Terrane (NHT), Scottish Caledonides, have been correlated with the Lewisian Gneiss Complex of the Laurentian foreland. New zircon U-Pb ages indicate that the NHT basement contains evidence for magmatism at 2823–2687 Ma, and 1772–1655 Ma. The first group compares with crystallization ages of the foreland Archean gneisses. However, the second group, and a supracrustal unit, formed ca. 100–250 myr after the youngest major phase of juvenile magmatism and sedimentation in the foreland. Also, there is no indication within the NHT basement of the Palaeoproterozoic mafic and felsic intrusions common within the foreland, leading us to conclude that there is no firm basis for correlation of the two crustal blocks. The Caledonian Moine Thrust, which separates the foreland and the NHT basement, is thought to have reworked a Grenvillian suture indicated by the presence of the ca. 1100–1000 Ma Eastern Glenelg eclogites. On the basis of the new isotopic data, we propose that the NHT basement was a fragment of Baltica that was emplaced onto Laurentia during the Grenvillian orogeny, representing a further example of basement terrane transfer in the circum-North Atlantic orogens.

INTRODUCTION

Orogenic belts commonly contain exotic terranes emplaced tectonically from one craton onto another as large nappes during collisional orogeny. Subsequent rifting/breakup can then lead to separation of these terranes from their parent craton. Examples include the basement inliers of the southeast Appalachians derived from Amazonia during the 1100–1000 Ma Grenvillian

orogeny (Fig 1; Hynes and Rivers, 2010), the Uppermost Allochthon of Norway derived from Laurentia during the 500–400 Ma Caledonian orogeny (Fig 1; Andersen and Andresen, 1994), and the Precordillera of Amazonia that also originated in Laurentia (Thomas et al., 2004). Thus, identifying exotic terranes enables insights into ancient cratonic configurations and plate reconstructions.

In NW Scotland, the Laurentian foreland of the Caledonian orogen is underlain by the Archean–Paleoproterozoic Lewisian Gneiss Complex (Figs. 1 and 2). The complex comprises different terranes (Kinny et al., 2005) that collectively record a protracted crustal evolution involving: (1) TTG magmatism at ca. 3100–2700 Ma; (2) high-grade metamorphism at ca. 2700 and 2500 Ma; (3) main phase intrusion of Scourie mafic dykes at ca. 2420–2380 Ma; (4) formation of Loch Maree Group supracrustals at ca. 1900 Ma, and; (5) Laxfordian reworking and high-grade metamorphism at ca. 1850 and ca. 1700–1650 Ma (e.g. Wheeler et al., 2010; Whitehouse and Kemp, 2010; Davies and Heaman, 2014). To the east, the Moine Thrust Zone separates the Laurentian foreland from the Northern Highland Terrane (NHT; Fig. 2). The NHT is dominated by the Neoproterozoic Moine Supergroup that is interleaved tectonically with inliers of orthogneissic basement (Fig. 2; Strachan et al., 2002; Cawood et al., 2015). Published U-Pb zircon geochronology permits broad correlation of the NHT basement with the Lewisian Gneiss Complex (Friend et al., 2008), as does new Hf isotopic data. However, new U-Pb ages presented here lead us to propose that the NHT basement is exotic, a part of Baltica that was emplaced onto Laurentia during the Grenvillian orogeny.

STRUCTURAL SETTING AND EXISTING GEOCHRONOLOGY OF THE NHT BASEMENT

The NHT basement inliers (Fig. 2) mainly comprise mafic to intermediate orthogneisses and, locally, supracrustal rocks (e.g. Friend et al., 2008). The inliers were reworked at amphibolite facies during Neoproterozoic and Ordovician–Silurian (Caledonian) orogenic events (e.g. Cutts et al., 2010; Cawood et al., 2015), but contain evidence of older, higher-grade metamorphism. U-Pb (SIMS) zircon data from the Ribigill, Borgie, Farr and western Glenelg–Attadale inliers (Fig. 2) suggest protolith ages of ca. 2900–2700 Ma (Friend et al., 2008) and the former three show isotopic disturbance at ca. 1740–1600 Ma. The protolith ages support correlation with the foreland Lewisian Gneiss Complex (Moorbath and Taylor, 1974) and a Laurentian affinity. However, greater tectonic complexity is indicated by the presence within the Eastern Unit of the Glenelg–Attadale inlier of eclogites that have yielded Sm–Nd mineral

isochrons of 1082 ± 22 Ma and 1010 ± 13 Ma, consistent with a Grenvillian-aged suture (Sanders et al., 1984; Storey et al., 2005).

NEW ISOTOPIC CONSTRAINTS ON THE NHT BASEMENT

Zircon U–Pb geochronology and hafnium isotope analysis were carried out by split-stream laser ablation inductively-coupled plasma mass spectrometry (LA–ICPMS) on a range of NHT inlier lithologies (Fig. 2), including clasts eroded from the inliers and reworked into the overlying Moine rocks (details in the Data Repository). Hf isotope analyses were also undertaken on samples from four inliers dated by Friend et al. (2008). Zircon data is grouped based on internal textures visible in cathodoluminescence (CL) images and U–Pb systematics.

A mylonitic intermediate orthogneiss from the Loch Fada inlier (Fig. 2; RS-MTZ-18-01) contains zircons with internal magmatic zoning, some nucleated on irregular-shaped structural cores. From sixty analyses, three age components are evident: a small group at ca. 2935 Ma interpreted as an inherited population, and two major magmatic components at ca. 2823 ± 14 Ma and 2766 ± 14 Ma (Fig. 3). Values of ϵHf_i for the magmatic populations ranged from -2.7 to $+0.7$, corresponding to $T_{\text{DM}(2)}$ ages of 3160 to 3080 Ma (Fig. 4).

A felsic orthogneiss from the Achininver inlier (Fig. 2; RS-TI-18-05) contains zircons with well-developed primary magmatic zoning. Eight analyses yielded a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2736 ± 14 Ma, interpreted as the magmatic crystallization age (Fig. 3). ϵHf_i for these range from -4.2 to $+3.3$, corresponding to $T_{\text{DM}(2)}$ of 3280 to 2950 Ma (Fig. 4). An intermediate orthogneiss from the Achininver inlier (RS-TI-18-10) contained few zircons, most of which were normally discordant (Fig. 3). The most concordant analysis with a $^{207}\text{Pb}/^{206}\text{Pb}$ age (2σ) of 2687 ± 28 Ma, is interpreted as the best estimate of the minimum protolith crystallization age. This analysis indicates a ϵHf_i of -0.2 . Two clasts of felsic orthogneiss derived from the Achininver basement were sampled from a basal Moine conglomerate. Zircons from RS-TI-18-07 exhibited both oscillatory and homogeneous textures under CL. Thirteen analyses yielded a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2701 ± 16 Ma (MSWD = 2.5) (Fig. 3), and ten analyses of oscillatory zoned zircon from RS-TI-18-09 yielded a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2725 ± 14 Ma (MSWD = 2.5) (Fig. 3). Both are interpreted as magmatic crystallization ages. ϵHf_i values ranged from -0.4 to $+2.0$ (sample 18-07) and -3.4 to $+1.0$ (sample 18-09), corresponding to $T_{\text{DM}(2)}$ ages between 3330 and 2980 Ma (Fig. 4).

Three samples were dated from the Loch Shin inlier (Fig. 2). An intermediate orthogneiss (RS-LSI-18-21) contained zircons with variable CL emission and texture, including oscillatory-zoned grains and homogeneous crystals. Thirteen analyses yielded a

weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1772 ± 39 Ma (MSWD = 1.3) (Fig. 3), interpreted as the age of magmatic crystallization. With one exception, εHf_i for these zircons ranges from -17.5 to -13.2 , corresponding to $T_{\text{DM}(2)}$ of 3390 to 3180 Ma (Fig. 4). In addition, numerous analyses from this sample define a crude discordia trend back to ca. 2545 Ma (Fig. 3), interpreted as inherited zircon that either has lost radiogenic Pb at the magmatic age or was physically mixed with the magmatic component in the analytical volume. A deformed intrusive felsic sheet within the orthogneisses (RS-LSI-18-20) contained zircons that generally display idiomorphic zoning with evidence for some magmatic resorption. Nineteen analyses yielded a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1711 ± 19 Ma (MSWD = 0.74) (Fig. 3), interpreted as the age of magmatic crystallization. εHf_i ranges from $+0.2$ to $+4.4$, corresponding to $T_{\text{DM}(2)}$ of 2310 to 2110 Ma. A biotite schist, part of a metasedimentary unit (RS-LSI-18-19), contained zircons of likely detrital origin that exhibit various internal textures, including concentric growth zoning, homogeneous domains and transgressive reabsorption fronts. Three analyses yielded a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1802 ± 51 Ma (MSWD = 0.89) (Fig. 2), which we regard as the best estimate for the maximum age of deposition of the sedimentary precursor. εHf_i for this group ranges from -2.0 to $+6.0$.

An intermediate orthogneiss from the Swordly inlier (Fig. 2; RS-SI-18-13) contained zircons that display concentric growth zoning truncated at grain edges. The analytical data spread along the Concordia curve (Fig. 3). A correlation between higher U content and younger $^{207}\text{Pb}/^{206}\text{Pb}$ apparent ages is consistent with radiogenic Pb loss from a ca. 1655 Ma magmatic component during a ca. 1008 Ma metamorphic overprint. εHf_i values for the least disturbed are between $+3.2$ and $+9.1$.

DISCUSSION

Significance of the new isotopic data

The isotopic data indicate that the NHT basement preserves evidence for two phases of magmatism: Group 1 is between ca. 2823 and ca. 2687 Ma, and Group 2 between ca. 1772 and ca. 1655 Ma. The former falls within the ca. 2905–2670 Ma protolith age range established for the NHT basement by Friend et al. (2008). The initial Hf isotope compositions for Group 1, including those of the Friend et al. (2008) samples (Fig. 4), are typically a few epsilon units either side of CHUR, consistent with derivation as TTG suite magmas from a mainly mafic precursor that was extracted from the mantle between ca. 3330 and 2950 Ma. The combined evidence from crystallization ages of inherited zircon cores points to limited involvement of

differentiated crust at least ca. 3540 myrs old. The oldest of these cores have Hf isotopic values that lie along a broad Hadean–Eoarchean crustal evolutionary array.

Group 2 has not been recognized before in the NHT. Their Hf data are more varied than Group 1 (Fig. 4). Orthogneiss RS-LSI-18-21 has highly negative ϵHf_i values that could plausibly represent re-melted Neoproterozoic crust similar in composition to Group 1, consistent with the inherited zircon component in this sample. By contrast, RS-LSI-18-20 and RS-SI-18-13 have ϵHf_i close to or greater than zero, which were likely derived from juvenile Paleoproterozoic mafic crust. Detrital zircons in the sedimentary cover to the Loch Shin inlier show a mixed provenance incorporating Hf from Archean and Proterozoic sources (e.g. Slagstad and Kirkland, 2017). Although the maximum depositional age constraint provided by the youngest detrital zircons is ca. 1802 Ma, deposition was likely younger than the ca. 1711 Ma age of RS-LSI-18-20, because the (meta)sedimentary rocks are not intruded by any (meta)igneous units.

A feature of the SIMS U-Pb data for the Archean inliers studied by Friend et al. (2008) was the strong disturbance (Pb loss) in latest Paleoproterozoic time. The new LA-ICPMS data from the Loch Fada, Achininver and Loch Shin inliers generally lack this discordance signature. Another difference from the previous study is the evidence for additional major isotopic disturbance at ca. 1008 Ma in the Swordly inlier.

Comparison with the Lewisian Gneiss Complex

Group 1 protolith ages from our new data fall within the range of ages obtained from the Archean gneisses of the Lewisian Gneiss Complex (Fig. 2; ca. 3135–2680 Ma; Friend and Kinny, 1995, 2001; Kinny and Friend, 1997; Love et al., 2004; Kinny et al., 2005; Goodenough et al., 2013), and the Hf isotopic compositions of the zircons are similar to the Lewisian also (Fig. 4). Further, although the Loch Fada and Achininver samples contained no evidence of younger metamorphic events, the Ribigill, Borgie and Farr inliers dated by Friend et al. (2008) provided evidence for isotopic disturbance between ca. 1740 and ca. 1600 Ma, which corresponds broadly to some mineral ages (titanite, rutile) from the Lewisian Gneiss Complex (Corfu et al., 1994). In contrast, there are two significant differences between the NHT inliers and the Lewisian Gneiss Complex of the foreland. Firstly, the Group 2 protolith ages and the Loch Shin supracrustal rocks formed at least ca. 100–250 myr after the youngest significant phase of *juvenile* magmatism and sedimentation recognized on the foreland, the ca. 1900 Ma Loch Maree Group (Park et al., 2001). Furthermore, there is no indication in the inliers of the Scourie dykes that are common within the foreland basement (Storey et al., 2010) or the

Laxfordian granites that are abundant within the Rhiconich Terrane (Fig. 2; Friend and Kinny, 2001; Goodenough et al., 2013).

Is the NHT basement part of Laurentia?

The issue addressed here is fundamental to the interpretation of many basement gneiss complexes. To what extent do differences in tectono-metamorphic and/or magmatic histories reflect the heterogeneous distribution of deformation, metamorphism and/or igneous activity rather than differences across collisional sutures? Isotopic data can assist in distinguishing between different crustal blocks although the results may be equivocal. Thus, the hafnium data presented here (Fig. 4) do not enable discrimination between Laurentia and Baltica, most likely because they were conjoined in successive continental assemblies in the Neoproterozoic (Superia; Bleeker and Ernst, 2006) and Paleoproterozoic (Nuna; Karlstrom et al., 2001) and hence record a very similar crustal evolution. However, U-Pb zircon and hafnium data in combination can provide additional insights into tectono-magmatic histories as shown by our comparison of the Lewisian Gneiss Complex and the NHT basement. In our view, these differences are greater than can be explained by the ca. 100 km likely displacement on the intervening Moine Thrust Zone (Strachan et al., 2002). We therefore question assignment of the NHT basement to Laurentia and propose an alternative tectonic model.

It is generally believed that Rodinia assembly during the late Mesoproterozoic culminated in the collision at ca. 1000 Ma of Amazonia with a combined Laurentia–Baltica (Fig. 1; Cawood and Pisarevsky, 2017, but see Slagstad et al., 2017). Prior to that, between ca. 1900 and 1200 Ma, the southern margin of Laurentia–Baltica was a relatively linear accretionary orogen (e.g. Karlstrom et al., 2001). At ca. 1270 Ma, present-day west Norway faced south (present-day coordinates), but by ca. 1000 Ma Baltica had rotated $\sim 90^\circ$ to face Rockall Bank and the Laurentian foreland of Scotland (Fig. 1; Cawood and Pisarevsky, 2006; Cawood et al., 2010). This rotation must have resulted in loss of oceanic lithosphere between Laurentia and Baltica. We interpret the ca. 1100–1000 Ma Eastern Glenelg eclogites to have formed along the suture across which Baltica and Laurentia were amalgamated before the collision of Amazonia. This could also account for the major isotopic disturbance at ca. 1008 Ma in the Swordly inlier and resetting of biotite ages in parts of the Caledonian foreland in Scotland (Cliff and Rex, 1989).

Our proposed model envisages that a northern arm of the Grenvillian orogen extended to Scotland (Fig. 1), and that the NHT basement may have originated from Baltica. Significant inliers of Archean–Paleoproterozoic basement occur in the Norwegian Caledonides, including

the West Troms Basement Complex, which has been compared with the Lewisian Gneiss Complex (Fig. 1; Bergh et al., 2015; Laurent et al., 2019). Further investigation of these inliers may provide a match for the orphaned NHT basement. The NHT may not have originated as part of Laurentia as generally believed, but was more likely transferred from Baltica during the Grenvillian orogeny, representing a further example of basement terrane transfer in the circum-North Atlantic orogens.

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328 **FIGURE CAPTIONS**

329 Figure 1. Laurentia-Baltica-Azonian reconstruction for mid-Neoproterozoic time showing:
330 a) major Archean, Paleoproterozoic and Mesoproterozoic tectonic elements, and b) extent of
331 the Lower Paleozoic Caledonian orogen of East Greenland, Scandinavia and the British Isles
332 and its lateral extension into the Appalachians (modified from Cawood et al., 2007). Red
333 arrow indicates the anticlockwise rotation of Baltica that occurred between c. 1270 Ma and c.
334 1000 Ma (see text for discussion). AI, Amazonian inliers; RB, Rockall Bank; UA, Uppermost
335 Allochthon; WTBC, West Troms Basement Complex.

336 Figure 2. Inset: map of northern Scotland showing terrane subdivisions and location of main
337 map. GA, Glenelg–Attadale inlier; GGF, Great Glen Fault; HBF, Highland Boundary Fault.
338 MT, Moine Thrust. Main map: geology of north Sutherland showing sample locations. B,
339 Borgie; F, Farr; R, Ribigill inliers. AT, Assynt Terrane; RT, Rhiconich Terrane (Kinny et al.,
340 2005).

341 Figure 3. Stacked Tera-Wasserburg U-Pb plot for zircon grains from the studied samples (see
342 also Supplementary Data).

343 Figure 4. Zircon ε_{Hf} evolution plot for the analyzed samples. Also shown are the
344 compositional fields for analyses of zircon grains from Baltica and Laurentia (Spencer et al.,
345 2018) and the Lewisian Gneiss Complex (Whitehouse and Kemp, 2010). s9612 = Borgie
346 inlier; s9641 = Western Glenelg-Attadale inlier; s991 = Farr inlier; s992 = Ribigill inlier.

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