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ABSTRACT

The presence of eclogites within continental crust is a key indicator of collisional orogenesis and they have been used worldwide to assist in the delineation of ancient collisional sutures. Eclogites within the Eastern Glenelg basement inlier of the Northern Highland Terrane (NHT) have been re-dated 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 c.1200 Ma which are interpreted to record the onset of convergence, 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 basement that was partially subducted along a suture and then obducted back up the subduction channel. Differences in 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 c. 1600 Ma. We therefore suggest that: 1) the NHT represents a fragment of Archean-Paleoproterozoic crust that was reworked within the c. 1600-1700 Ga Labradorian-Gothian belt, although whether it was derived from Laurentia or Baltica (Strachan et al., 2020b) 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 c. 1000 Ma.

HIGHLIGHTS

1200 Ma eclogites from the Scottish Northern Highlands

Scottish Northern Highlands reworked within Labradorian-Gothian belt (1.6-1.7Ga)

Scottish Northern Highland eclogites record onset of Rodinia amalgamation

Scottish Northern Highlands and Laurentian foreland amalgamation occurred after 1Ga

1.1 INTRODUCTION

The presence of eclogites within continental crust is a key indicator of collisional orogenesis. 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 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, 2017; Himalaya, O'Brian, 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 c.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; Bingen et al., 2021, Cawood and Pisarevsky, 2017). Alternatively, following its rifting from Laurentia at or after c. 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., 2019, 2013; Slagstad and Kirkland, 2017). In this paper we present new isotopic data 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 Lower Palaeozoic Caledonide orogen in NW Scotland (Fig. 2 inset) is dominated by the Neoproterozoic Moine Supergroup, 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 & 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-age collision and subsequent Ediacaran rifting of Rodinia to form the Iapetus

Ocean (Strachan et al., 2020a). 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 c. 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 critical evidence for high-pressure Grenville metamorphism in this segment of Rodinia, 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). 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 c. 1680-1630 Ma, which is largely absent on the Laurentian foreland, 2) eclogite-facies metamorphism occurred at c. 1180 Ma, at least c. 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.

2.1 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., 2020b, 2020a, 2010). 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 which 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 c. 2000 Ma on pre-existing orthogneisses of probable Neoarchean protolith age (Storey et al., 2010 and 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 c. 20 kbar and 730-750°C, consistent with burial to depths of c. 70 km. 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, 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 banded 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).

3.1 SAMPLE DESCRIPTIONS

Three samples were collected from the supracrustal sequence within the Eastern Unit of the Glenelg-Attadale, one from a garnet-kyanite-phengitic white mica pelite and two from eclogitic pods. The garnet-kyanite-phengitic pelite (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 (2002) 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, opaques and quite large rounded zircons (70µm). Zircons are also present within biotites where they have pleochroic halos. 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 veins/ streaks 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 dominant early fabric and has prominent lineations. 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, indicating non-coaxial shearing within the streaks. Garnets are up to 4 mm in size, extremely plentiful and quite inclusion-free with some alteration to amphibole around the rims. Inclusions, where present, consist of rutile, omphacite, quartz, zircon and opaques 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 garnet-clinopyroxene orthogneiss (AB-07-18) 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 often with some amphibole around the edges, and contain inclusions of clinopyroxene, rutile and opaques. The amphibole typically is replacing the clinopyroxene around grain rims and sometimes along cleavage planes. The plagioclase is multiple twinned and has inclusions of clinopyroxene.

4.1 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. 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. 4 A and E), suggesting that the Lu-Hf dates are likely to relate to garnet growth or close to peak metamorphism. AB07-12 and AB07-18 do not show zoning. As AB07-18 records granulite facies metamorphism, 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 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 pelite 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.

5.1 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 1039-1162 Ma, and have a strong positive correlation with Lu/Hf ratio and Lu content, and a negative correlation with Hf ($r2 = 0.9985$). Measured Hf contents in the dissolved garnet fractions range from 1 to 1.6 ppm, substantially higher than the 0.1ppm measured in the garnet by LA-ICP-MS, suggesting that Hf-bearing inclusions such as zircon were dissolved. Combining grt fractions 3 and 4 along with the fused whole rock gives a 3-point Lu-Hf isochron date of 1039.6 ± 3.7 Ma (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, in contrast to the Lu-Hf system, where they yield lower 2-point dates 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 zircon U-Pb Concordia age of 1648.8 ± 5.5 Ma (MSWD=9.1, n=24, all grains less than 15% discordant, Fig. 5C). 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 can 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).

The Borgie garnet-clinopyroxene orthogneiss sample (AB-07-18) 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 Lu-Hf model age for the sample and slightly younger than the Nd model age (1.9 Ga).

Samples from eclogite AB-07-09 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 (0.19-0.28ppm), suggesting minimal dissolution of Hf-bearing inclusions. The correlation likely indicates mixing between unidentified growth zones, implying core growth at >1218 Ma (see Supplementary Data 2 for graphs and more information), 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 a garnet from this rock, which has two Lu concentration peaks at around 1.2 and 0.8 ppm, comparable to the maximum 1.22 ppm and minimum 0.67 ppm Lu measured on the dissolved garnet fractions. Individual Sm-Nd two-point ages range from 949±8 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 1.9ppm 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 (3.8ppm) suggesting 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 1.4Ga.

Samples from eclogite AB-07-10 scatter around a six-point Lu-Hf garnet-whole rock errorchron of 1170 ± 21Ma (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±5Ma) 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 and 1218 ± 4 Ma.

6.1 DISCUSSION

6.1.1 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 c. 1600 Ma from the Borgie inlier, which was interpreted to represent a significant isotopic disturbance with further ~1600-1750 Ma dates recorded in the Rigibill, Loch Shin, Rosemarkie, Farr and Swordly inliers (Fig. 3). Together, the data suggest that a c. 1600-1700 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 c. 1870 Ma (Baba, 1998, Fig 5D), with subsequent events at c.

1750-1650 Ma restricted to amphibolite-facies reworking and minor magmatism and anatexis (Kinny et al., 2005; Wheeler et al., 2010). Whether the c. 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 c. 1202 Ma and c. 1218 Ma obtained from the Eastern Glenelg eclogites are c. 100 Ma older than the published Sm-Nd ages of c. 1010-1080 Ma (Sanders et al., 1984). 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 whereas Sm and Nd are more homogenous throughout the garnets as a whole (Supplementary Data 1). The Lu-Hf date from the Eastern Unit pelite (1039 Ma) is younger than the eclogite dates, perhaps reflecting a bigger influence from dissolved Hf-rich phases. The new Sm-Nd garnet and Rb-Sr white mica ages range from c. 1042 Ma to 943 Ma and probably result from two separate metamorphic events (Fig 5D). The two older ages of c. 1042 Ma (AB07-12, Rb-Sr white mica) and c. 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 c. 935 Ma (AB07-10) and c. 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 c. 950-940 Ma, which has been assigned to the onset of Valhalla accretionary orogenesis around the Laurentian margin of Rodinia (Cawood et al. 2010; Bird et al., 2018, Fig 5D).

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

Published c. 1010-1080 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 (<1300 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), 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). 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 c. 1200 Ma, and 2) the differences in metamorphic history between the NHT and the Laurentian foreland. A possible solution is found in tectonic models that propose a c. 90° rotation of Baltica relative to Laurentia between c. 1265 and 1000 Ma (Cawood and Pisarevsky, 2006). Prior to c. 1265 Ma, present-day west Norway faced south (present-day coordinates) and an open ocean, but by c. 1000 Ma it was juxtaposed against the sector of the Laurentian margin that contained Rockall Bank and the Laurentian foreland (Fig 1). One effect of this rotation was to open a new oceanic tract, the Asgard Sea, along the edge of Rodinia (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. 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 c. 1000 Ma. 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 partially subducted along a suture and then obducted back up the subduction channel. Differences in the ages of igneous protoliths and intrusive histories (Storey et al. 2010; Strachan et al. 2020a), and metamorphic events (this paper) between the NHT basement and the Laurentian foreland, suggests that they were separate crustal blocks until after c. 1600 Ma. We therefore suggest that: 1) the NHT represents a fragment of Archean-Paleoproterozoic crust that was reworked within the c. 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 c. 1000 Ma.

The c. 1000 Ma suture between the Laurentian foreland and the NHT is presumably located some distance (c. 100 kms?) 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 c. 1180 Ma Stoer Group (Parnell et al., 2011) 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 c. 1150 Ma in the northern Outer Hebrides (Cliff and Rex, 1995), and ^{40}Ar/^{39}Ar ages obtained from pseudotachylyte veins in the Outer Hebrides (c. 1200-1300 Ma) and on the Scottish mainland (c. 910-1019 Ma; Sherlock et al., 2008, 2009).

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 Ireland, and thence further east to link with its continuation in west Norway (Fig 6; e.g. Buchan et al., 2000). This does not explain the 1200-1000 Ma events in NW Scotland, which was probably located c. 500-700 km further north once late Caledonian strike-slip displacement along the Great Glen Fault is restored (Fig 6). 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. (2016). Grenville-aged metamorphism at c. 1050 Ma has been recorded in the Shetland Islands (Walker et al. 2020) although there is no reason to suppose that this arm of the orogen extended any further north.

REFERENCES CITED

Anczkiewicz, R., Viola, G., Müntener, O., Thirlwall, M.F., Villa, I.M., Quong, N.Q., 2007. Structure and shearing conditions in the Day Nui Con Voi massif: Implications for the evolution of the Red River shear zone in northern Vietnam. Tectonics 26, n/a-n/a. https://doi.org/10.1029/2006TC001972

Baba, S., 1998. Proterozoic anticlockwise P-T path of the Lewisian Complex of South Harris, Outer Hebrides, NW Scotland. J. Metamorph. Geol. 16, 819–841. https://doi.org/10.1111/j.1525-1314.1998.00163.x

Baker, T.R., Prave, A.R., Spencer, C.J., 2019. 1.99 Ga mafic magmatism in the Rona terrane of the Lewisian Gneiss Complex in Scotland. Precambrian Res. 329, 224–231. https://doi.org/10.1016/j.precamres.2018.12.027

Bergh, S.G., Corfu, F., Priyatkina, N., Kullerud, K., Myhre, P.I., 2015. Multiple post-Svecofennian 1750-1560Ma pegmatite dykes in Archaean-Palaeoproterozoic rocks of the West Troms Basement Complex, North Norway: Geological significance and regional implications.

Precambrian Res. 266, 425–439. https://doi.org/10.1016/j.precamres.2015.05.035

Bingen, B., Viola, G., Möller, C., Vander Auwera, J., Laurent, A., Yi, K., 2021. The Sveconorwegian orogeny. Gondwana Res. 90, 273–313. https://doi.org/10.1016/j.gr.2020.10.014

Bird, A.F., Thirlwall, M.F., Strachan, R.A., Manning, C.J., Holloway, R., Oex, E.T.W., 2013. Lu – Hf and Sm – Nd dating of metamorphic garnet : evidence for multiple accretion events during the Caledonian orogeny in Scotland 170, 301–317. https://doi.org/10.1144/jgs2012-083.Lu

Brown, M., 2007. Metamorphic conditions in orogenic belts: A record of secular change. Int. Geol. Rev. 49, 193–234. https://doi.org/10.2747/0020-6814.49.3.193

Buchan, K.L., Mertanen, S., Park, R.G., Pesonen, L.J., Abrahamsen, N., Bylund, G., 2000. Comparing the drift of Laurentia and Baltica in the Proterozoic : the importance of key palaeomagnetic poles 319, 167–198.

Cawood, P.A., Pisarevsky, S.A., 2017. Laurentia-Baltica-Amazonia relations during Rodinia assembly. Precambrian Res. 292, 386–397. https://doi.org/10.1016/j.precamres.2017.01.031

Corfu, F., Heaman, L.M., Rogers, G., 1994. Polymetamorphic evolution of the Lewisian complex, NW Scotland, as recorded by U-Pb isotopic compositions of zircon, titanite and rutile. Contrib. to Mineral. Petrol. 117, 215–228. https://doi.org/10.1007/BF00310864

Crowley, Q.G., Key, R., Noble, S.R., 2015. High-precision U-Pb dating of complex zircon from the Lewisian Gneiss Complex of Scotland using an incremental CA-ID-TIMS approach. Gondwana Res. 27, 1381–1391. https://doi.org/10.1016/j.gr.2014.04.001

Daly, J.S., 1996. Pre-Caledonian History of the Annagh Gneiss Complex North-Western Ireland , and Correlation with Laurentia-Baltica Author (s): J . Stephen Daly Source : Irish Journal of Earth Sciences , 1996 , Vol . 15 (1996), pp . 5-18 Published by : Royal Irish Aca. Irish J. Earth Sci. 15, 5–18.

Daly, J.S., 1991. A precise U-Pb zircon age for the Inishtrahull syenitic gneiss, County Donegal, Ireland. J. Geol. Soc. London. 148, 639–642. https://doi.org/10.1144/gsjgs.148.4.0639

Davies, J.H.F.L., Heaman, L.M., 2014. New U-Pb baddeleyite and zircon ages for the Scourie dyke swarm: A long-lived large igneous province with implications for the Paleoproterozoic evolution of NW Scotland. Precambrian Res. 249, 180–198. https://doi.org/10.1016/j.precamres.2014.05.007

Fischer, S., Prave, A.R., Johnson, T.E., Cawood, P.A., Hawkesworth, C.J., Horstwood, M.S.A., EIMF, 2021. Using zircon in mafic migmatites to disentangle complex high-grade gneiss terrains – Terrane spotting in the Lewisian complex, NW Scotland. Precambrian Res. 355, 106074. https://doi.org/10.1016/j.precamres.2020.106074

Friend, C.R.L., Strachan, R. a., Kinny, P.D., 2008. U-Pb zircon dating of basement inliers within the Moine Supergroup, Scottish Caledonides: implications of Archaean protolith ages. J. Geol. Soc. London. 165, 807–815. https://doi.org/10.1144/0016-76492007-125

Holdsworth, R.E., Strachan, R.A. & Alsop, G.I. 2001. *Geology of the Tongue District.* Memoir of the British Geological Survey, HMSO.

Love, G.J., Kinny, P.D., Friend, C.R.L., 2004. Timing of magmatism and metamorphism in the Gruinard Bay area of the Lewisian Gneiss Complex: Comparisons with the Assynt Terrane and implications for terrane accretion. Contrib. to Mineral. Petrol. 146, 620–636. https://doi.org/10.1007/s00410-003-0519-1

Mendum, J.R., Noble, S.R., 2010. Mid-Devonian sinistral transpressional movements on the Great Glen Fault: The rise of the Rosemarkie Inlier and the Acadian event in Scotland. Geol. Soc. Spec. Publ. 335, 161–187. https://doi.org/10.1144/SP335.8

Rawson, J.R., Carswell, D.A., Smallwood, D., 2001. Garnet-bearing olivine-websterite within the Eastern Glenelg Lewisian of the Glenelg Inlier, NW Highlands. Scottish J. Geol. 37, 27–34. https://doi.org/10.1144/sjg37010027

Sanders, I.S., 1989. Phase relations and P-T conditions for eclogite-facies rocks at Glenelg, north-west Scotland. Geol. Soc. London, Spec. Publ. 43, 513–517. https://doi.org/10.1144/GSL.SP.1989.043.01.49

Sanders, I.S., van Calstreren, P.W.C., Hawkesworth, C.J., 1984. A Grenville Sm–Nd age for the Glenelg eclogite in north-west Scotland. Lett. to Nat. 312.

Scherer, E.E., Cameron, K.L., Blichert-Toft, J., 2000. Lu – Hf garnet geochronology : Closure temperature relative to the Sm – Nd system and the effects of trace mineral inclusions. Geochim. Cosmochim. Acta 64, 3413–3432.

Slagstad, T., Kirkland, C.L., 2017. The use of detrital zircon data in terrane analysis: A nonunique answer to provenance and tectonostratigraphic position in the Scandinavian Caledonides. Lithosphere 9, 1002–1011. https://doi.org/10.1130/L663.1

Slagstad, T., Kulakov, E., Kirkland, C.L., Roberts, N.M.W., Ganerød, M., 2019. Breaking the Grenville–Sveconorwegian link in Rodinia reconstructions. Terra Nov. 31, 430–437. https://doi.org/10.1111/ter.12406

Slagstad, T., Roberts, N.M.W., Marker, M., Røhr, T.S., Schiellerup, H., 2013. A non-collisional, accretionary Sveconorwegian orogen. Terra Nov. 25, 30–37. https://doi.org/10.1111/ter.12001

Smit, M.A., Scherer, E.E., Mezger, K., 2013. Lu-Hf and Sm-Nd garnet geochronology: Chronometric closure and implications for dating petrological processes. Earth Planet. Sci. Lett. 381, 222–233. https://doi.org/10.1016/j.epsl.2013.08.046

Stewart, A.D., 2002. The Later Proterozoic Torridonian Rocks of Scotland: Their Sedimentary, Geochemistry and Origin. Geological Society of London, Issue 24 of Memoir.

Storey, C.D., Brewer, T.S., Anczkiewicz, R., Parrish, R.R., Thirlwall, M.F., 2010. Multiple high-pressure metamorphic events and crustal telescoping in the NW Highlands of Scotland. J. Geol. Soc. London. 167, 455–468. https://doi.org/10.1144/0016-76492009-024

Strachan, R.A., Alsop, G.I., Ramezani, J., Frazer, R.E., Burns, I.M., Holdsworth, R.E., 2020a. Patterns of silurian deformation and magmatism during sinistral oblique convergence, northern scottish caledonides. J. Geol. Soc. London. 177, 893–910. https://doi.org/10.1144/jgs2020-039

Strachan, R.A., Holdsworth, R.E., Krabbendam, M., Alsop, G.I., House, M., Rd, W.M., Andrews, S., 2010. The Moine Supergroup of NW Scotland : insights into the analysis of polyorogenic supracrustal sequences. Geol. Soc. London, Spec. Publ.

Strachan, R.A., Johnson, T.E., Kirkland, C.L., Kinny, P.D., Kusky, T., 2020b. A Baltic heritage in Scotland: Basement terrane transfer during the Grenvillian orogeny. Geology 48, 1094–1098. https://doi.org/10.1130/G47615.1

Weller, O.M., 2017. Record of modern-style plate tectonics in the. https://doi.org/10.1038/NGEO2904

7.1 Acknowledgements

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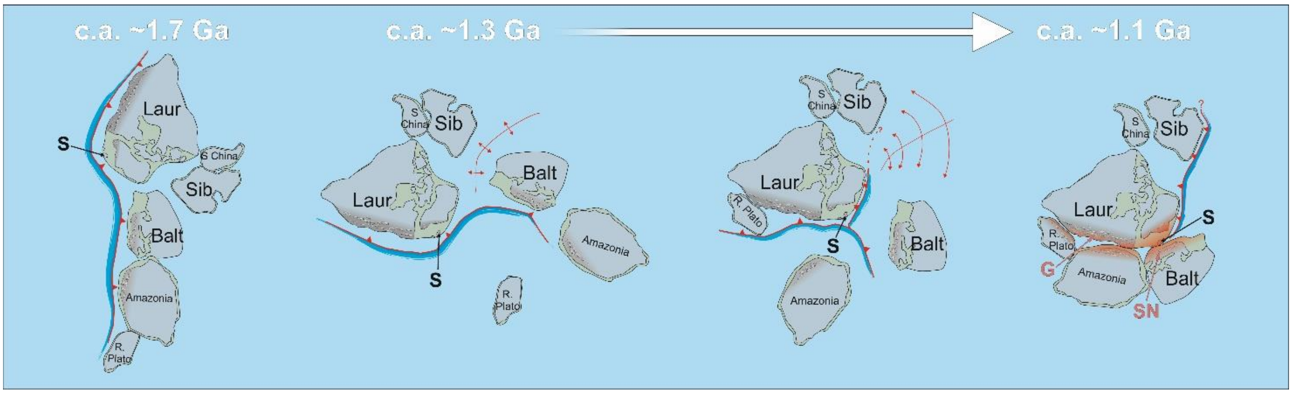

Figure 1 Schematic plate reconstruction of the amalgamation of Rodina from 1.7 G.a. to 1.1 G.a. based on the reconstructions of, Li et al. 2008, Perhssson et al 2016, Cawood et al. 2016 and Cawood & Pisarevsky 2017. Laur = laurentia, S= Scotland, S China = South China Craton, Sib = Siberian cranon, Balt = 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 = ~1.1G.a. orogenesis.

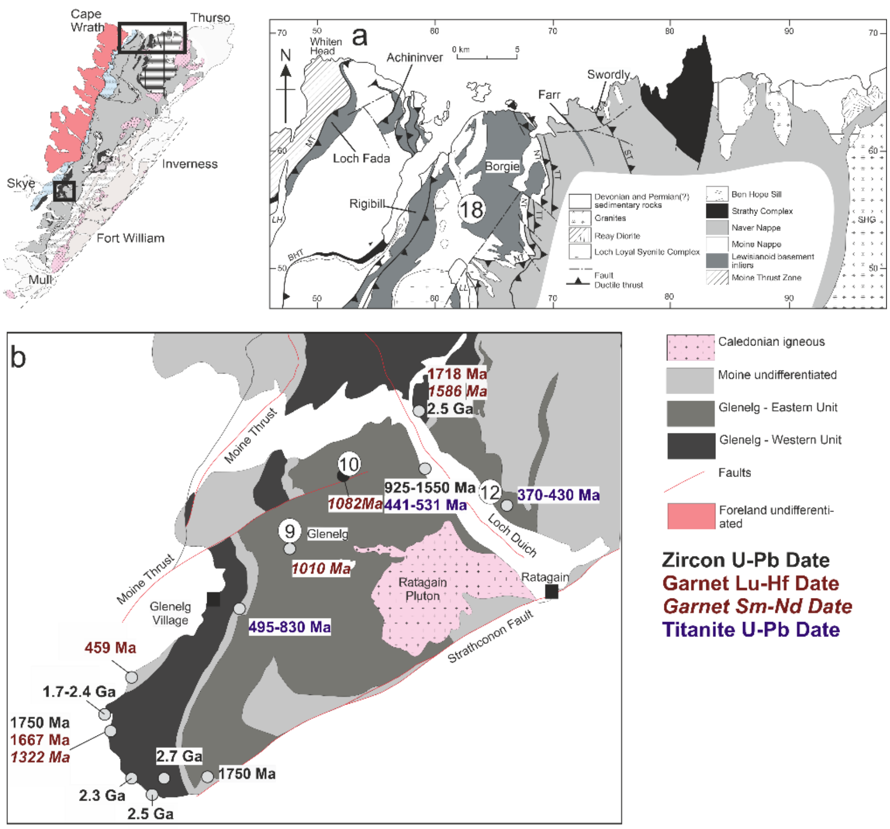

Figure 2 Simplified map of the Northern Highlands, Scotland and study areas. Fig. 2a shows the geology of Northern Sutherland and the location of the Borgie and other inliers mentioned within the text. Fig. 2b shows the geology of the Glenelg region and the locations of samples with published data and locations of the samples within this study.

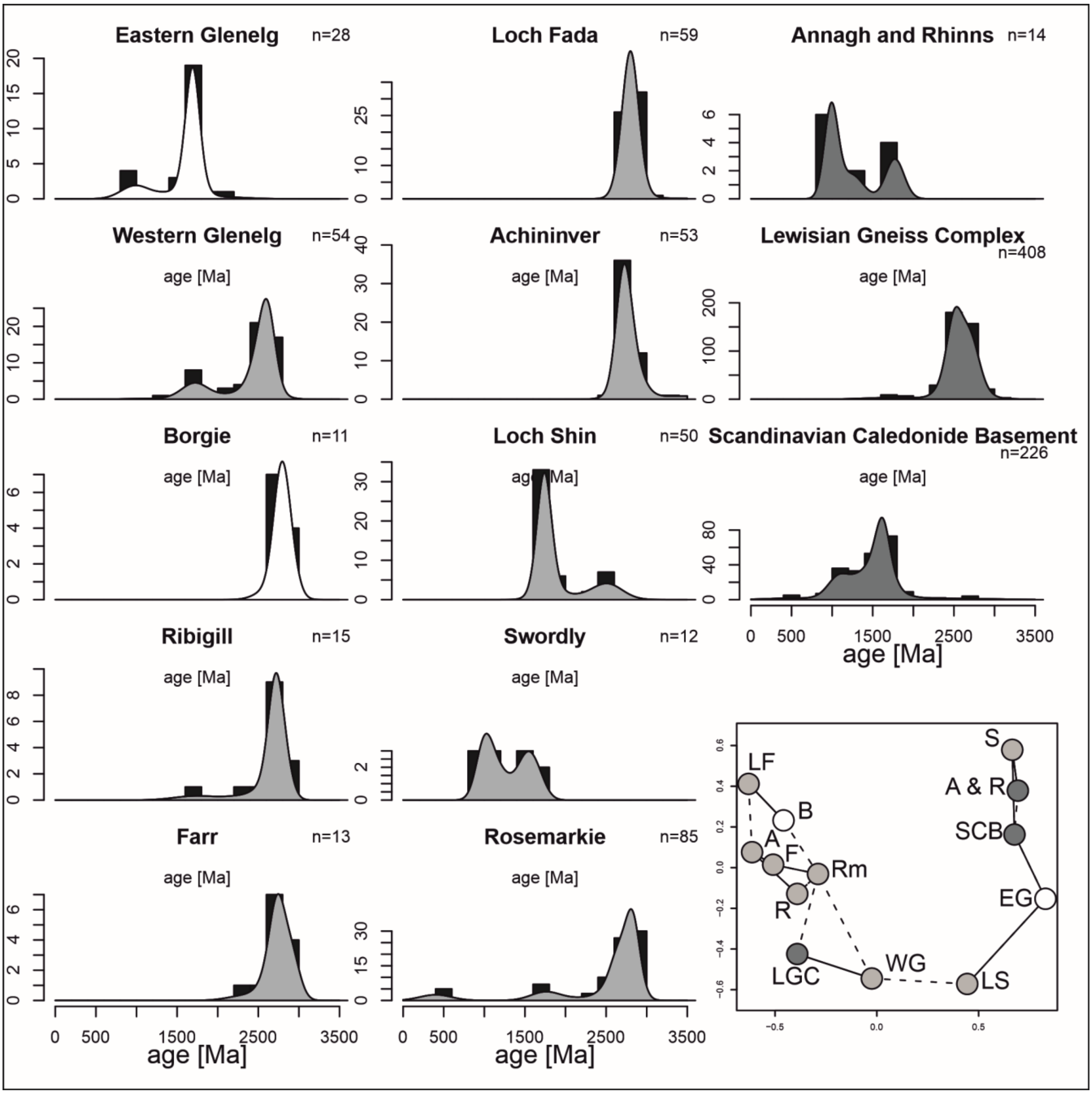

Figure 3 Zircon U-Pb dates for the inliers from Friend et al., 2008; Strachan et al., 2020a; Storey et al., 2010; Brewer et al., 2003; Mendum and Noble, 2010 . The dates from the Lewisian Gneiss Complex are only from mainland Scotland and are from Baker et al., 2019; Corfu et al., 1994; Crowley et al., 2015; Davies and Heaman, 2014; Fischer et al., 2021; Love et al., 2004. Irish dates are from Daly, 1996, 1991. 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).

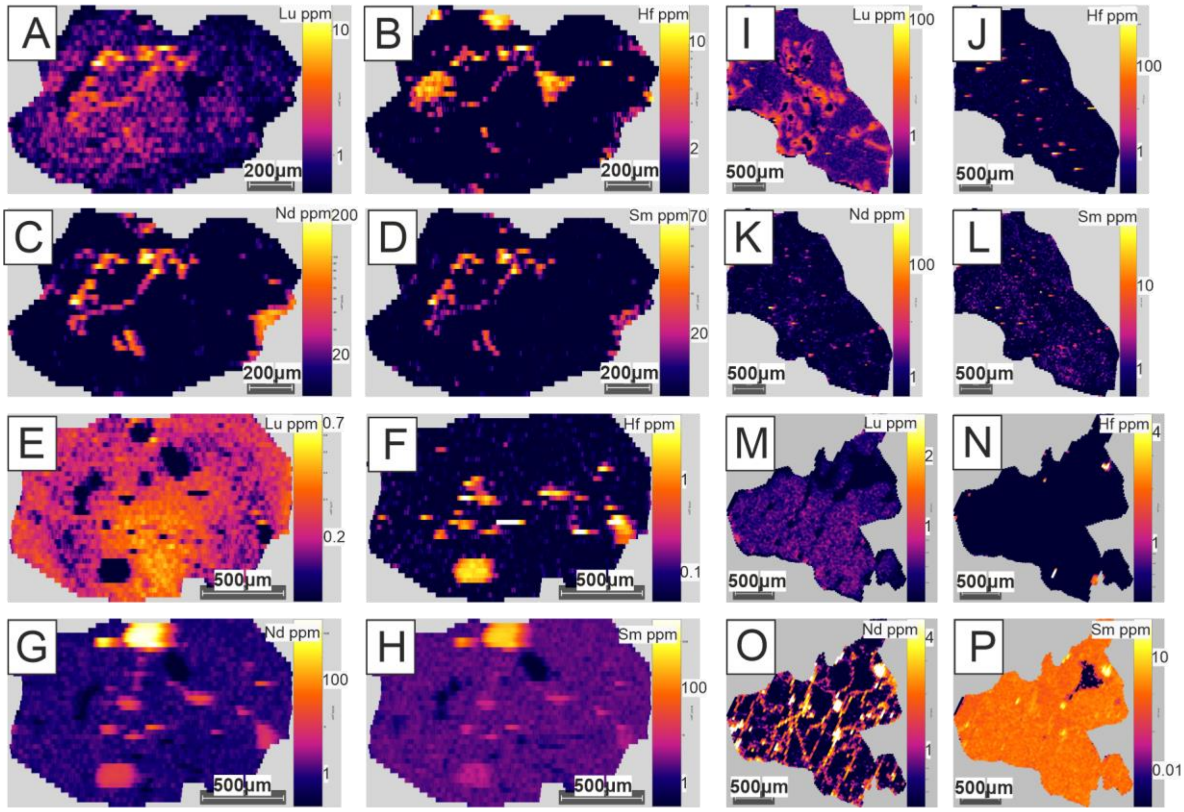
A
Lu ppm
10
1
200µm
B
Hf ppm
10
2
200µm
I
Lu ppm
100
1
500µm
J
Hf ppm
100
1
500µm
C
Nd ppm
200
20
200µm
D
Sm ppm
70
20
200µm
K
Nd ppm
100
1
500µm
L
Sm ppm
10
1
500µm
E
Lu ppm
0.7
0.2
500µm
F
Hf ppm
1
0.1
500µm
M
Lu ppm
2
1
500µm
N
Hf ppm
4
1
500µm
G
Nd ppm
100
1
500µm
H
Sm ppm
100
1
500µm
O
Nd ppm
4
1
500µm
P
Sm ppm
10
0.01
500µm

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

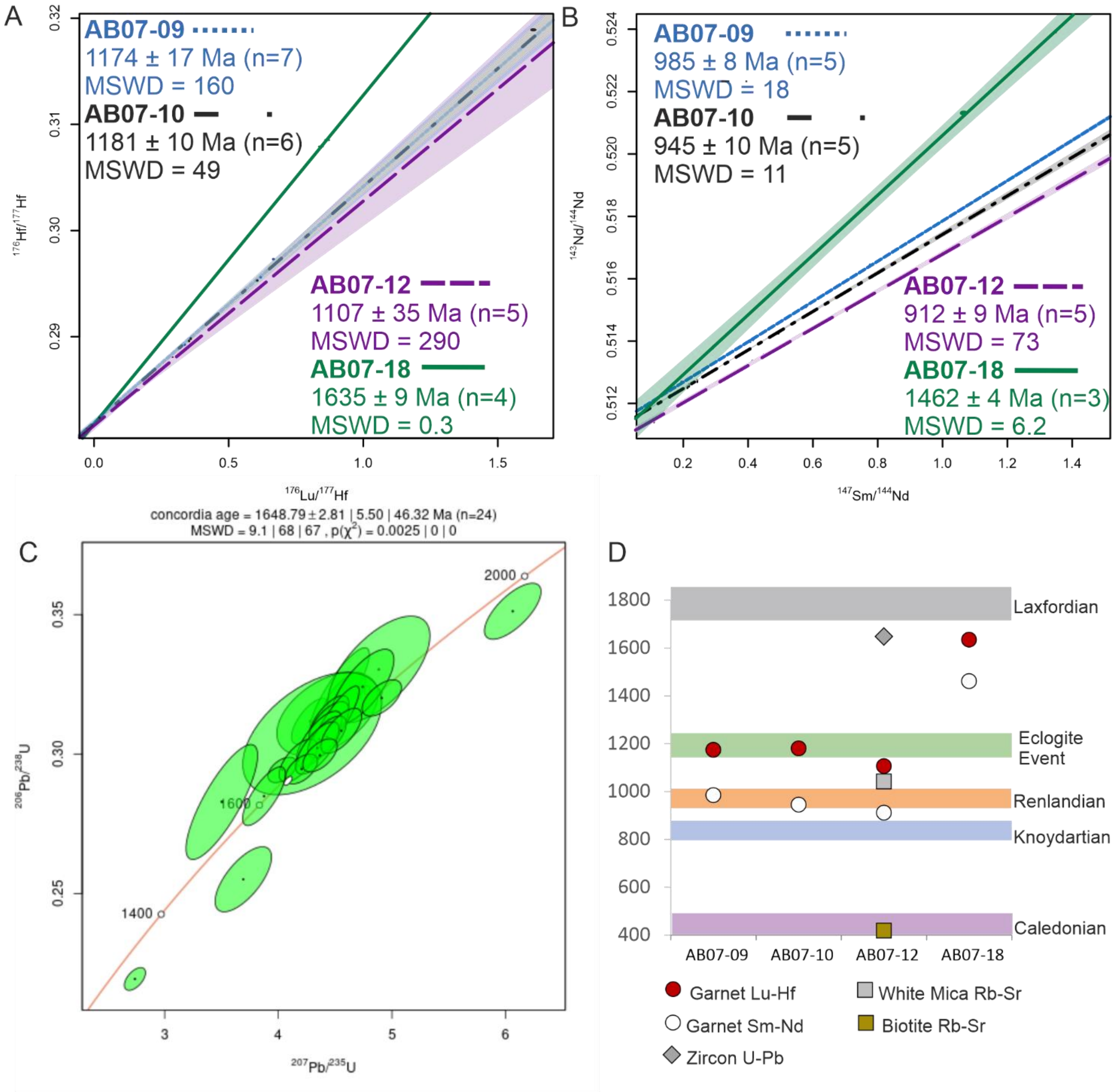

Figure 5 A – garnet Lu-Hf data; B - garnet Sm-Nd data; C - zircon U-Pb dates; D - summary plot relating new dates to known orogenic episode.

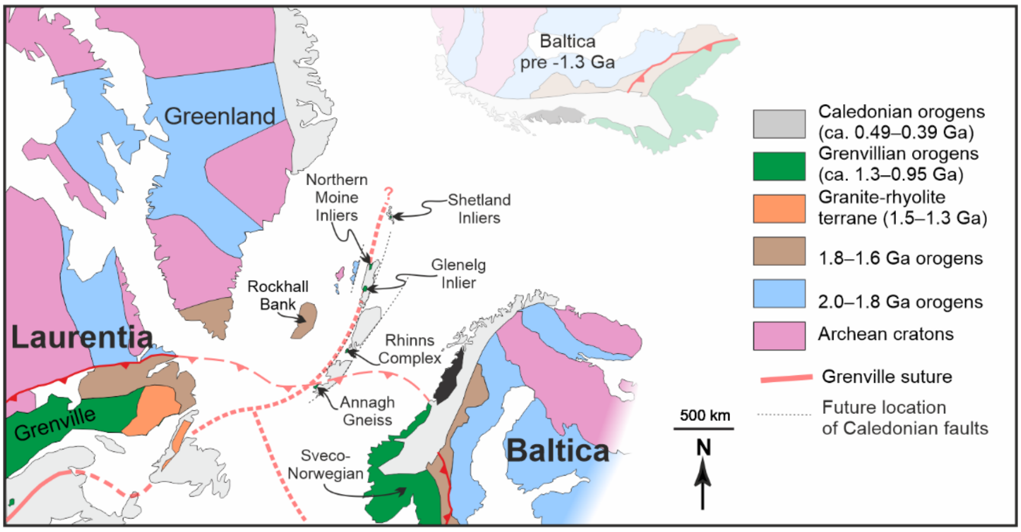

Figure 6 Distribution of orogenic events on the north Atlantic region as distributed at the end of the Grenville orogeny (modified from Cawood et al 2010) with the position of Baltic prior to the Grenville orogeny also shown (semi-transparent). Location of NHT inliers indicates the revised northern extent of Grenville orogenesis.

8.1 Supplementary Data 1

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

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4. Geochronology and Tracers Facility, British Geological Survey, Keyworth, Nottinghamshire, NG12 5GG

SUPPLEMENTARY DATA

Trace Element LA ICPMS Analyses – University of Hull

Laboratory and Sample Preparation	
Laboratory name	Geography, Geology and Environment, University of Hull
Sample type/mineral	Metamorphic thick sections
Sample preparation	Polished sections

Imaging	Thin Section photos and scans
Laser ablation system	
Make, Model and type	Applied Spectra, RESOlution-SE 193nm
Ablation cell and volume	Laurin Technic S155 two volumn cell
Laser wavelength	193 nm
Pulse width (ns)	5 ns
Fluence (J cm-2)	2.5 J sm-2
Repition rate (Hz)	10 Hz
Ablation duration (s)	30s
Spot diameter	30 microns
Sample mode/pattern	Raster - Scan Speed 0.002cm/s
Carrier gas	He + N2 in the cell, Ar carrier gas to torch
ICP-MS Instrument	
Make, Model and type	Agilent 8800
Sample introduction	Ablation aerosol mixed with Ar and sent to ICP-Ms
RF power (w)	1170 W
Nebuliser gas flow	Ar 0.90 l min-1
Detection system	Electron multiplier in counts per second mode
Masses measured	Mg25, Si29, P31, K39, Ca43, Ti47, Cr52, Fe56, Rb85, Sr88, Y89, Zr90, Ce140, Nd146, Sm146, Eu153, Gd157, Dy163, Yb172, Lu175, Hf178, Pb206, Pb207, U235, U238
Integration time	56 = 0.0005, 90 = 0.002, 89 = 0.003, 25, 31, 39, 29 = 0.004, 88 = 0.005, 85, 43 = 0.006, 52 = 0.008, 147 = 0.015, 235, 238, 206, 178, 208, 47, 207= 0.02, 140 = 0.04, 175, 153, 157, 163, 172 = 0.05,
Data Processing	
Calibration strategy	Si content used as normalisation channel. 610 and 612 used as secondaries/validation
Reference Material Information	NIST610 and NIST612
Data processing package	Iolite v4, Cellspace, Semi-Quant (Woodhead et al., 2007; Paton et al., 2011; Paul et al., 2012)
Common Pb correction	No common Pb correction applied to this data

LA ICPMS Elemental Maps

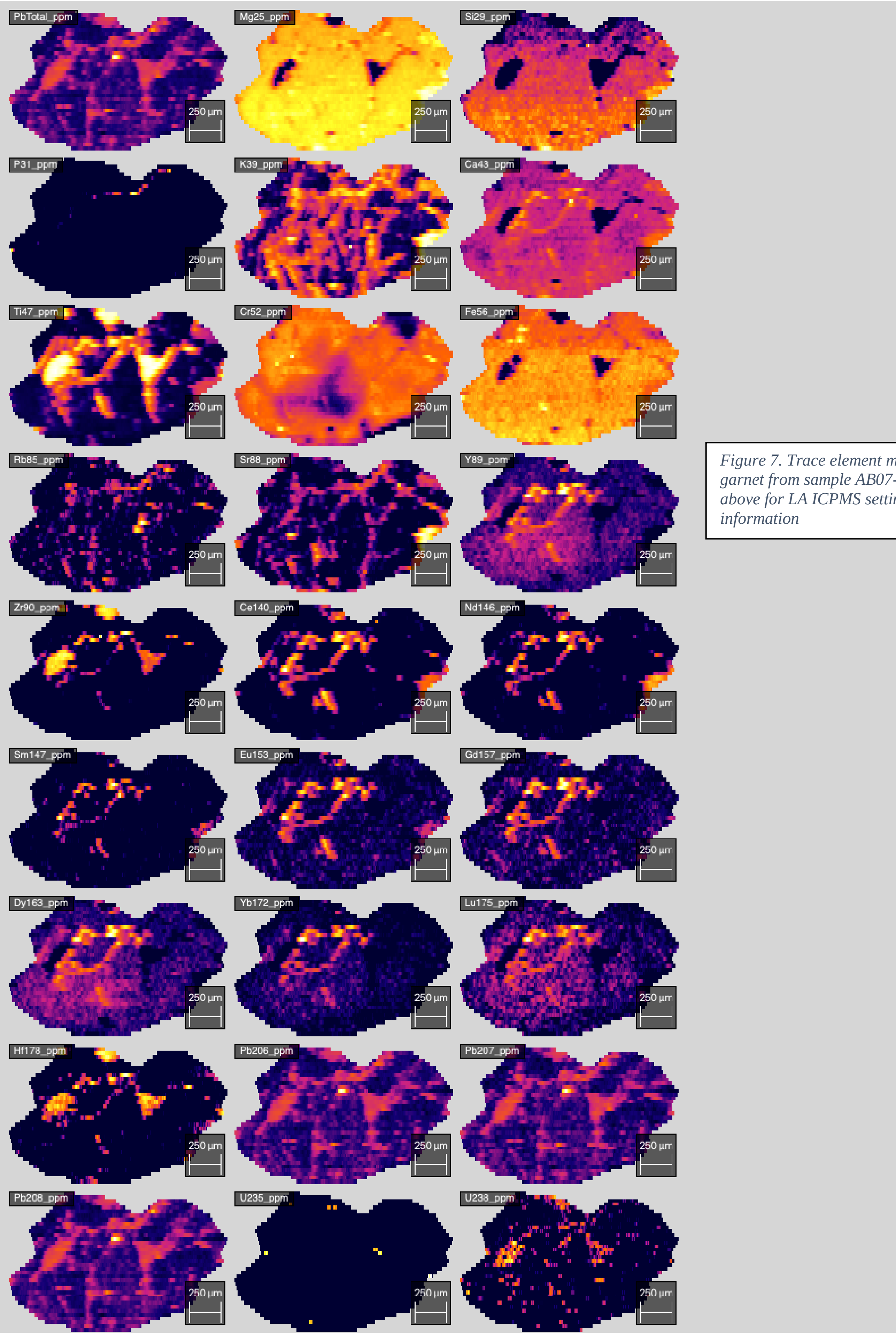


Figure 7. Trace element maps from a garnet from sample AB07-09, see above for LA ICPMS settings and DRS information

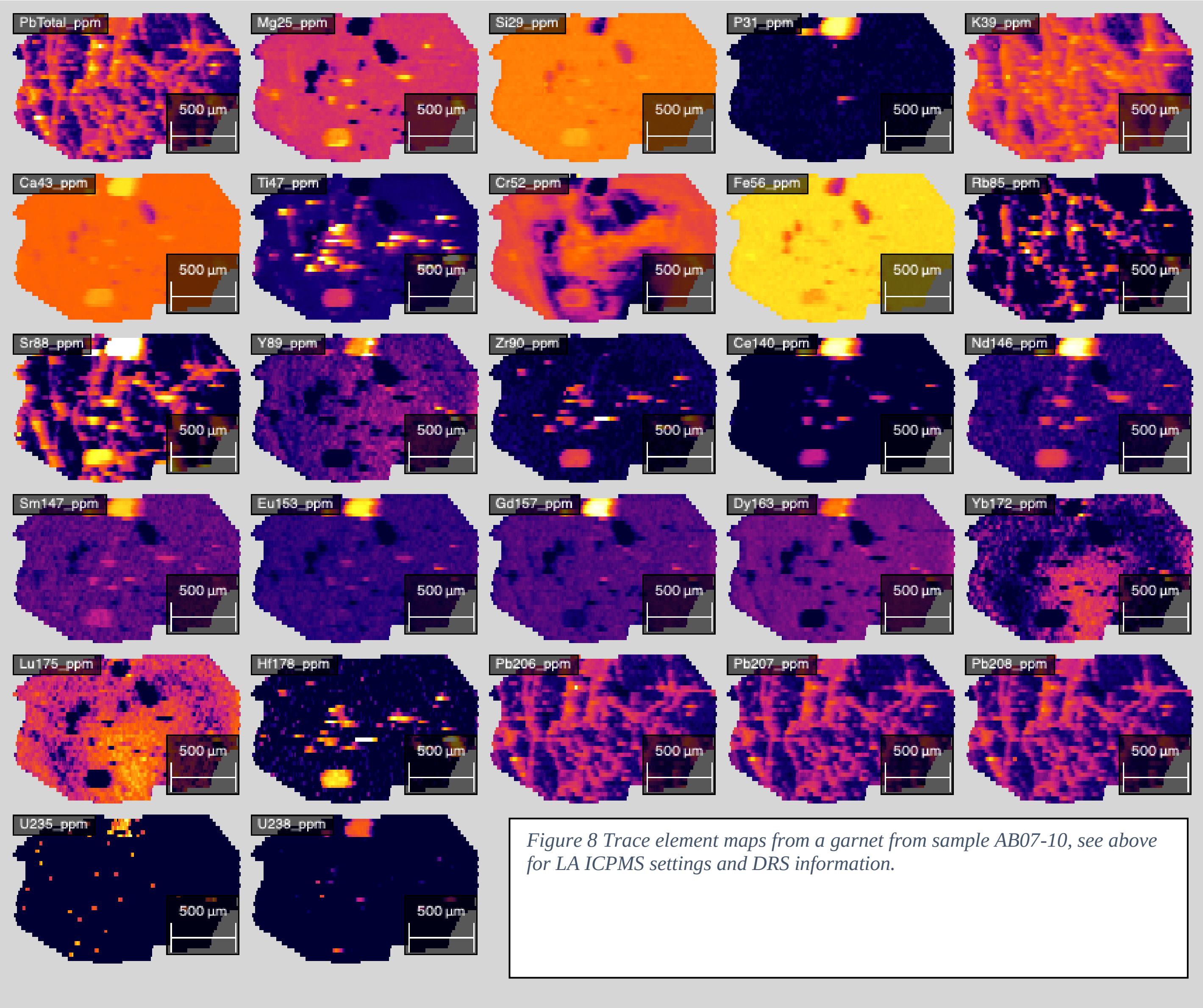
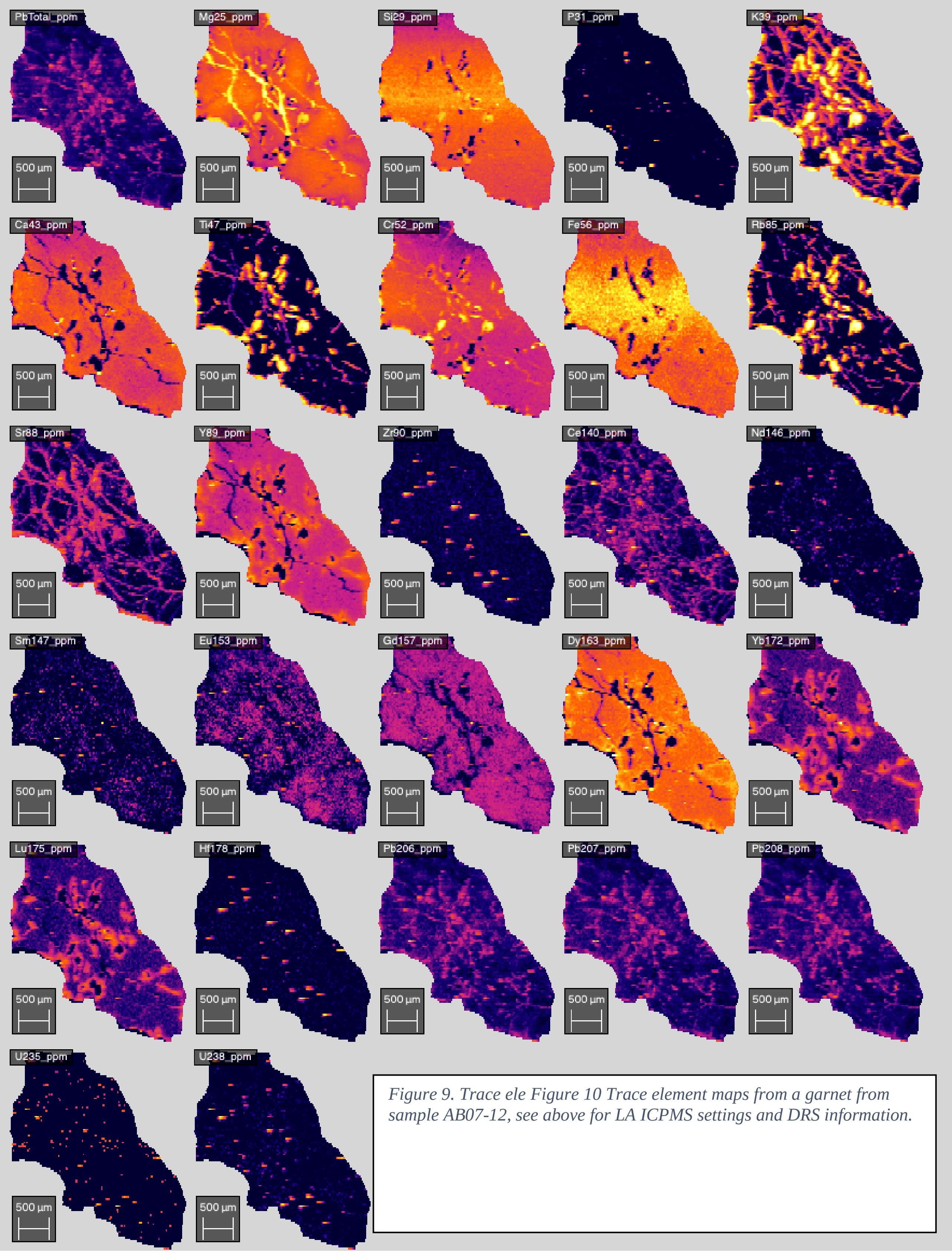


Figure 8 Trace element maps from a garnet from sample AB07-10, see above for LA ICPMS settings and DRS information.



474 *Figure 9. Trace ele Figure 10 Trace element maps from a garnet from sample AB07-12, see above for LA ICPMS settings and DRS information.*

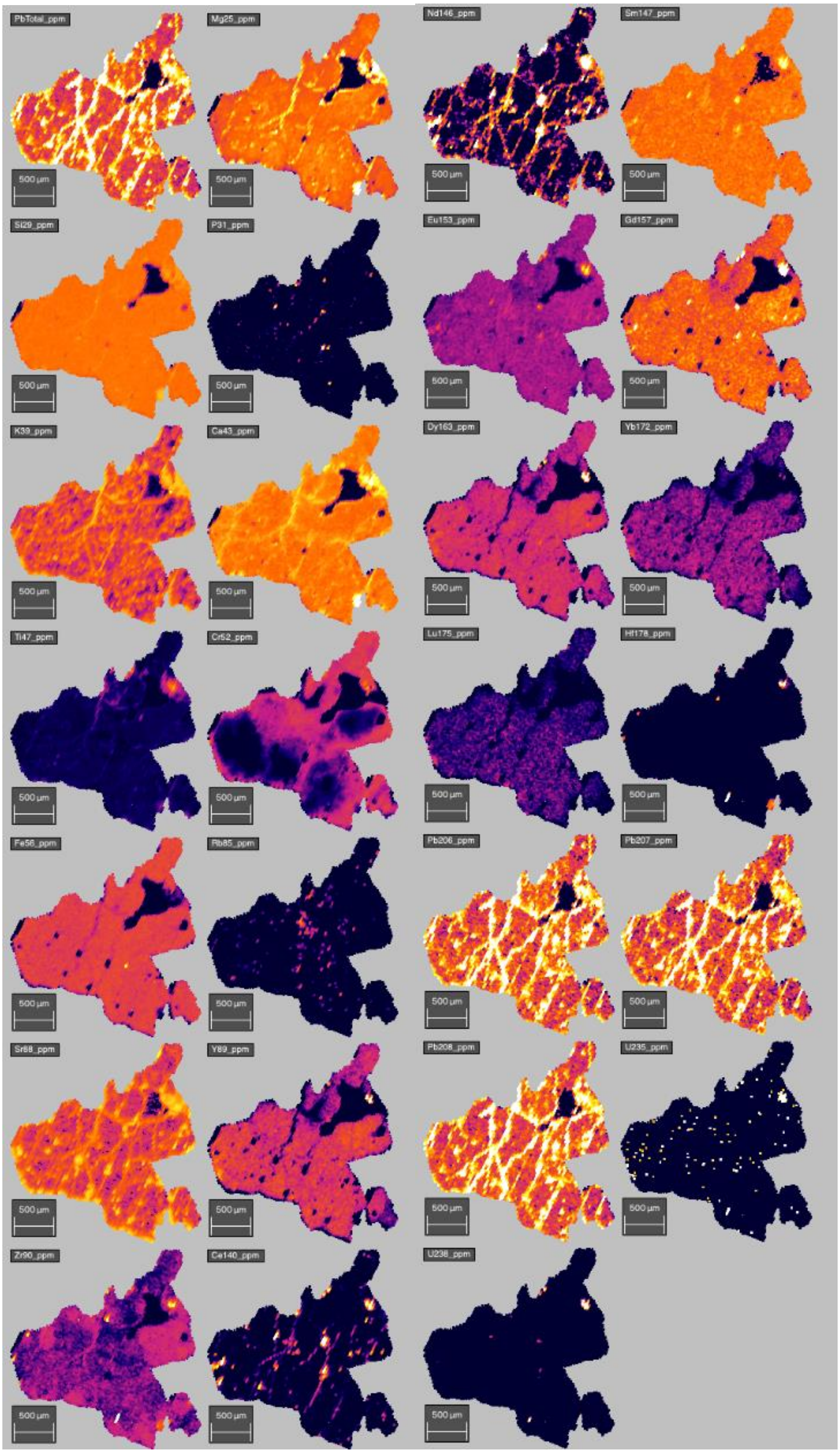


Figure 11. Trace element maps from a garnet from sample AB07-18, see above for LA ICPMS settings and DRS information

LA ICPMS U-Pb Analyses – British Geological Survey

Laboratory and Sample Preparation	
Laboratory name	Geochronology & Tracers Facility, BGS, Keyworth, UK
Sample type/mineral	Zircon grains
Sample preparation	Conventional mineral separation, 1-inch resin mount, 1μm polish to finish
Imaging	Photos

Laser ablation system	
Make, Model and type	ESI/New Wave Research, UP193SS
Ablation cell and volume	NIGL low volume cell, with low effective volume (ca. 3-4 cm^3), washout time ca. 1 sec
Laser wavelength	193 nm
Pulse width (ns)	3-4 ns
Fluence (J cm-2)	2.6 J cm^2
Repition rate (Hz)	10 Hz
Ablation duration (s)	30 s
Spot diameter	35 microns
Sample mode/pattern	Static spot ablation
Carrier gas	0.6 l/min

ICP-MS Instrument	
Make, Model and type	Nu Instruments Attom SC-ICP-MS
Sample introduction	Free air aspiration of desolvator
RF power (w)	1300W
Nebuliser gas flow	0.70 l min-1
Detection system	Discrete dynode MassCom ion counter
Masses measured	Pb204, Pb206, Pb207, Pb208, Th232, U235, U238
Integration time per peak	ca. 200 ms
Integration time/reading	Ca.1 sec
Sensitivity	Not determined
IC Dead time (ns)	15 ns

Data Processing	
Gas blank	>30 second on-peak zero subtracted
Calibration strategy	91500 used as primary reference materil and GJ1 and Plesovic used as secondaries/validation
Reference Material Information	91500 (Wiedenbeck et al. 1995) Plešovice (Sláma et al. 2008), GJ-1 (Horstwood et al. 2016).
Data processing package	Nu Instruments TRA acquisition software, In-house spreadsheet.
Common Pb correction	No common Pb correction applied to this data

Lu-Hf, Sm-Nd and Rb-Sr analyses – RHUL

Samples were crushed in a steel jaw-crusher to chips of < $1cm^3$. A fraction of this crushed material was saved for whole rock analysis, which was powdered in a tungsten carbide TEMA mill ready for XRF and isotopic analysis. The X-ray fluorescence (XRF) analyses were also undertaken at Royal

Holloway using the methods described by Thirlwall et al. (2000). This remaining material was sieved to different grain sizes, washed repeatedly in de-ionised water, and magnetically separated using a Frantz isodynamic separator. Garnets and other mineral fractions were handpicked under a binocular microscope from the 250-500µm magnetic fraction, taking care to pick only grains that were visibly inclusion-free. Mica fractions were then ground in an agate pestle and mortar under methanol, washed in MQ water, and further sieved between 200 and 75µm to remove non-mica impurities, then picked under a binocular microscope from the <250µm fraction. The garnet fractions underwent a moderate leaching procedure using sulfuric acid, (Anczkiewicz & Thirlwall 2003; Bird et al 2013; Walker et al 2020), this dissolves phosphate inclusions that can negatively affect Sm-Nd ages.

Amounts of mixed $^{176}Lu/^{180}Hf$, $^{149}Sm/^{150}Nd$ and $^{87}Rb/^{84}Sr$ spike spikes for mineral separates and whole-rocks were estimated using concentrations of these elements, and of analogues such as Y and Zr, from LA-ICPMS and XRF respectively. Leaching, spiking, dissolution, and chemical separation procedures were those of Anczkiewicz & Thirlwall (2003), Bird et al. (2013), Walker et al (2016; 2020) with concentrations and isotopic data being determined on the same aliquot.

A $HF-HNO_3$ digestion procedure was utilized for all fractions in sealed beakers on a hotplate, followed by a dissolution in 6M HCl for the garnet fractions. This minimizes dissolution of refractory zircon inclusions, which can worsen the precision of Lu-Hf ages, as they have very high Hf concentrations. Further, detrital zircons in metasediments can be much older than the surrounding garnets, which may artificially skew the age of any mixtures of garnets and zircons (Anczkiewicz et al. 2004).

For the whole-rock fractions analysed for Lu-Hf, we treated one fraction in the same manner as the garnets (table-top dissolution using $HF-HNO_3$), and a second whole-rock powder fraction was fused for one hour at 1100°C in Pt-Au crucibles in a 1:3 ratio with lithium tetraborate flux. Glass fragments were then spiked and subjected to the normal Lu-Hf dissolution and chemical separation. The samples were first passed through AG50W-X8 cation resin to separate high field strength elements (HFSE), light rare earth elements (LREE) and heavy rare earth elements (HREE) fractions. The HFSE fraction required a second pass through these columns to minimise the HREE that may be in the fraction. The fractions were individually passed through Eichrom LN resin to separate respectively Hf, Sm and Nd, and Lu. Total procedure blanks were typically 24pg for Hf and 23pg for Nd. Sr was separated using Eichrom Sr-spec resin, and Rb was separated from K using 0.5M HNO3 on Bio-rad AG50W-X8 cation exchange resin.

Lu, Hf, Sm Nd and Rb isotopic analyses were undertaken on the GV Instruments IsoProbe MC-ICPMS at RHUL using methods outlined in Thirlwall & Anczkiewicz (2004), Bird et al (2013) and Walker et al 2016; 2020.

During the course of the study the Hf standard JMC475 analysed on the RHUL IsoProbe yielded an average (static) ^{176}Hf/^{177}Hf of 0.282182±12 and ^{180}Hf/^{177}Hf of 1.88683±17 (2sd, n=36), with no significant change with time. All sample data were corrected to the accepted JMC475 ^{176}Hf/^{177}Hf value of 0.282165 (Scherer et al. 2000).

In contrast to Hf, Nd standard isotope ratios can vary significantly between analytical sessions (Thirlwall and Anczkiewicz 2004), although the effect of this on ages was minimized by analyzing all fractions relating to a sample during one analytical session. The Aldrich Nd and mixed Ce-Nd standard solutions yielded ^{142}Nd/^{144}Nd of 1.141461±239 and a slope corrected (see Thirlwall & Anczkiewicz 2004) ^{143}Nd/^{144}Nd of 0.511408±14 (2sd, n=97). The uncertainty on the ^{176}Lu/^{177}Hf ratio is less than 0.3% and assumed to be 0.3% in age calculations. The uncertainty on the ^{147}Sm/^{144}Nd is less than 0.1% and assumed to be 0.1% in age calculations.

Correction of mass fractionation of Rb used methods described in Walker et al 2016, this technique allows for the correction of the mass fractionation of Rb using Zr, leading to higher precision compared with conventional TIMS analysis, where mass fractionation correction possibilities are limited (Halliday et al 1998; Waight *et al.* 2002). Uncertainties on Rb/Sr ratios were monitored using the method described in Walker et al, 2016, modified from Waight *et al.* (2002), where the normalizing Zr ratios (^{92}Zr/^{90}Zr and ^{91}Zr/^{90}Zr) was used to correct for Rb mass fractionation are determined daily using the Sr standard SRM987 admixed with Zr (see Charlier *et al.* 2006). The Rb standard SRM984 was analysed at least every four samples during analytical sessions (*n* = 31 for the duration of this study), to test the accuracy and precision of this technique.

Analysed for Sr isotopes by TIMS were undertaken on a VG354 system. Isotope ratios and concentrations were determined using a multidynamic method modified from Thirlwall (1991). The accuracy and reproducibility of Sr isotope data were monitored using the external standard SRM987. During the course of this study, 87Sr/86Sr of SRM987 was 0.710256 ± 19 2SD. Total procedural blanks for Sr were typically less than 0.2% (0.5 ng) of the analyte mass, and hence a blank correction has no significant effect on ages presented. The ^{87}Rb/^{86}Sr uncertainty used in age calculations was taken as 0.3% (2σ), although this is likely to be an overestimate.

Isochron ages and uncertainties were calculated using IsoplotR (Vermeesch, 2018), using the decay constants of 1.865 x 10^{-11} a^{-1} for ^{176}Lu (Scherer et al. 2001), 6.524 x 10^{-12} a^{-1} for ^{147}Sm (Villa et al 2020), and 1.3792 x $10^{-11}a^{-1}$ for ^{87}Rb (Villa *et al.* 2015). All isotope data and age uncertainties are quoted at the 2-sigma level and uncertainties from Nd and Hf standards have been propagated into the date calculations.

REFERENCES CITED

Anczkiewicz, R., & Thirlwall, M. F. (2003). Improving precision of Sm-Nd garnet dating by H2SO4 leaching: a simple 815 solution to the phosphate inclusion problem. Journal of the Geological Society, London, 220, 83–91.

Anczkiewicz, R., Platt, J. P., Thirlwall, M. F., & Wakabayashi, J. (2004). Franciscan subduction off to a slow start: 817 evidence from high-precision Lu–Hf garnet ages on high grade-blocks. Earth and Planetary Science Letters, 225(1–2), 147–161. https://doi.org/10.1016/j.epsl.2004.06.003

Baxter, E. F., Ague, J. J., & Depaolo, D. J. 2000. Prograde temperature – time evolution in the Barrovian type – 825 locality constrained by Sm / Nd garnet ages from Glen Clova, Scotland. Journal of the Geological Society, London, 159(1985), 71–82.

Bird, A.F., Thirlwall, M.F., Strachan, R.A., Manning, C.J., Holloway, R., Oex, E.T.W., 2013. Lu – Hf and Sm – Nd dating of metamorphic garnet : evidence for multiple accretion events during the Caledonian orogeny in Scotland 170, 301–317. doi:10.1144/jgs2012-083.Lu

B.L.A. Charlier, C. Ginibre, D. Morgan, G.M. Nowell, D.G. Pearson, J.P. Davidson, C.J. Ottley. 2006. Methods for the microsampling and high-precision analysis of strontium and rubidium isotopes at single crystal scale for petrological and geochronological applications, Chemical Geology, Volume 232, Issues 3–4, 2, Pages 114-133

Alex N. Halliday, Der-Chuen Lee, John N. Christensen, Mark Rehkämper, Wen Yi, Xiaozhong Luo, Chris M. Hall, Chris J. Ballentine, Thomas Pettke, Claudine Stirling. 1998. Applications of multiple collector-ICPMS to cosmochemistry, geochemistry, and paleoceanography. Geochimica et Cosmochimica Acta, 62, 919–940.

Scherer, E.E., Cameron, K.L., Blichert-Toft, J., 2000. Lu – Hf garnet geochronology : Closure temperature relative to the Sm – Nd system and the effects of trace mineral inclusions. Geochim. Cosmochim. Acta 64, 3413–3432.

Thirlwall, M.F. 1991. Long-term reproducibility of multicollector Sr and Nd isotope ratio analysis. Chemical Geology, 94, 85–104.

Thirlwall, M. F., & Anczkiewicz, R. 2004. Multidynamic isotope ratio analysis using MC–ICP–MS and the causes of secular drift in Hf, Nd and Pb isotope ratios. International Journal of Mass Spectrometry, 235(1), 59–81. https://doi.org/10.1016/j.ijms.2004.04.002

Vermeesch, P., 2018, IsoplotR: a free and open toolbox for geochronology. Geoscience Frontiers, v.9, p.1479-1493, doi: 10.1016/j.gsf.2018.04.001

Villa, I.M., De Bièvre, P., Holden, N.E. & Renne, P.R. 2015. IUPAC–IUGS recommendation on the half life of 87Rb. Geochimica et Cosmochimica Acta, 164, 382–385.

I.M. Villa, N.E. Holden, A. Possolo, R.B. Ickert, B. Hibbert, P.R. Renne. 2020. IUPAC-IUGS recommendation on the half-lives of 147Sm and 146Sm. Geochimica et Cosmochimica Acta, 285, 70-77.

Walker, S., Thirlwall, M.F., Strachan, R.A., Bird, A.F., 2016. Evidence from RB-Sr mineral ages for multiple orogenic events in the caledonides of Shetland, Scotland. J. Geol. Soc. London. 173. doi:10.1144/jgs2015-034

Waight, T., Baker, J. & Willigers, B. 2002. Rb isotope dilution analyses by MC-ICPMS using Zr to correct for mass fractionation: Towards improved Rb–Sr geochronology? Chemical Geology, 186, 99–116.

Woodhead, J., Hellstrom, J., Hergt, J., Greig, A. & Maas, R (2007) Isotopic and elemental imaging of geological materials by laser ablation Inductively Coupled Plasma mass spectrometry. Journal of Geostandards and Geoanalytical Research, 31, p. 331-343.

Paton, C., Hellstrom, J., Paul, B.,Woodhead, J. and Hergt, J. (2011) Iolite: Freeware for the visualisation and processing of mass spectrometric data. Journal of Analytical Atomic Spectrometry. doi:10.1039/c1ja10172b.

Paul, B., Paton, C., Norris, A., Woodhead, J., Hellstrom, J., Hergt, J., and Greig, A. (2012) CellSpace: A module for creating spatially registered laser ablation images within the Iolite freeware environment. Journal of Analytical Atomic Spectrometry, v. 27, no. 4, p. 700, doi: 10.1039/c2ja10383d.