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Caledonian and pre-Caledonian orogenic events in Shetland, Scotland: evidence from garnet Lu-Hf and Sm-Nd geochronology

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Caledonian and pre-Caledonian orogenic events in Shetland, Scotland: evidence from garnet Lu-Hf and Sm-Nd geochronology

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Abstract

Garnet Lu-Hf and Sm-Nd ages from the Shetland Caledonides provide evidence of a polyorogenic history as follows: 1) c. 1050 Ma Grenvillian reworking of Neoarchaean basement; 2) c. 910 Ma Renlandian metamorphism of the Westing Group; 3) c. 622-606 Ma metamorphism of the Walls Metamorphic Series but of uncertain significance because the eastern margin of Laurentia is thought to have been in extension at that time; 4) Grampian I ophiolite obduction at c. 491 Ma followed by crustal thickening and metamorphism between *c*. 485 and *c*. 466 Ma; 5) Grampian II metamorphism between *c*. 458 and *c*. 442 Ma that appears to have been focused in areas where pre-existing foliations were gently-inclined and thus may have been relatively easily reworked; 6) Scandian metamorphism at *c*. 430 Ma, although the paucity of these ages suggests that much of Shetland did not attain temperatures for garnet growth. There is no significant difference in the timing of Caledonian orogenic events either side of the Walls Boundary Fault, although this need not preclude linkage with the Great Glen Fault. However, the incompatibility of Ediacaran events either side of the Walls Boundary Fault may indicate significant lateral displacement and requires further investigation.

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The pre-Devonian rocks of Shetland (northern Scotland) form part of the North Atlantic Caledonides, which resulted from the Ordovician-Devonian closure of the Iapetus Ocean and collision of Laurentia, Baltica and Avalonia. Rocks affected by the Caledonian orogeny currently crop out in the North Atlantic region in the British Isles, Ireland, Greenland and Scandinavia (Fig. 1A). In mainland Scotland (Laurentia), the Caledonian orogeny resulted from two Ordovician accretionary events and the culminating Siluro-Devonian continental collision (Lambert & McKerrow 1976; Oliver et al. 2000; Chew et al. 2010; Bird et al. 2013; Tanner 2014; Dewey et al. 2015). The rock units affected by these orogenic events in the high-grade 'orthotectonic' zone north of the Highland Boundary Fault-Clew Bay Line (Fig. 1A) were deposited between the early Neoproterozoic and the Cambrian. The distinction between geological structures and metamorphic assemblages formed in the various Ordovician-Silurian orogenic events in this sector of the Caledonides therefore relies almost entirely on geochronological studies and is commonly problematic.

Shetland is the northernmost sector of the Scottish Caledonides, situated almost equidistant between mainland Scotland, and the western Scandinavian Caledonides in Norway (Baltica) (Fig. 1A). Despite the importance of Shetland as a central location between the Scottish and Scandinavian Caledonides, relatively few modern geochronological studies have been undertaken here. Most recent published geochronological studies of the timing of metamorphism in Shetland have utilized the U-Pb system in monazite and zircon (Cutts et al. 2009, 2011; Crowley & Strachan 2015; Jahn et al. 2017). These systems are extremely robust against alteration and retrogression, and high-spatial resolution methods (e.g. LA-ICPMS or SIMS) allow for targeting specific regions within an individual crystal. However, that zircons are so robust can be problematic when utilized to understand low- and medium-grade metamorphic rocks, as they may have been inherited (as a detrital mineral or from an igneous protolith), and do not commonly crystallize at these temperatures and pressures (see however Dempster et al. 2004). For monazite U-Pb this is less of an issue as it can crystallize at lower temperatures and pressures. A further limitation is that it can be difficult to relate accessory minerals such as zircon and monazite to specific deformation fabrics and metamorphic assemblages. In contrast, here we utilize Lu-Hf and Sm-Nd geochronology to establish the timing of garnet growth in Shetland.

This approach has three key advantages: 1) garnet is a common metamorphic mineral that crystallizes over a wide range of pressures and temperatures, 2) garnet often forms porphyroblasts that can be related to deformation fabrics and therefore provide age constraints on tectonic structures, and 3) garnet can be dated accurately and precisely using two different isotopic systems (Lu-Hf and Sm-Nd).

This study aims to test existing models for the timing of Caledonian and pre-Caledonian metamorphic episodes in Shetland using Lu-Hf and Sm-Nd garnet geochronology, and thus provide key correlations with related areas elsewhere in the orogen.

Geological setting

Tectonic overview of the Scottish Caledonides

In Scotland and Ireland, Caledonian convergent tectonics began during the late Cambrian to early Ordovician (*c*. 480-470 Ma) when the Laurentian margin collided with an intra-oceanic arc that had developed above an oceanward-dipping subduction zone (Dewey & Ryan 1990). Supra-subduction zone ophiolites were obducted onto the Laurentian margin (Dewey & Shackleton 1984; Chew et al 2010), and crop out along the Highland Boundary Fault – Fair Head-Clew Bay Line (Fig. 1A.). The best exposed of these is the Shetland Ophiolite Complex, which crops out on the islands of Unst and Fetlar in northern Shetland (Fig. 1B; Garson & Plant 1973; Flinn 1985; Prichard 1985). The early-to-mid Ordovician arc-continent collision resulted in the Grampian orogeny and widespread regional deformation and Barrovian metamorphism of the Moine and Dalradian supergroups that are exposed, respectively in the Northern Highland and Grampian terranes (Fig 1A; Lambert & McKerrow 1976; Oliver et al. 2000; Chew et al. 2010; Bird et al. 2013; Tanner 2014). Arc-continent collision was followed by a reversal of subduction polarity and development of an accretionary prism in the Southern Uplands Terrane (Leggett et al. 1979).

A late Ordovician metamorphic event, termed 'Grampian II' resulted in widespread garnet growth at *c*. 450-445 Ma in the western part of the Moine Supergroup (Bird et al. 2013) and mica fabrics also formed at this time in Shetland (Walker et al. 2016). However, whether this event was caused by the collision of a micro-continental fragment with the margin of Laurentia (Bird et al. 2013) or flat-slab subduction (Dewey et al. 2015) is uncertain.

Sinistrally oblique collision of Baltica and Laurentia occurred in the Silurian-Devonian during the Scandian event (Gee 1975; Soper et al. 1992; Dewey & Strachan 2003). In Scotland, this event only caused significant deformation and metamorphism in the Northern Highland Terrane, which was opposite southern Baltica during continental collision (Coward 1990; Dallmeyer et al. 2001; Dewey & Strachan 2003). Late-orogenic sinistral displacement of c. 700-500 km along the Great Glen Fault juxtaposed the Northern Highland and Grampian terranes of mainland Scotland (Dewey & Strachan 2003). Late- to post-orogenic extensional and transtensional faulting formed the basins in which the Siluro-Devonian 'Old Red Sandstone' clastic sediments were deposited (Seranne 1992; Dewey & Strachan 2003; Wilson et al. 2010; Dichiarante et al. 2016).

There is widespread evidence for Neoproterozoic orogenic events in the Northern Highland and Grampian terranes of mainland Scotland and Shetland, despite extensive Caledonian re-working . Isotopic ages obtained from metamorphic assemblages and syn-tectonic pegmatites cluster at 940-930 Ma ('Renlandian'), 820-780 Ma and 740-725 Ma ('Knoydartian') and are interpreted to date pulses of prograde amphibolite faces metamorphism (Noble et al. 1996; Rogers et al. 1998; Vance et al. 1998; Highton et al. 1999; Tanner & Evans 2003; Cutts et al. 2009, 2010; Cawood et al. 2015; Jahn et al. 2017; Bird et al. 2018). During the Neoproterozoic, Scotland was likely located close to the edge of Rodinia and these and potentially correlative metamorphic events in eastern Laurentian rocks of East Greenland, Svalbard and Pearya have been interpreted as resulting from periods of accretionary orogenesis in the hangingwall of a continentward-dipping subduction zone (Cawood et al., 2010; Malone et al., 2017).

Caledonian geology of Shetland

The *c*. N-S trending Walls Boundary Fault (WBF) in Shetland (Fig. 1B) has been interpreted as the northern continuation of the Great Glen Fault (Flinn 1961, 1977, 1992; Watts et al. 2007) and provides a convenient basis for subdividing the pre-Devonian geology. If correct, this linkage implies that the rocks to the west of the WBF form part of the Northern Highland Terrane, and the rocks to the east part of the Grampian Terrane. However, the magnitude of displacements along, and potential correlations across this fault are uncertain.

West of the Walls Boundary Fault

Late Caledonian igneous rocks and Devonian sediments dominate the geology to the west of the Walls Boundary Fault (Fig. 1B). Greenschist to amphibolite facies metamorphic units crop out at North Roe, Hillswick, and on the north coast of the Walls Peninsula (Fig. 1B).

In northwestern Shetland, the east-dipping Wester Keolka Shear Zone (WKSZ) separates the Archaean Uyea Gneiss Complex (Kinny et al. 2019) from the Sand Voe Group (SVG) metasediments (Pringle 1970). This structure has been regarded as an extension of the Moine Thrust Zone which defines the northwest margin of the Caledonides in mainland Scotland (Fig. 1A; Andrews 1985; Ritchie et al 1987; Flinn 1992; 1993; McBride & England 1994). However, the lowermost part of the SVG contains pebbles that are lithologically similar to the underlying Uyea Gneiss Complex (Pringle 1970, Kinny et al 2019), indicating that the WKSZ may in fact be a tectonically modified unconformity. Further, the penetrative mica fabric in the WKSZ has been dated as Neoproterozoic using Rb-Sr mica geochronology (Walker et al. 2016). Both lines of evidence suggest that the WKSZ is not the equivalent of the Moine Thrust. The Devonian Uyea Shear Zone *c*. 2 km to the west may be structurally equivalent to the Moine Thrust or any correlative may be located offshore (Walker et al. 2016). The Sand Voe Group psammites have been correlated on lithological grounds with the Moine Supergroup in mainland Scotland (Flinn 1988). Farther east, the SVG is overthrust by felsic and mafic orthogneisses, the 'Eastern Gneisses', which have been regarded as equivalent to the Archaean basement inliers found within the Northern Highland Terrane in mainland Scotland (Flinn 1988). The Virdibreck Shear Zone separates these from the Queyfirth Group, a series of metasediments and metavolcanics which may correlate with the Dalradian Supergroup in mainland Scotland (Flinn et al. 1972; Flinn 2007).

The Hillswick area (Fig. 1B) contains units that have been correlated with the Eastern Gneisses, the Sand Voe Group, and the Queyfirth Group. On the northern margin of Walls Peninsula (Fig. 1B), the Walls Metamorphic Series comprises quartzofeldspathic gneisses, amphibolites, limestones, and calc-silicates. The foliation strikes east-west and dips gently southwards. Whilst being distinct from other lithologies in Shetland (Flinn et al. 1979), Mykura (1976) proposed a similar tectonic and amphibolite to greenschist facies metamorphic history to the Sand Voe Group. Hornblende K-Ar ages ranging from *c.* 863-363 Ma have been interpreted as indicating that the earliest prograde metamorphism of the Walls Metamorphic Series occurred during the Grenvillian orogeny (Flinn et al. 1979). However, Rb-Sr white mica ages (Walker et al. 2016) indicate fabric development at *c.* 500 Ma and *c*. 450 Ma, suggesting a multiphase Caledonian history with no evidence for an older Grenvillian component.

East of the Walls Boundary Fault

The geology east of the WBF is dominated by two major metasedimentary successions: the Yell Sound Group (YSG) and the East Mainland Succession (EMS) (Fig. 1B). Regional foliation trends N-S and dips steeply, except on Unst where it dips gently to moderately east. The YSG is the older of the two and is exposed on Mainland Shetland and on Yell. The dominant lithologies are psammitic and semi-pelitic gneisses with subordinate quartzites (Flinn 1988). The succession has a structural thickness of 10 km (Flinn 1988), but in the absence of any sedimentary structures it is difficult to know how closely this approximates to original depositional thickness. Flinn (1988) correlated the YSG with the Moine Supergroup in mainland Scotland. The YSG metasediments are intruded by pre- to syn-tectonic felsic orthogneisses and mafic amphibolites (Flinn 1994), and are interleaved with Meso-Neoarchaean TTG orthogneisses, similar to the Lewisian basement gneisses of northwest mainland Scotland (Jahn et al. 2017). In NE Yell, one of these basement inliers separates the YSG from the much thinner and lithologically contrasting Westing Group, also found in west Unst (Fig. 1B). This comprises marbles and pelites and may form part of the same sedimentary package as the Yell Sound Group.

Overlying the Westing Group on Unst, and the YSG on Mainland Shetland, the eastward-younging East Mainland Succession (EMS) comprises psammites, pelites, marbles, and meta-volcanics that are lithologically similar to the Dalradian Supergroup in mainland Scotland (Flinn et al. 1972; Flinn 2007). However, differences in the timing of deposition and thickness of the succession suggest that the EMS may have been deposited in a separate basin (Strachan et al. 2013). Metamorphic grade is highest in the western and lowest parts of the succession which contain kyanite, staurolite, and garnet, progressively decreasing eastwards to upper greenschist facies assemblages (Flinn et al. 2013).

On Unst and Fetlar (Fig. 1B), the East Mainland Succession is structurally overlain by the Shetland Ophiolite Complex (Flinn 1958). This is disposed in two thrust sheets, and comprises serpentinised metaharzburgite and metadunite, metaclinopyroxenite, and metagabbro, all metamorphosed to greenschist facies (Flinn 1985; Prichard 1985). Chemical characteristics of these units indicate formation in a supra-subduction zone setting (Spray & Dunning 1991; Prichard et al 1996; Flinn 2001; O'Driscoll et al 2012). In contrast, the tectonic slices of a metamorphic sole that underlie the ophiolite on Unst and Fetlar have MORB-type chemistry and record upper amphibolite faces metamorphism (Spray 1988). These are interpreted as remnants of subducted oceanic lithosphere that were juxtaposed against the ophiolite during its obduction (Spray 1988). The lower ophiolite sheet is overlain by the metasedimentary rocks of the Muness Phyllite, and, on Fetlar, the deformed and metamorphosed Funzie Conglomerate (Flinn 2014).

Structural and metamorphic framework

Published data indicate the following sequence of Proterozoic and Caledonian events in Shetland:

1) The Yell Sound and Westing groups were deposited after *c*. 1020 Ma (the age of the youngest detrital zircons that they contain (Cutts *et al* 2009)) and affected by high-grade Renlandian metamorphism at 940-920 Ma (U-Pb zircon and monazite; Cutts et al. 2009, 2011; Jahn et al. 2017).
2) Deposition of the East Mainland Succession is believed to have been initiated after *c*. 700 Ma as a result of the breakup of Pannotia which culminated in the formation of the Iapetus Ocean (Prave et al. 2009).
3) 'Grampian I' regional deformation (D1) and amphibolite facies metamorphism of the Yell Sound and Westing groups and the East Mainland Succession is thought to have occurred at *c*. 485-475 Ma and to have resulted from crustal thickening that accompanied and followed ophiolite obduction (Fig. 2; Cutts et al. 2011). The opholite is known to have formed at 492 ± 3 Ma, the U-Pb zircon age of a plagiogranite (Spray & Dunning 1991), and was obducted at 484 ± 4 Ma, as constrained by a U-Pb zircon age from the metamorphic sole (Crowley & Strachan 2015). The transport direction is believed to have been towards the west, based on kinematic and lineation data preserved in west Unst (Cannat 1989;

Flinn & Oglethorpe 2005; Flinn 2014). Peak pressure-temperature conditions were *c*. 10 kbar and *c*. 775°C (Cutts et al. 2011).

4) Reworking of thrust-related fabrics into a regionally steep (D2) orientation across Yell and much of Mainland Shetland was likely complete by *c*. 465-460 Ma (Walker et al. 2016) and certainly by 464.6 ± 4.6 Ma, the age of the late- to post-tectonic Brae Pluton (Fig. 1B; U-Pb zircon; Lancaster et al. 2017). When traced eastwards, the composite D1/D2 foliation progressively shallows to dip west to define the lower limb of a large-scale, eastward-closing recumbent fold (Fig. 2; the 'Shetland Mega-Monocline' of Flinn 2007). The precise mechanism for formation of this fold is uncertain, but it may have developed at a late stage during D2.
5) 'Grampian II' metamorphism of metasedimentary successions at *c*. 450-445 Ma (Rb-Sr muscovite; Walker et al. 2016), although little is understood of the tectonic driver of this event. It could have resulted from accretion of an arc or microcontinental fragment to the Laurentian margin (Bird et al. 2013) or flat-slab subduction (Dewey et al. 2015).
6) Sinistrally-oblique, top-to-the-NNE shear on Unst and Fetlar juxtaposed the lower ophiolite thrust sheets against their current footwall rocks (Cannat 1989; Beijat et al. 2018). The associated deformation fabrics are recorded in the Funzie Conglomerate and so must be younger than its depositional age, i.e. <440 Ma (Beijat et al. 2018). This is consistent with Rb-Sr mica ages of *c*. 440-430 Ma obtained in west Unst and also thought to date this deformation event (Walker et al. 2016). The tectonic driver is unknown: did it result from gravitational instability arising from crustal thickening at a deeper structural level, or from sinistral relative displacement between Laurentia and Baltica following oblique continental collision (Dewey & Strachan 2003)?
7) Scandian (*c*. 430-410 Ma) westerly-directed thrusting is indicated by emplacement of the upper ophiolite nappe onto the Funzie Conglomerate on Fetlar (Beijat et al. 2018) and displacement on the Uyea Shear Zone (Walker et al. 2016). The upper ophiolite nappe is believed to be the same tectonic unit as the lower ophiolite nappe, repeated by thrusting.

Sample descriptions

Twenty-two samples were collected to provide geochronological insights into the timing of garnet growth and metamorphism in the Caledonian rocks of Shetland. Key targets for sample collection were metamorphic lithologies to the west of the Walls Boundary Fault, where there are relatively few modern geochronological constraints. Sample numbers, location, lithologies, structural significance, and metamorphic assemblages can be found in Table 1.

Analytical methods

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. 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. Some samples had multiple populations of garnets, recognised by different colours, and assumed to represent different garnet age-populations. This assumption of the relationship between colour and garnet population was supported by close inspection of hand-specimen, petrographic thin-section, and both colour and chemistry of the crystals analysed by LA-ICPMS (Fig. 3). Where multiple garnet fractions of a sample are noted, each individual fraction represents a new separation from the picking stage of preparation.

Prior to isotopic analysis, representative garnet crystals from each sample were analysed for trace element, and selected major element, concentrations using the LA-ICPMS system at RHUL (methods outlined in Müller et al. 2009 and Bird et al. 2013). Traverses were the preferred method of data acquisition as they permit detailed study of garnet zoning profiles and tentative identification of mineral inclusions. Laser ablation spot size, laser repetition rates, and scan speed were 15 µm, 10 Hz, and 0.6 mm s^{-1} respectively, and data were calibrated against the NIST612 standard glass.

Amounts of mixed ^{176}Lu-^{180}Hf and ^{149}Sm-^{150}Nd 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), and Bird et al. (2013), with concentrations and isotopic data being determined on the same aliquot. A HF-HNO_3 digestion procedure was utilized for garnets in sealed beakers on a hotplate, followed by a dissolution check in 6M HCl. This should minimize 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). A moderate leaching procedure using sulfuric acid was performed on all garnet fractions, after the methods of Anczkiewicz & Thirlwall (2003), attempting to dissolve phosphate inclusions that can negatively affect Sm-Nd ages. A more rigorous leaching procedure, such as that of Baxter et al (2002) using HF, was not used because, while it is clear that this procedure is excellent for producing 'clean' garnet fractions with high Sm/Nd ratios for Sm-Nd dating, no testing has been done on this procedure for Lu-Hf dating, and may fractionate Lu from Hf.

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^{o}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. Blanks were 60pg Hf and 85pg Lu, which is insignificant based on the amount of analyte for these elements.

Most Lu, Hf, and all Sm and Nd isotopic analyses were undertaken on the GV Instruments IsoProbe MC-ICPMS at RHUL using methods outlined in Thirlwall & Anczkiewicz (2004), and Bird et al (2013). One batch of samples (those marked with § in Table 2) was analysed on the Thermo *Neptune* MC-ICPMS at the Institute of Geological Sciences (IGS), Polish Academy of Sciences, Kraków Research Centre following a similar analytical procedure to that described in Thirlwall & Anczkiewicz (2004).

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. The same standard analysed on the Neptune at IGS yielded respective $^{176}Hf/^{177}Hf$ and $^{180}Hf/^{177}Hf$ ratios of 0.282158±08, and 1.88687±10 (2sd, n=8). 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.

Isochron ages and uncertainties were calculated using IsoplotR (Vermeesch, 2018), using the decay constants of 1.865×10^{-11} a^{-1} for ^{176}Lu (Scherer et al. 2001) and 6.54×10^{-12} a^{-1} for ^{147}Sm (Lugmair & Marti 1978). All isotope data and age uncertainties are quoted at the 2-sigma level.

Interpreting garnet ages

When a garnet grows on the prograde path, the heavy rare earth elements (HREE), including Lu, will partition into the garnet and produce a zoning profile with a large central peak, decreasing exponentially in concentration towards the rim as the garnet rapidly depletes the surrounding volume of HREE (Skora et al. 2006). However, this can be complicated if a garnet has experienced metamorphic conditions above the temperature of diffusion, or has been subject to multiple orogenic cycles. In these scenarios, the garnet Lu profile may be flattened and/or disrupted. It is therefore important to assess the trace element zoning of a garnet before linking any determined ages to a specific prograde event. Trace element traverses for representative garnet crystals from most samples are provided in the supplementary information.

Studies that present Lu-Hf and Sm-Nd ages from the same garnet dissolution have concluded that the Lu-Hf system has a higher closure temperature than Sm-Nd, due to systematically older ages in the former (Scherer et al. 2000; Lapen et al. 2003; Skora et al. 2006; Bird et al. 2013; Smit et al. 2013). It has been alternatively suggested that, rather than different closure temperatures of the two systems, the difference lies in fundamentally different processes recorded in the systems during garnet growth (Lapen et al. 2003; Bloch & Ganguly 2015). High central Lu peaks, and relatively homogenous Sm profiles of garnets may skew ages towards recording early and 'average' states of garnet growth respectively (Lapen et al. 2003; Skora et al. 2006), hence explaining the systematic differences in Sm-Nd and Lu-Hf ages for a given sample. Alternatively, Bloch & Ganguly (2015) argue that the chemical differences between Lu^{3+} and Hf^{4+} lead to preferential retention of radiogenic ^{176}Hf if metamorphic temperatures are above that of diffusion for prolonged periods. This would produce anti-clockwise rotation of an isochron, leading to erroneously old ages. They however point out that it is unlikely that natural garnets would be affected significantly by this process providing they are greater than 0.5mm in diameter and have not been subjected to temperatures exceeding 700°C for "unusually long periods".

In addition to potential differences in closure temperature for the Sm-Nd and Lu-Hf systems in garnets, they both may be detrimentally affected by different mineral inclusions. Zircons have the potential to seriously affect any Lu-Hf ages, especially if the zircons formed from a reservoir that is considerably older than the timing of garnet formation. Very low Lu/Hf (as a function of high Hf concentration) in zircons may have the effect of flattening the isochron, leading to erroneously young ages, if the whole-rock analysis did not incorporate a similar zircon population, for example if not all zircons in the whole rock powder were dissolved. Similarly, the Sm-Nd system may be affected by light rare earth element (LREE)-rich inclusions such as apatite, monazite, and epidote. The effect of these inclusions on a garnet Sm-Nd age could be similar to that of zircon inclusions on the Lu-Hf system, as the LREE-rich inclusions would have significantly higher concentration of the daughter element compared to the garnet (Anczkiewicz & Thirlwall 2003). Phosphate inclusions with high LREE can, in theory, be removed by sulphuric acid leaching, as we did in this study (Anczkeiwicz & Thirlwall 2003). However, epidote inclusions are robust against such procedures and can detrimentally affect Sm-Nd ages.

Results

The potential significance of a Lu-Hf or Sm-Nd garnet age will depend on the temperature and duration of metamorphism, and the size and composition of the garnet (Baxter & Scherer 2013). Providing a garnet grows below the closure temperature of the isotopic system (*c*. 650°C for Sm-Nd, Baxter et al. 2017), then the age will most likely relate to the prograde history of the sample (Ganguly & Tirone 1999, Baxter & Scherer 2013, Smit et al. 2013). The garnet ages for each sample have been assessed with regards to petrological, chemical, and structural information before assigning geological significance. The results and the new Lu-Hf and Sm-Nd garnet ages are presented in Table 2, and are placed in their geological and geographical contexts in Fig. 4.

Hf concentrations in whole-rock (WR) samples

Table 2 reports Lu, Hf, Sm and Nd concentrations in the analysed samples, which provide strong constraints on what minerals have been digested. Measured Nd contents in WR samples (all digested without flux-fusion on a hotplate, denoted as tt = tabletop) are similar to XRF Nd data for the same samples (Supplementary data 1). The same tt WR powder fractions however yield Hf contents that are much less than would be expected from XRF Zr/40, leading to $^{176}Lu/^{177}Hf$ ratios often > 0.2, sometimes higher than $^{176}Lu/^{177}Hf$ measured on garnets from the same sample (e.g. AB08-08). Hf contents in WR fractions digested after flux-fusion are however much higher, 1.8-50x higher than those measured on tt WR fractions, and similar to those expected from XRF Zr/40. This implies that very little of the zircon content of WR samples was dissolved when no flux-fusion took place, and that all or nearly all the zircon content was digested by flux fusion. Notably, for more than half the samples, Hf contents of some or all of the garnet fractions are significantly higher than the Hf contents of the tt WR fractions. Given that LA-ICP-MS data (Supplementary data 2) show that Hf contents of pure garnets are usually 0.1-0.5ppm, the identical tt digestion process must be dissolving a much greater proportion of the zircon inclusions in garnet than it is dissolving zircons in the WR powder. This implies that ages calculated from garnet and ttWR are likely to be in error. This is because the analysed garnets include a zircon population, with potentially old unradiogenic Hf, that is not represented in the ttWR analysis, and also because the $^{176}Lu/^{177}Hf$ ratios measured in the ttWR may have been influenced by preferential leaching of Lu rather than Hf from partially dissolved zircon. In general in this study, the ttWR does not lie on an isochron with garnet and flux-fused WR. Where the garnet is radiogenic, the difference between ttWR and flux-fused WR has no significant effect on the Lu-Hf age. Where the garnet has only moderate $^{176}Lu/^{177}Hf$, between 0.1 and 0.5, the choice between tt and flux-fused WR often has a very large effect on age. Based on the preceding discussion, the flux-fused WR is preferred, and this is supported by better MSWDs and more plausible ages.

Walls Peninsula ages

All three samples studied from the Walls Metamorphic Series (WMS: SW15-01, pelite; SW15-03, granite gneiss; and SW15-06, amphibolite) yield some pre-Caledonian ages. All contain chlorite-biotite assemblages suggesting metamorphic grades no higher than middle amphibolite facies. Both garnet fractions in SW15-06 yield 606-622 Ma Lu-Hf ages and early to mid Ordovician Sm-Nd ages of 483.3 ± 4.9 and 461.9 ± 3.7 Ma in the pink (core) and orange (rim) fractions respectively. The garnets only have moderate $^{176}Lu/^{177}Hf$ (0.28-0.52), but both WR fractions lie on isochrons with each individual garnet, suggesting that zircon inclusions have no significant effect on the age. The orange garnet core of SW15-03 has very low $^{176}Lu/^{177}Hf$ (0.078) but moderate $^{147}Sm/^{144}Nd$, and yields a suspect 689 ± 8 Ma Lu-Hf age but a 617 ± 9 Sm-Nd age consistent with the Lu-Hf ages of SW15-06. The rims of this garnet yield early Ordovician ages by both Lu-Hf (486.3 ± 2.5 Ma) and Sm-Nd (473.2 ± 6.2 Ma). Thirdly, the two garnet fractions of SW15-01 yield Cambrian Lu-Hf ages of *c*. 510 Ma that are within error of each other, but no Sm-Nd data were obtained for this sample. Sample SW13-17, collected just 4km away in the WMS, yields a 510.0 ± 2.3 Ma white mica age (Walker et al., 2016, recalculated), within error of these Lu-Hf ages.

There seems to be clear evidence for Ediacaran and Cambrian metamorphic events in the Walls Peninsula. In SW15-03, the orange cores give older ages than the rims for both Lu-Hf and Sm-Nd, with the Sm-Nd age younger in both core and rim. This can reasonably be explained by two stage growth of the garnets, with the slightly younger Sm-Nd rim age perhaps explained by lower closure temperatures for Sm-Nd in garnets (e.g. Yakymchuck et al 2015). The younger Sm-Nd ages in SW15-06 would require Ordovician loss of radiogenic Nd from the whole garnet crystals, rather than just the rim. This behaviour of the Sm-Nd system may reflect the relatively high metamorphic grade of these samples. The amphibolite shows a syn-tectonic relationship with surrounding deformed felsic sheets, and both are intruded by undeformed felsic sheets. All of the deformed material in this area shares a strong gneissose fabric that dips towards the SSE.

This fabric can be observed in thin section of these samples and wraps the garnets. This fabric was dated further to the west in the Walls Metamorphic Series, using white mica Rb-Sr, as having formed at 450.8 ± 1.4 Ma (Walker et al. 2016). This indicates that the garnet-growth was not coeval with the main fabric development, and that the Walls Metamorphic Series was subject to late stage foliation development which was not accompanied by significant garnet growth.

Northwest Shetland ages

Ages have been obtained from seven samples in the area of North Roe and Hillswick, in a region that has been subjected to west-directed thrust-stacking. Ages seem to become progressively older going up through the tectonostratigraphy. In the west, amphibolite SW15-12 occurs within strongly reworked Archaean orthogneisses in the footwall of the WKSZ at North Roe (Fig. 4), and yields a Silurian Lu-Hf age of 426.9 ± 2.5 Ma. It should be noted that no flux-fused WR is available for this sample. However, it is an amphibolite with only 61 ppm Zr, so expected WR Hf of *c*. 1.5ppm is not much greater than the measured ttWR Hf of 0.54ppm. Further, the garnet has high $^{176}Lu/^{177}Hf$ so small changes in WR Hf systematics would have little impact on the age. The garnets in this sample are skeletal, as shown in the LA-ICPMS traverse, with large inclusions of amphibole, plagioclase, and epidote. Nevertheless, the Lu profile exhibits prograde zoning (Fig. 5), suggesting that the Lu-Hf garnet age determined on this sample relates to the timing of peak metamorphism in this area, although it is possible that the garnets in this sample are amalgamations of multiple smaller garnets which can be observed in Fig. 5.

Five samples have been studied from the Sand Voe Group and Eastern Gneisses, between the WKSZ and the Virdibreck shear zone. No evidence was found of pre-Caledonian ages, despite the Eastern Gneisses being thought to represent basement inliers (Pringle 1970). A sample of the Benigarth Pelite (AB08-11) on the Fethaland peninsula in northwestern Mainland records a late Ordovician Lu-Hf age of 446.5 ± 1.3 (n=3, MSWD: 0.17). The garnets did not yield $^{147}Sm/^{144}Nd$ significantly higher than the WR. The Benigarth Pelite is mapped as part of the 'Eastern Gneisses' (Pringle 1970) but could equally well represent an infold or tectonic slice of the Sand Voe Group. White mica and quartz define the main fabric in the matrix of this sample and this fabric wraps the garnets, therefore the top-to-the-west shear band fabric in this area has to have been formed during or after this 446 Ma episode of garnet growth.

Garnet from another Sand Voe Group pelite (AB08-13), collected a few kilometres to the southeast, also gives a late Ordovician Lu-Hf age of 456.7 ± 2.2 Ma for the orange fraction, and a Sm-Nd isochron age of 470 ± 6 Ma (n=3, MSWD: 1.7). The purple garnet fraction has very low ^{176}Lu/^{177}Hf (0.056) and thus the 582 ± 9 Ma age is not considered robust. The ^{147}Sm/^{144}Nd ratio for the orange fraction is lower than that of the whole-rock, which indicates that the leaching procedure has not produced a 'clean' fraction. However, the point lies on the isochron which suggests that the low Sm/Nd inclusions were in isotopic equilibrium with the garnet and the rest of the rock. On the Hillswick peninsula, a Hillswick Group pelite (SW13-27, correlated with the Sand Voe Group) yields an almost identical Lu-Hf garnet age to AB08-13, of 458.8 ± 2.3 Ma from orange garnets which we interpret as the garnet cores, and 453.0 ± 2.3 Ma from a red population which we interpret as garnet rims. The cores of the garnets from this sample are inclusion-rich, with quartz, biotite, and ilmenite. The inclusion trails are slightly curved and are perpendicular to the main fabric. The rims of the garnets are inclusion-poor. That the garnets from this sample record two different Late Ordovician ages may indicate that there was more than one pulse of metamorphism at this time, or that garnet growth was protracted. Again like AB08-13, the Sm-Nd ages from SW13-27 are substantially older than the Lu-Hf ages (478 ± 14 Ma and 505 ± 21 Ma from the core and rim respectively, similar to the 470 ± 6 Ma Sm-Nd age of AB08-13), but these have poor precision due to the unradiogenic nature of the garnet separates, which may also lead to poor accuracy.

A "basement" amphibolite (AB08-12) was collected from the Fethaland peninsula 250m SE of Benigarth Pelite AB08-11, and provides a 33 Ma older Lu-Hf age of 479.6 ± 1.2 (n=3, MSWD: 1.4, using two separate garnet fractions and flux-fused WR, with amphibole lying significantly above this line). None of the garnet fractions, nor amphibole, yielded a useful Sm-Nd age presumably because inclusions were inadequately removed by leaching. A second amphibolite within the Eastern Gneisses SW13-08, yields mid-Ordovician Lu-Hf ages of 466.3 ± 2.2 Ma and 459.7 ± 4.3 Ma on orange and red garnet fractions respectively. This was collected *c*. 130m SE of

AB08-13 pelite and like AB08-12, gives Lu-Hf ages >10 Ma older than the nearby pelite. 150m NE of SW13-08, Walker et al. (2016) reported a white mica Rb-Sr age of 443.2 ± 1.3 Ma.

To the east of the Virdibreck shear zone, SW15-05 is a rare amphibolite from the Queyfirth Group, and yields an early Ordovician Lu-Hf age of 474.1 ± 3.8 Ma. Garnets in this sample are small and partially retrogressed to chlorite, however the Lu profile determined using LA-ICPMS indicates that the age relates to prograde growth, and that there was no significant diffusion or exchange of the HREE during retrogression. For this sample, we have used the whole-rock that underwent simple table-top dissolution rather than the one that underwent the fused stage of processing, because the slope between the two whole rocks was significantly steeper than the one between the garnets and the whole-rocks, which may imply that there is a significantly older population of refractory minerals in the fused whole-rock, which would artificially skew the age.

East Mainland ages

Only two samples have been studied from Mainland east of the Walls Boundary Fault. A semi-pelitic gneiss from the East Mainland Succession in central Mainland (SW12-07) provides an early Ordovician Lu-Hf age of 479.0 ± 1.5 Ma, and a somewhat younger Sm-Nd age of 470.7 ± 1.0 Ma, which complements the 473.6 ± 0.9 Ma Rb-Sr white-mica age determined on this sample by Walker et al. (2016). This suggests that the steep mica fabric in central Mainland formed towards the end of garnet growth, and that the Lu-Hf garnet age represents prograde growth, whereas the Sm-Nd age represents cooling from this peak metamorphism due to differences in closure temperatures of the two systems.

An amphibolite collected from the Valayre granitic orthogneiss on Lunna Ness in eastern Mainland (AB08-18) yields a Lu-Hf age of 496.2 ± 5.4 Ma for the three garnets alone (MSWD = 0.07; N=3). No flux-fused WR is available for this sample, and individual two-point garnet-ttWR ages for the three differently-coloured garnet fractions increase with increasing $^{176}Lu/^{177}Hf$ (0.34 to 0.69) from 438 Ma (pink) to 469.6±2.5 Ma (orange fraction). The ttWR digestion has Hf content of about 40% of the expected Hf content based on Zr/40, so it may be that it is a reasonable estimate of the WR Lu-Hf isotope system. If so, the 469.6 Ma age is likely to be the most robust for this sample. No Sm-Nd age was determined. Several samples from Lunna Ness were dated by

Cutts et al. (2011), using LA-ICPMS U-Pb monazite dating. They concluded that there were multiple phases of metamorphism in this area, with monazite growth at *c.* 913 Ma, *c*. 470 Ma, and *c*. 460 Ma. Cutts et al. (2011) also constrained the peak metamorphic conditions for the Caledonian phase (as opposed to the Neoproterozoic) of monazite growth to 10 kbar, 775^{o}C.

Ages from Yell

AB08-6, a garnet-pyroxene-amphibolite from a Neoarchaean basement inlier, yields a 1051.2 ± 3.2 Ma Lu-Hf age from an extremely radiogenic garnet, and a Sm-Nd age of 863.1 ± 3.6 Ma. The lower Sm-Nd age probably reflects a later metamorphic event as *c*. 920 Ma in situ monazite ages are reported from the Valayre Gneiss at Lunna Ness (Cutts et al. 2011), and from the Westing Group on Unst (Cutts et al. 2009).

Amphibolite AB08-08 intrudes the host Yell Sound Group pelitic gneisses in northeastern Yell and yields an early Ordovician Sm-Nd isochron age using both garnet fractions of 478.1 ± 2.3 Ma (MSWD=0.42, N=3), with both being highly radiogenic. The garnets have lower Lu/Hf ratios than the ttWR, but the purple garnet yields a Lu-Hf age of 453.6 ± 5.1 Ma (MSWD=0.16 with both WR samples), and the orange garnet yields a 2-point age of 442 ± 6 Ma with the fused WR. This is the third sample in this study in which Lu-Hf ages are younger than Sm-Nd ages. The low ^{176}Lu/^{177}Hf of the garnets (0.15-0.17), together with the isochron age calculated with the implausible ttWR, suggest that these Lu-Hf ages may not be meaningful. The large (≥6mm) garnets in AB08-08 have slightly curved inclusion trails, and are wrapped by the main fabric in the rock which is dominated by amphibole.

On the north coast at the Sands of Breckon, a pelitic gneiss from within the Yell Sound Group (AB08-04) yields a slightly younger middle Ordovician Sm-Nd age of 467.2 ± 1.4 Ma. No Lu-Hf data are available from this sample. The dated garnets are wrapped by a steep D2 foliation and rimmed by pressure shadows that are elongate parallel to a gently-plunging L2 mineral and stretching lineation. A lower limit on the age of the D2 fabrics here is provided by an Rb-Sr white mica age of 459.4 ± 1.4 Ma obtained from a folded syn-kinematic pegmatite at the same locality (Walker et al. 2016). D2 deformation in NE Yell is thus constrained to have occurred between *c*. 468 Ma and c. 460 Ma.

Ages from Unst and Fetlar

Two orange and two pink garnet fractions were analysed from AB08-14, a pelitic gneiss from the Westing Group of Unst. A Lu-Hf errorchron of 837 ± 42 Ma (MSWD = 57) can be obtained from the three most radiogenic garnets and the flux-fused WR, while the Sm-Nd data yield an errorchron of 585 ± 17 Ma (MSWD = 24, N=5). Neither colour garnet yields an isochron for either Lu-Hf or Sm-Nd, but pink garnet-WR two-point Lu-Hf ages are nearly within error at 837 and 846 Ma, while the orange garnets yield 759 and 815 Ma. ^{176}Lu/^{177}Hf ratios in the garnets are fairly low (0.18-0.27), lower than the ttWR sample. The three most radiogenic garnets (two pink, one orange) lie on a Lu-Hf isochron of age 907 ± 14 Ma, MSWD = 0.26. The garnets have moderate ^{147}Sm/^{144}Nd ratios (0.39-0.63) and give fairly consistent two-point ages from 573 ± 4 to 589 ± 3 Ma. There is no indication of older Sm-Nd ages for the pink garnets. Three of the garnets (all except the least radiogenic) yield a Sm-Nd isochron of 607 ± 6 Ma, MSWD = 0.02. The Lu-Hf data, especially the 3-garnet age, are consistent with the *c*. 930 Ma Tonian metamorphic event identified in the Westing Group by Cutts et al. (2009), while the lower Sm-Nd ages may reflect a late Proterozoic event or partial Caledonian reworking.

The garnets of metabasite SW15-07 yield the oldest Caledonian age determined in this study. The sample comes from the metamorphic sole of the upper thrust sheet of the Shetland Ophiolite Complex on Fetlar. At outcrop, the lithology carries a strong, near horizontal deformation fabric, parallel to the contact with the overlying metaharzburgite. The lithology appears to have distinct relict garnet-clinopyroxene layers, which have a pronounced boundary, defined by titanite, with a stable garnet-amphibole assemblage. Trace-element profiles across garnets determined by LA-ICPMS show that concentrations of the HREE, including Lu, are slightly higher at the centre of the garnet crystals compared to the rims, although the crystals do not show a bell-shaped Lu profile which would be expected for a sample recording prograde growth. This may indicate some degree of diffusion of the HREE due to high-temperature metamorphism, or that the garnet analysed for trace-elements was not cut precisely down the centre of the crystal. Garnet-clinopyroxene thermometry was undertaken on this lithology by Spray (1988), which yielded temperatures of c. 750^{o}C on the peak temperature assemblage. Garnets, pyroxenes, and amphiboles were separated from the two assemblages, using a saw to separate the two assemblages, to resolve any potential differences in the timing of formation of the garnet-pyroxene and garnet-amphibole assemblages. A Lu-Hf isochron of 491.4 ± 5.5 Ma (N=4, MSWD 4.1) is defined by both garnet fractions, the amphibole, and pyroxene. This indicates that the prograde and retrograde assemblages formed within the uncertainty of the isochron.

The remaining analyses from Unst and Fetlar were all obtained from samples of the East Mainland Succession. The pink garnet fraction of pelite AB08-15 from west Unst yields early Ordovician Lu-Hf and Sm-Nd ages of 484.5 ± 1.5 Ma and 472.3 ± 4.8 Ma respectively, and we interpret this age as an early garnet population, perhaps garnet cores, based on thin-section and hand-specimen observations of garnet colouration. The presence of kyanite in the cores of these garnets indicates that this age relates to an early phase of kyanite-grade metamorphism. The sample was collected from the same lithology (although not the same outcrop) as sample KSH07-12 from Cutts et al. (2011), who constrained the age and peak metamorphic conditions to 7.5 Kbar and 630^{o}C at 462 ± 10 Ma. Their age was determined by LA-ICPMS U-Pb dating of monazite inclusions within the rim of garnet. They did note that the garnets in this sample had distinct cores and rims, with different peak assemblages, but could not date the cores due to a lack of monazite inclusions. The orange garnet fraction of this pelite (AB08-15), which we interpret as the garnet rims, yields middle to late Ordovician ages (Lu-Hf 462.9 ± 1.7 Ma, Sm-Nd 455.4 ± 3.5), 21 to 17 Ma younger than the (pink) garnet cores. The rim ages are within error of the 462 ± 10 Ma U-Pb monazite age determined by Cutts et al. (2011), which is consistent with their location in the garnet rims.

A pelitic gneiss from west Fetlar (sample SW12-14) was collected from approximately the same structural level as AB08-15 on Unst (Fig. 4), and yields an identical Lu-Hf isochron age of 484.5 ± 1.4 Ma (n=5; MSWD = 1.6), indicating that the timing of garnet growth in this unit was synchronous with the equivalent unit in Unst. There appears to be no difference in the growth times of the pink and orange garnet fractions, which were separated based on colour when picking, given that they all fall on the same isochron with low MSWD. However, these garnets yield younger Sm-Nd ages. The first pair analysed yielded a late Ordovician isochron age of 453.7 ± 3.8 (N=3, MSWD 0.64), within error of the rim Sm-Nd age of AB08-15. Orange and pink garnets analysed in a second analytical batch give an older age of 472 ± 10 Ma, but these have lower Sm/Nd and were not analysed at the same time as the WR, so it is hard to make accurate corrections for instrumental drift. The mica fabrics wrapping the garnets in this sample were dated using Rb-Sr on both white mica and biotite, yielding ages of 468.9 ± 1.4 Ma and 451.2 ± 1.4 Ma respectively (Walker et al. 2016).

Three garnet fractions and three separate fused WR samples from pelite SW12-16, from northeast Unst, define a Lu-Hf isochron age of 470.0 ± 1.2 Ma (n=4; MSWD: 1.1). Peak pressure-temperature constraints of 7.5 kbar, 550^{o}C have been calculated on the same unit (Cutts et al. 2011). Given that the LA-ICPMS garnet traverse for this sample shows typical prograde Lu zoning pattern of a bell-shaped central peak (Fig. 5C), and the relatively low temperature determined in Cutts et al. (2011) it is very likely that these metamorphic conditions were reached at *c*. 470 Ma, and that the age represents garnet growth.

A late Ordovician Lu-Hf garnet age was determined from SW12-15, a pelitic schist from western Unst that yielded a Lu-Hf age of 452.0 ± 1.4 Ma and a Sm-Nd age of 454.3 ± 7.5 Ma. Porphyroblasts of staurolite and chloritoid in this sample overprint the foliation that wraps the garnets, indicating that post-deformational metamorphism reached at least (lower) amphibolite facies after garnet growth at *c*. 452 Ma (Fig. 5D).

The Saxa Vord pelite SW12-16 in NE Unst gives a Sm-Nd isochron age of 430.4 ± 4.2 Ma (N=4, MSWD=0.88), despite the same garnets giving a Lu-Hf isochron age of 470.0 ± 1.2 Ma. This time gap suggests that a second Silurian metamorphic event re-equilibrated garnet Nd but not Hf. The fact that 3 different garnet fractions lie on each isochron suggests that we are not preferentially sampling Lu-rich cores to obtain the older age.

Discussion and regional correlations

Pre-Caledonian events in Shetland

The Lu-Hf age of c. 1050 Ma obtained from reworked Neoarchaean basement in NE Yell (sample AB-08-06) predates deposition of the Yell Sound and Westing groups (Cutts et al. 2009; Jahn et al 2017). It compares with Sm-Nd mineral isochron ages of c. 1082 Ma and c. 1010 Ma for eclogite facies metamorphism of the Eastern Glenelg basement inlier in the Caledonides of NW Scotland, which has been attributed to the Grenvillian orogeny (Sanders et al. 1984). It seems reasonable to assign the new age from NE Yell to the same tectonic event which in Scotland likely resulted from the collision of Baltica and Laurentia during the assembly of Rodinia (Li et al. 2008; Strachan et al. 2020a). The 3-garnet isochron age of 907 ± 14 Ma obtained from the Westing Group (sample AB-08-14) is consistent with the 938-925 Ma span of zircon and monazite ages reported by Cutts et al. (2009) and attributed to the Renlandian event of Cawood et al. (2010).

The Lu-Hf ages of *c*. 622-606 Ma and the Sm-Nd age of 617 ± 9 Ma obtained from the Walls Metamorphic Series (samples SW15-06 and 15-03) are more problematic as they suggest that these rocks were undergoing high-grade metamorphism at the same time as the East Mainland Succession was being deposited in an extensional basin immediately east of the Walls Boundary Fault (Prave et al. 2009). The mismatch could be explained in one of two ways. Either the Walls Metamorphic Series or the East Mainland Succession is grossly allochthonous and rests on an as-yet-undetected major thrust, or alternatively there has been substantial displacement along the Walls Boundary Fault. It is noteworthy that Slagstad et al. (2020) report a similar *c*. 623 Ma age for high-grade metamorphism within the Uppermost Allochthon in Norway which is believed to have a Laurentian parentage. The eastern Laurentian margin is widely thought to have been under extension during the Ediacaran breakup of Pannotia, so the tectonic significance of *c*. 620 Ma metamorphic events represents an unresolved problem.

The *c*. 510 Ma Lu-Hf age obtained from the Walls Metamorphic Series (sample SW-15-01) is easier to explain as there is no reason to suppose that it overlaps with the depositional history of the East Mainland Succession. Furthermore, it is only 20 Ma older than the onset of ophiolite obduction (see below) and could conceivably simply indicate that the Grampian I event was more complex and protracted than envisaged in current tectonic models. This solution is supported by the recognition of an early phase of thrusting at *c*. 515 Ma in the Uppermost Allochthon of Scandinavia (Slagstad et al. 2020).

Onset and duration of Grampian I metamorphism in Shetland

The garnet ages determined in this study show that the dominant period of garnet growth in Shetland related to Grampian (Ordovician) accretionary events. The new data are consistent with the ages obtained in Shetland in recent geochronological studies using U-Pb and Rb-Sr isotopic systems (Cutts et al. 2011; Crowley & Strachan 2015; Walker et al. 2016; Jahn et al. 2017). The Lu-Hf isochron age of 491.4 ± 5.5 Ma obtained from the metamorphic sole of the ophiolite on Fetlar consists of minerals that are not in metamorphic equilibrium. This suggests that the change from upper to middle amphibolite grade happened within the age uncertainty of 5.5 Ma. Titanite porphyroblasts along the boundaries of the regions that have preserved higher temperature pyroxene-bearing assemblages and those that have been completely recrystallized to amphibole (Fig. 5) suggest that a calcic fluid was interacting with the rock at this time, and contributed to the mineralogical changes (Spray 1988). The age most likely relates to high temperature metamorphism of the subducting oceanic slab that formed the protolith of the metamorphic sole (Spray 1988). It is within analytical uncertainty of the 484 ± 4 Ma U-Pb zircon age obtained by Crowley & Strachan (2015) from the same unit on Unst, which we suggest probably relates to subsequent decompression melting during exhumation and obduction. Similar ages are found within the Highland Border Ophiolite in SW Mainland Scotland, where U-Pb zircon ages of 499 ± 8 Ma have been interpreted as dating magmatism, and $^{40}Ar/^{39}Ar$ dating of hornblende and muscovite yield 490 ± 4 Ma and 488 ± 1 Ma ages respectively, and relate to the timing of obduction (Chew et al. 2010).

The age of (pink) garnet cores from western Unst pelite, AB08-15, and the metamorphic conditions calculated on the same unit by Cutts et al. (2011), indicate that prograde Barrovian metamorphism of 7 kbar and 630^{o}C was underway in this part of Shetland as early as 484.5 ± 1.5 Ma. This suggests that growth of a significant orogenic wedge took place within ~6 Ma of the formation of the metamorphic sole of the ophiolite. Near identical garnet ages are also recorded from the same structural level on Fetlar, and in rims of late Proterozoic garnets, and by Sm-Nd, in the Walls Metamorphic Series. Slightly younger ages of 478-480 Ma in Yell, east Mainland and in the Eastern gneisses of North Roe indicate that this metamorphic event was widespread through Shetland. This suggests that the onset of peak Grampian metamorphism occurred slightly earlier than in the Dalradian Supergroup in mainland Scotland, where peak metamorphism occurred between 473 ± 3 Ma and 465 ± 3 Ma, giving a maximum possible duration of 14 Ma (Oliver et al. 2000; Baxter et al. 2002; Viete et al. 2013).

Peak Grampian I metamorphism in Shetland occurred over a duration of 33 Ma based on garnet core ages that span 491.4 ± 5.5 Ma to 466.3 ± 2.2 Ma, significantly longer than in mainland Scotland. Both age constraints are Lu-Hf garnet ages, and are therefore directly comparable, bypassing any potential differences between the Lu-Hf and Sm-Nd garnet systems (e.g. Bloch et al. 2015). Many of the samples that record Grampian ages exhibit prograde zoning in trace-element (HREE) LA-ICPMS traverses, which suggests that these Lu-Hf ages relate to the prograde growth of garnet. The difference in the timing of Grampian peak metamorphism between Shetland and the Grampian Highlands shows that, in Shetland, this event is longer in duration and not just earlier than in mainland Scotland.

There are strong similarities between the Grampian I event in Shetland and coeval events preserved along strike in Scandinavia (Fig. 1A). It has long been recognised that the highest structural units in central Norway, grouped as the 'Uppermost Allochthon' (Fig. 1A; Roberts & Gee 1985), represent a fragment of Laurentia that was emplaced as a composite terrane onto the down-going Baltican plate during Scandian continental collision (Roberts 2003; Roberts et al. 2007; Corfu 2014 and references therein). The 'Uppermost Allochthon' contains various metasedimentary units that have been deduced to have a Laurentian parentage, partly on palaeontological grounds (e.g. Bruton & Brockelie 1980), and record deformation and metamorphism during the Lower Ordovician (480-475 Ma) prior to emplacement of arc-related plutons (470-455 Ma) (e.g. Nordgulen et al. 1993; Yoshinobu et al. 2002; Barnes et al. 2007). In SW Norway, the Karmøy-Bergen ophiolites (Fig 1A) and associated island arc sequences are also thought to have originated in a peri-Laurentian setting (Pedersen & Hertogen 1990; Pedersen & Dunning 1997). The metasedimentary rocks of the Jæren nappe (Fig 1A) have Laurentian affinities and were affected by eclogite facies metamorphism at c. 470 Ma (Smit et al. 2010). The Lower Ordovician tectonothermal events recorded within these structurally highest nappes have been correlated directly with the Grampian orogeny of Scotland (Roberts 2003; Roberts et al. 2007) and clearly correspond closely in timing to the 'Grampian I' event in Shetland.

Evidence for the Grampian II event in Shetland

The late Ordovician ages reported here significantly widen the geographical extent of the Grampian II event within the Scottish Caledonides. However, the differentiation between Grampian I and II events is less clear than in mainland Scotland. In Shetland, Lu-Hf data do not show any age gaps greater than 4 Ma between 453 and 484 Ma. However, there is a gap from 466.3 to 458.8 Ma if only core ages are considered, which may reflect the gap between Grampian I and II. Within this gap there are only two Lu-Hf rim ages, and one Sm-Nd rim age. In Shetland, evidence of garnet growth during the late Ordovician is found on both sides of the Walls Boundary Fault. In North Roe, garnets of this age are found in two samples (AB08-11 and AB08-13; 446.5 and 456.7 Ma), east of and structurally above the Wester Keolka Shear Zone. In contrast, samples (AB08-12 and SW13-08) collected 250m and 130m southeast from the previous samples, and also from the Eastern Gneisses, but from amphibolites rather than pelites, yield Grampian I ages (479.6 and 466.3 Ma respectively). The difference in ages may indicate that the two samples are separated by a cryptic tectonic break. The Hillswick pelite, SW13-27, also yields a core age (458.8 Ma) on the boundary between late and middle Ordovician, and a clearly late Ordovician rim age (453.0 Ma). A Late Ordovician age of 452.0 ± 1.4Ma is also recorded in western Unst, and can be attributed to the Grampian II event. Pressure-temperature estimates for western Unst range between 7.5 – 8.5 kbar, and 630 – 650^{o}C (Cutts et al. 2011). This suggests that regional metamorphism in Unst occurred at both *c*. 450 Ma and *c*. 470 Ma. There is also some evidence for late Ordovician garnet growth on Yell (sample AB08-8), although the garnets from this sample are relatively unradiogenic.

There is evidence of a possible structural control on the locations of Grampian II garnet growth. Post-Grampian I metamorphism only occurs where the dominant tectonic fabrics are shallowly dipping (i.e. not in the Central Steep Zone in Central Shetland and Yell, Fig. 2), which may reflect that these were easier to reactivate during subsequent tectonic events. Set against this, sample AB08-18 was obtained from an area of steeply-dipping fabrics in the Lunna Ness peninsula (Fig. 4) and yielded a Lu-Hf age of *c*. 449 Ma. However, this anomaly might indicate that some fabric steepening occurred *after c*. 450-445 Ma. Areas with shallowly-dipping fabrics do not exclusively record later Caledonian events as there are several examples of these west of the

Walls Boundary Fault and in the footwall of the Shetland Ophiolite Complex in both Unst and Fetlar where only c. 480-470 Ma garnet ages have been recorded.

Metamorphic events of broadly the same age have been recorded along strike of Shetland in the Uppermost Allochthon of Scandinavia, for example the c. 450 Ma eclogite facies event of Corfu et al. (2003). One possibility is that here the Late Ordovician event(s) resulted from the accretion to Laurentia of the outermost segments of a hyper-extended Baltican continental margin (Jakob et al. 2019).

Scandian garnet growth in Shetland

Our data provides evidence of Silurian metamorphism on both sides of the Walls Boundary Fault. The 427 Ma Lu-Hf age obtained from reworked Archaean basement between the Uyea and Wester Keolka shear zones is only slightly older than the Rb-Sr muscovite ages of *c*. 416 Ma and *c*. 410 Ma yielded by the same orthogneisses *c*. 2 km farther west (Walker et al. 2016). The consistency of the two data sets provides an additional indication that the widespread reworking of basement here occurred at least in part during the Scandian orogenic event. However, if garnet grade metamorphic conditions prevailed during the Silurian, it is difficult to understand why *c*. 720-700 Ma Rb-Sr muscovite ages recorded from the vicinity of the Wester Keolka Shear Zone (Walker et al. 2016) only 300 m structurally higher were not reset. Further isotopic investigations are needed to resolve this issue. The Sm-Nd age of 430 Ma recorded in NE Unst is also consistent with Scandian metamorphism, and published Rb-Sr mica ages of 440-430 Ma from Unst (Walker et al. 2016).

The Silurian to Lower Devonian age indicated for Scandian deformation and metamorphism in Shetland overlaps with that established along strike in both the Northern Highland Terrane of mainland Scotland (Dallmeyer et al. 2001; Kinny et al. 2003; Goodenough et al. 2011; Mako et al. 2019; Strachan et al. 2020b) and the thrust allochthons of Scandinavia (Corfu 2014).

Significance of the Walls Boundary Fault

Substantial displacements have been proposed for the Great Glen Fault in mainland Scotland, which has been correlated with the Walls Boundary Fault (Flinn 1961, 1977, 1992; Watts et al. 2007). Both terranes either side of the Great Glen Fault were affected by Grampian I deformation and metamorphism (Kinny et al. 1999; Cutts et al. 2010; Bird et al. 2013), but evidence for the Scandian orogenic event and Grampian II episode are restricted to the Northern Highland Terrane (Kinny et al. 2003). Because the Scandian orogeny is attributed to the collision of Laurentia and Baltica, it is thought that the Northern Highland Terrane must have been located opposite southern Norway during plate collision, and was then displaced sinistrally along the Great Glen Fault by *c*.700-500 km to juxtapose it against the Grampian Terrane (Coward 1990; Dallmeyer et al. 2001; Dewey & Strachan 2003; Strachan et al. 2020b). By contrast, there does not appear to be any significant difference in the timing of Caledonian metamorphic events either side of the Walls Boundary Fault (Fig. 6), although this is not unexpected given that any northern extension of the Great Glen Fault would at some point be separating crustal blocks that were both affected by the Scandian orogeny. However, the potential incompatibility of Ediacaran events either side of the Walls Boundary Fault alluded to above may be indicative of significant lateral displacement and requires further investigation.

Conclusions

1. The Lu-Hf and Sm-Nd garnet ages presented here indicate a complex Neoproterozoic and Lower Palaeozoic orogenic history for the Laurentian Caledonides of Shetland.

2. A Lu-Hf age of c. 1050 Ma obtained from Neoarchaean basement in NE Yell compares with the timing of eclogite facies metamorphism of basement in the Caledonides of NW Scotland during the Grenvillian orogeny. We assign the new age from NE Yell to the same tectonic event which in Scotland probably resulted from the collision of Baltica and Laurentia during the assembly of Rodinia (Li et al. 2008; Strachan et al. 2020a).

3. A 3-garnet Lu-Hf isochron age of 907 ± 14 Ma obtained from the Westing Group is consistent with the 938-925 Ma span of published zircon and monazite ages and attributed to the Renlandian accretionary orogenic event of Cawood et al. (2010).

4. Ediacaran garnet ages of c. 622-606 Ma obtained from the Walls Metamorphic Series are more difficult to explain because the eastern margin of Laurentia is thought to have been in extension at that time during the break-up of Pannotia. However, similar metamorphic ages have been recorded from Laurentian-derived allochthons in Scandinavia, suggesting a more widespread event that is not yet understood fully.

5. Lu-Hf garnet ages of *c*. 510 Ma obtained from the Walls Metamorphic Series and *c*. 491 from metamorphic sole of the Shetland ophiolite are interpreted as corresponding to the onset of Grampian I orogenic activity which has been widely documented in mainland Scotland, Ireland and in the Laurentian-derived allochthons of Scandinavia. Peak metamorphism was reached by *c.* 485 Ma, which is *c*. 10 Ma earlier than in mainland Scotland. There is widespread evidence of garnet growth on both sides of the Walls Boundary Fault until *c.* 466 Ma which also indicates a more protracted Grampian event in Shetland.

6. Lu-Hf and Sm-Nd ages ranging between *c.* 459 and *c.* 442 Ma are attributed to the Late Ordovician Grampian II event, significantly widening its geographical extent from mainland Scotland and providing linkage with similar-age events in the Laurentian-derived allochthons of Scandinavia. Garnet growth of this age is recorded on both sides of the Walls Boundary Fault and appears to have been focused in areas where pre-existing foliations were gently-inclined and thus may have been relatively easily reworked.

7. Lu-Hf and Sm-Nd ages of *c*. 430 Ma obtained from two samples in Shetland are interpreted to correspond to the Scandian orogeny. The relative paucity of Silurian ages suggests that the Scandian orogenic event here was not characterized by sufficiently high temperatures and pressures to result in widespread garnet growth.

8. There is no significant difference in the timing of Caledonian orogenic events either side of the Walls Boundary Fault, although this need not preclude linkage with the Great Glen Fault. However, the incompatibility of Ediacaran events either side of the Walls Boundary Fault may indicate significant lateral displacement and requires further investigation.

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Figure and table captions

Fig. 1. (A) Regional context of Shetland in its pre-Mesozoic rifting setting (modified from Bird et al. 2013) NHT – Northern Highland Terrane; MTZ = Moine Thrust Zone; GGF – Great Glen Fault;

SUF – Southern Uplands Fault; HBF – Highland Boundary Fault; IS – Iapetus Suture; CB – Clew Bay (B) Geological map of Shetland including sample locations.

Fig.2. Speculative, sketch cross-section of the orogenic wedge in the Shetland region following west-directed ophiolite obduction and Grampian I folding and ductile thrusting, and showing the east-facing recumbent fold which developed east of the Walls Boundary Fault (the Shetland 'mega-monocline' of Flinn 2007). Late (Mesozoic?) east-side-down displacement on the Bluemull Sound Fault resulted in the present juxtaposition of lower, west-dipping (east Yell) and upper, east-dipping (Unst) fold limbs. The kinematic significance of this fold is uncertain, one possibility is that it resulted from backthrusting, perhaps in combination with underthrusting/tectonic wedging of a basement block. SVG, Sand Voe Group; YSG, Yell Sound Group; WMC, Walls Metamorphic Complex; WBF, Walls Boundary fault; A, Archaean; WG, Westing Group; SG, Scatsta Group, WNG, Whiteness Group; CHG, Clif Hills Group; BSF, Bluemull Sound Fault.

Fig. 3. Example of the relationship of colour, trace-element characteristics, and age of garnets. This is sample SW13-27 from the Hillswick Peninsula in western Mainland Shetland.

Fig. 4. Geological map of Shetland with sample locations and garnet ages placed in geographical setting.

Fig. 5. Thin section photographs of samples (A) SW15-12, (B) SW15-07, (C) SW12-16, and (D) SW12-15 along with LA-ICPMS traverse data for those samples. Note that the LA-ICPMS traverses were not determined on the minerals shown in this figure, and that they are representative of the garnets in each sample. Mineral abbreviations from Kretz (1983).

Fig. 6. Graphical representation of Caledonian Lu-Hf and Sm-Nd garnet ages determined in this study, along with those from other modern geochronological studies from metamorphic lithologies in Shetland. 1 = Walker et al. 2016; 2 = Crowley & Strachan 2015; 3 = Cutts et al. 2011; 4 = Jahn et al. 2017.

Table 1. Locations, lithologies, geological significance, and mineral assemblages of the dated samples. WG – Wilgi Geos group; WKSZ – Wester Keolka Shear Zone; SVG – Sand Voe Group; EG – Eastern Gneisses; WMS – Walls Metamorphic Series; BFL – Burra Firth Lineament; YSG – Yell Sound Group; EMS – East Mainland Succession. Mineral abbreviations from Kretz (1983).

Table 2. Lu-Hf and Sm-Nd data and ages. Samples marked with * are not considered robust and are not discussed in the text. Ages in italics are multi-point isochrons. Samples marked with § were analysed at the Institute of Geological Sciences, Polish Academy of Sciences, Kraków. All uncertainties are stated at 2σ. Mineral abbreviations from Kretz (1983).

Table 1.

Sample	Location	Grid Ref	Lithology	Geological significance	Mineral assemblage
West of the WBF					
SW15-12	North Roe	HU 34860 91768	WG Garnet amphibolite	Metamorphism west of the WKSZ	Amph+Ep+Qtz+Grt+Bt+Opaque
AB08-11	Fethaland	HU 37230 93435	SVG Benigarth Pelite	Eastern Gneiss basement	Qtz+Wm+Bt+Chl+Grt+Opaque+Tur
AB08-12	Fethaland	HU 37388 93234	Amphibolite	Eastern Gneiss basement	Qtz+Pl+Mc+Amph+Grt+Ttn+Zo+Rt+Wm+Ap+Chl
AB08-13	Burra Voe	HU 37410 89054	SVG Pelitic schist	Moine-equivalent	Grt+Wm+Qtz+Chl+Ttn+Chd
SW13-8	Burra Voe	HU 37340 89159	EG Amphibolite	Interleaved basement inlier	Amph+Qtz+Grt+Wm+Bt+Czt+Ap+Zrc+Rt
SW13-27	Hillswick	HU 2795 7723	EG Pelite	Metamorphism in the Eastern Gneisses	Amph+Qtz+Plag+Wm+Rt+Grt+Chl+Zrc+Bt
SW15-5	Queyfirth	HU 354 829	Amphibolite	Metamorphism in the Eastern Gneisses	Amph+Qtz+Ep+Bt+Grt+Ap+Zrc+Ttn
SW15-01	Shaabers Head	HU 27817 59096	WMS pelite	Metamorphism in the WMS	Qtz+Kspar+Pl+Wm+Bt+Chl+Grt+Opaque
SW15-3	Neeans	HU 27249 59112	WMS Granite gneiss	Metamorphism in the WMS	Qtz+Kspar+Wm+Chl+Bt+Ep+Zrc+Grt+Rt
SW15-6	West Burrafirth	HU 24896 56918	WMS amphibolite	Metamorphism in the WMS	Qtz+Kspar+Pl+Bt+Chl+Grt+Zrc+Opaque+Amph+Ap+Rt
East of the WBF					
Mainland					
SW12-7	East Burrafirth	HU 3695 5080	Semi-pelitic gneiss	Metamorphism in Central Mainland	Qtz+Pl+Wm+Ep+Grt
AB08-18	Lunna Ness	HU 51842 74106	Valayre Gneiss amphibolite	Metamorphism of the Valayre Gneiss	Qtz+Amph+Pl+Grt+Opaque+Ttn
Yell					
AB08-4	Sands of Breckon	HP 52751 05341	YSG paragneiss	Migmatisation of the YSG	Qtz+Pl+Wm+Bt+Grt+Opaque+Ap+Zrc+Ttn+Rt+Chl
AB08-6	Migga Ness	HP 53974 05230	Basement amphibolite	Basement metamorphism	Qtz+Cpx+Amph+Pl+Ttn+Opaques
AB08-8	Kirkrabister	HU 54004 9501	Amphibolite	Prograde metamorphism in the YSG	Grt+Amph+Pl+Qtz+Opaques+Zrc
SW12-20	North Sandwick	HP 5501 9696	Pelite	Prograde metamorphism in the YSG	Qtz+Kspar+Bt+Wm+Chl+Grt+Ky+Zrc+Gr+Rt
Unst					
AB08-14	Westing Group	HP 56784 07120	Gneiss	Metamorphism in the	Qtz+Pl+Wm+Bt+Grt+Ky+Stau+Opaque+Zrc+Sill

AB08-15	Burrafirth	HP 58766 11098	Valla Field Pelite	Westing Group Metamorphism W of the BFL	Qtz+Plag+Wm+Bt+St+Ky+And+Sil+Grt+Chd+Chl+Zrc+Opaque
SW12-15	W. of Watlee	HP 5814 0548	Valla Field Pelite	Metamorphism W of the BFL	Qtz+Wm+Opaque+Staur+Ky+Chd+Chl
SW12-16	Saxa Vord	HP 6315 1652	Saxa Vord Pelite	Metamorphism E of the BFL	Wm+Chd+Grt+Chl+Opaque+Staur+Qtz
Fetlar					
SW12-14	Hamars Ness	HU 5789 9287	EMS migmatitic schist	High grade met in ophiolite footwall	Qtz+Pl+Kspar+Wm+Bt+Grt+Chl+Opaque+Zrc+Rt
SW15-7	Virva	HU 64449 92009	Metabasite	Metamorphic sole of the ophiolite	Cpx+Pg+Grt+Ttn+Cal+Chl

Table 2.

Sample fraction	Lu ppm	Hf ppm	$^{176}Lu/^{176}Hf$	$^{176}Hf/^{177}Hf$	2se	$^{176}Hf/^{177}Hf_0$	Age (Ma)	Sm ppm	Nd ppm	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	2se		
West of the WBF														
SW15-12 wr tt	0.3094	0.5355	0.08164	0.283025	0.000018									
SW15-12 grt	3.047	0.4930	0.8746	0.289363	0.000025	0.282353±20	**426.9±2.5**							
AB08-11 wr §	0.5813	2.970	0.02766	0.282493	0.000006	X		3.639	15.01	0.1466	0.511967	0.000007	X	
AB08-11 wr fl *	0.5858	5.245	0.01578	0.282437	0.000008	0.282305±8	**446.5±1.3**							
AB08-11 grt red §	4.845	1.464	0.4680	0.286221	0.000008	N=3	**MSWD=0.17**	1.508	6.772	0.1346	0.512001	0.000007	X	
AB08-11 grt ora §	7.408	1.214	0.8634	0.289522	0.000012			0.7020	2.859	0.1484	0.512039	0.000008	X	
AB08-12 wr tt	0.7099	1.042	0.09629	0.283517	0.000009	X		4.727	17.41	0.1641	0.512440	0.000006	X	
AB08-12 wr fl*	0.7184	5.163	0.01966	0.282576	0.000009	0.282399±10	**479.6±1.2**							
AB08-12 grt 1	2.728	0.3711	1.0405	0.291758	0.000016		MSWD=1.4	0.2947	1.1172	0.1595	0.512432	0.000010	X	
AB08-12 grt 2	0.5118	0.0553	1.3107	0.294164	0.000017			1.711	6.465	0.1600	0.512445	0.000005	X	
AB08-12 amph	0.2014	0.9177	0.03101	0.283157	0.000006	X		4.373	15.88	0.1665	0.512493	0.000006	X	
AB08-13 wr tt	0.4289	2.672	0.02268	0.282402	0.000009	X		4.019	17.87	0.13594	0.511779	0.000009		470±6
AB08-13 wr fl*	0.5228	7.371	0.01002	0.282247	0.000005									**MSWD 1.7, N=3**
AB08-13 grt ora	3.742	1.0393	0.5092	0.286517	0.000013	0.282161±5	**456.7±2.0**	4.563	22.44	0.12291	0.511748	0.000011		
AB08-13 grt pur	1.793	4.548	0.05572	0.282746	0.000006	0.282138±6	**582±9***	1.890	2.753	0.4151	0.512643	0.000009	0.511358±14	
SW13-08 wr tt								2.581	13.40	0.11650	0.512453			
SW13-08 wr fl*	0.3684	2.063	0.02523	0.282707	0.000049									
SW13-08 grt ora §	3.547	0.3110	1.616	0.296601	0.000014	0.282487±50	**466.3±2.2**							
SW13-08 grt red §	3.839	0.8053	0.6744	0.288297	0.000007	0.282490±50	**459.7±4.3**							
SW15-01 wr tt	0.289	0.2367	0.171	0.283595	0.000051									
SW15-01 wr fl*	0.3193	7.092	0.00636	0.281940	0.000005									
SW15-01 grt Ora	4.922	2.804	0.2481	0.284269	0.000018	0.281879±5	**514.1±4.4**							
SW15-01 grt Pink	4.548	2.015	0.3190	0.284919	0.000010	0.281879±5	**508.5±2.5**							
SW15-03 wr tt	0.4036	0.2782	0.2051	0.283871	0.000032	X		4.459	21.74	0.12396	0.511810	0.000010		
SW15-03 wr fl*	0.4145	8.122	0.00721	0.282111	0.000006									
SW15-03 grt ora	8.736	15.90	0.07765	0.283022	0.000008	0.282018±6	**689±8***	1.906	2.924	0.3942	0.512903	0.000013	0.511309±16	**617±9**

SW15-03 grt red	6.798	2.897	0.3318	0.285068	0.000011	0.282045±6	**486.3±2.5**	1.641	1.900	0.5224	0.513045	0.000016	0.511426±14	**473.2±7.2**
SW15-05 wr tt §	0.620	0.9137	0.095	0.283284	0.000016									
SW15-05 wr fl	0.6415	4.702	0.01928	0.282252	0.000011									
SW15-05 grt §	2.024	0.2324	1.234	0.293400	0.000074	0.282426±15	**474.3±3.5**							
SW15-06 wr tt §	0.7507	5.186	0.02045	0.282405	0.000012			9.273	47.46	0.11810	0.511925	0.000009		
SW15-06 wr fl	0.8067	9.529	0.01196	0.282299	0.000008	N=3	**MSWD=0.93**							
SW15-06 grt ora	7.218	3.668	0.2782	0.285407	0.000010	0.282162±7	**621.9±3.1**	0.9478	0.5520	1.0386	0.514710	0.000020	0.511568±10	**461.9±3.7**
SW15-06 grt pink	15.36	4.207	0.5164	0.288039	0.000010	0.282163±8	**606.4±2.9**	2.019	1.0078	1.2121	0.515388	0.000034	0.511551±11	**483.3±4.9**
						N=3	**MSWD=1.7**							
SW13-27 wr tt §	0.2744	0.2816	0.1377	0.283187	0.000019			2.311	9.605	0.1455	0.511470	0.000006		
SW13-27 wr fl	0.2913	3.527	0.01167	0.282078	0.000011									
SW13-27 grt ora §	3.298	0.9347	0.4990	0.286266	0.000013	0.281978±11	**458.8±2.3**	0.8421	1.867	0.2727	0.511868	0.000010	0.511015±17	**478±14**
SW13-27 grt red §	3.935	1.123	0.4955	0.286183	0.000012	0.281979±11	**453.0±2.3**	1.0058	2.649	0.2295	0.511748	0.000010	0.510988±24	**505±21**
East of the WBF Mainland														
SW12-07 wr tt	0.2093	0.6808	0.04344	0.282583	0.000020	X		0.8049	2.405	0.2023	0.512022	0.000018		
SW12-07 wr fl	0.2255	1.234	0.02583	0.282394	0.000044									
SW12-07 grt	47.06	1.438	4.659	0.323966	0.000013	0.282162±44	**479.0±1.5**	4.830	0.5261	5.572	0.528577	0.000026	0.511398±18	**470.7±1.0**
AB08-18 wr tt	0.7555	1.968	0.05427	0.283061	0.000007									
AB08-18 grt ora	3.053	0.6278	0.6881	0.288637	0.000023	0.282584±8	**469.6±2.5**							
AB08-18 grt red	3.417	1.1798	0.4096	0.286050	0.000009	0.282605±8	**449.2±2.3**							
AB08-18 grt pink	2.886	1.1863	0.3439	0.285436	0.000017	0.282616±9	**437.9±3.7**							
Yell														
AB08-04 wr tt								4.388	21.83	0.1215	0.511842	0.000009		
AB08-04 grt								2.487	0.5463	2.757	0.519908	0.000021	0.511470±9	467.2±1.4
AB08-06 wr tt	0.7905	0.4009	0.2789	0.287950	0.000037	X		3.256	9.754	0.2019	0.512864	0.000012		
AB08-06 wr fl	0.7745	1.467	0.07464	0.284861	0.000030									
AB08-06 grt	4.518	0.1193	6.735	0.416718	0.000080	0.283383±32	**1051.2±3.2**	2.849	1.743	0.9891	0.517320	0.000013	0.511721±16	863.1±3.6
AB08-08 wr tt	0.8507	0.4315	0.2787	0.285073	0.000023	0.282707±16	**453.6±5.1**	2.521	4.735	0.3218	0.512924	0.000015	0.511916±19	**478.1±2.3**

AB08-08 wr fl	0.8553	2.625	0.04604	0.283099	0.000011	N=3	MSWD=0.16						N=3	MSWD=0.42
AB08-08 grt purp	1.083	0.9945	0.1539	0.284017	0.000006			1.489	0.5826	1.5472	0.516766	0.000017		
AB08-08 grt ora	1.121	0.9123	0.1737	0.284156	0.000010	0.282718±16	**442±6**	1.282	0.4901	1.5835	0.516872	0.000015		
SW12-20 wr tt	0.4186	0.2627	0.2253	0.284157	0.000023	X		5.869	29.94	0.11849	0.511821	0.000008		
SW12-20 wr fl	0.4696	5.356	0.01239	0.282095	0.000005									
SW12-20 grt	18.62	2.241	1.1762	0.292509	0.000014	0.281984±5	**477.7±1.6**	0.6775	0.3528	1.16184	0.515010	0.000044	0.511459±10	**466.6±6.6**
Unst														
AB08-14 wr tt	0.6710	0.2030	0.4676	0.288160	0.000090	X		2.653	12.41	0.12925	0.511765	0.000005		
AB08-14 wr fl	0.7937	6.595	0.01700	0.282236	0.000005		or 1 change							
AB08-14 ora 1	2.862	2.178	0.1858	0.284820	0.000013	0.281976±6	**814.6±5.1**	1.751	1.717	0.6166	0.513645	0.000007	0.511266±7	**588.7±2.8**
AB08-14 ora 2	2.608	2.074	0.1778	0.284530	0.000008	0.281994±6	**759.5±4.0**	1.651	1.587	0.6293	0.513666	0.000006	0.511274±7	**580.2±2.5**
AB08-14 pink 1	3.586	1.852	0.2739	0.286323	0.000010	0.281966±6	**846.3±3.5**	1.882	2.919	0.3899	0.512744	0.000005	0.511280±8	**573.2±4.2**
AB08-14 pink 2	3.520	2.103	0.2366	0.285692	0.000012	0.281969±6	**837.3±4.1**	1.796	2.071	0.5244	0.513279	0.000005	0.511270±7	**584.7±2.8**
AB08-15 wr tt	0.4122	0.9122	0.06386	0.282678	0.000015	X		3.633	20.62	0.10650	0.511449	0.000009		
AB08-15 wr fl 1	0.4513	4.702	0.01356	0.282103	0.000007									
AB08-15 wr fl 2	0.4201	4.200	0.01413	0.282114	0.000008									
AB08-15 pink	10.050	1.270	1.1204	0.292153	0.000008	0.281982±5	**484.5±1.5**	0.9312	0.7170	0.7853	0.513549	0.000019	0.511120±11	**472.3±4.8**
AB08-15 ora	7.537	1.546	0.6897	0.287968	0.000012	0.281988±5	**462.9±1.7**	1.0770	0.5214	1.2494	0.514858	0.000024	0.511131±10	**455.4±3.5**
						MSWD=1.2	For both: 3-point using both fl WR							
SW12-15 wr tt	0.2632	0.2426	0.1534	0.283418	0.000042	X		7.696	43.70	0.10643	0.511514	0.000004		
SW12-15 wr fl	0.3716	4.708	0.01115	0.281966	0.000008									
SW12-15 grt	15.21	0.5859	3.6893	0.313103	0.000026	0.281872±8	**452.0±1.4**	0.6459	0.3890	1.0041	0.514185	0.000044	0.511197±6	**454.3±7.5**
SW12-16 wr tt 1	0.2218	1.369	0.02290	0.282123	0.000009	X		2.715	16.28	0.10079	0.511302	0.000005	0.511018±6	**430.4±4.2**
SW12-16 wr fl1	0.2542	4.176	0.00860	0.281883	0.000008	0.281814±4	**470.0±1.2**						N=4	MSWD=0.88
SW12-16 wr fl2	0.2575	4.157	0.00875	0.281892	0.000007	N=6	MSWD=1.1							
SW12-16 wr fl3*	0.2481	4.068	0.00862	0.281891	0.000005									
SW12-16 grt 1	4.351	1.867	0.3295	0.284714	0.000007			0.2175	0.1941	0.6774	0.512936	0.000020		
SW12-16 grt 2	4.376	1.837	0.3368	0.284774	0.000008			0.2023	0.1865	0.6559	0.512854	0.000027		
SW12-16 grt 3	3.641	1.831	0.2811	0.284293	0.000006			0.2214	0.2009	0.6662	0.512889	0.000036		
Fetlar														
***swapped 12-14WR for 12-16WR and vv														
SW12-14 wr 1 tt	0.3200	0.2958	0.1529	0.283223	0.000025	X		6.783	38.02	0.10782	0.511584	0.000006		
SW12-14 wr 2 tt	0.2934	0.1337	0.3101	0.284685	0.000044	X								

SW12-14 wr fl	0.4198	7.100	0.00835	0.281933	0.000008								
SW12-14 grt 1	7.801	1.983	0.5564	0.286919	0.000007			0.9167	1.1249	0.4927	0.512731	0.000011	0.511264±8	**453.7±3.8**
SW12-14 grt 2	7.860	1.985	0.5601	0.286935	0.000008			0.8715	0.8987	0.5863	0.513002	0.000014	N=3	MSWD=0.64
SW12-14 grt pink §	7.742	1.978	0.5536	0.286885	0.000008			0.9355	1.4208	0.3980	0.512473	0.000011	0.511251±8	**472±10**
SW12-14 grt ora §	8.545	2.243	0.5388	0.286731	0.000016	0.281857±4	**484.5 ± 1.4**	0.9835	1.5489	0.3839	0.512444	0.000010	N=3	MSWD=3.8
							MSWD=1.6							
SW15-07 cpx §	0.0879	0.7649	0.01624	0.282801	0.000034									
SW15-07 grt core §	3.840	0.3192	1.705	0.298404	0.000078									
SW15-07 amph §	0.1685	1.145	0.02079	0.282912	0.000044									
SW15-07 grt rim §	2.592	0.3688	0.9950	0.291772	0.000096	N=4, MSWD 4.1	**491.4±5.5**							

figure

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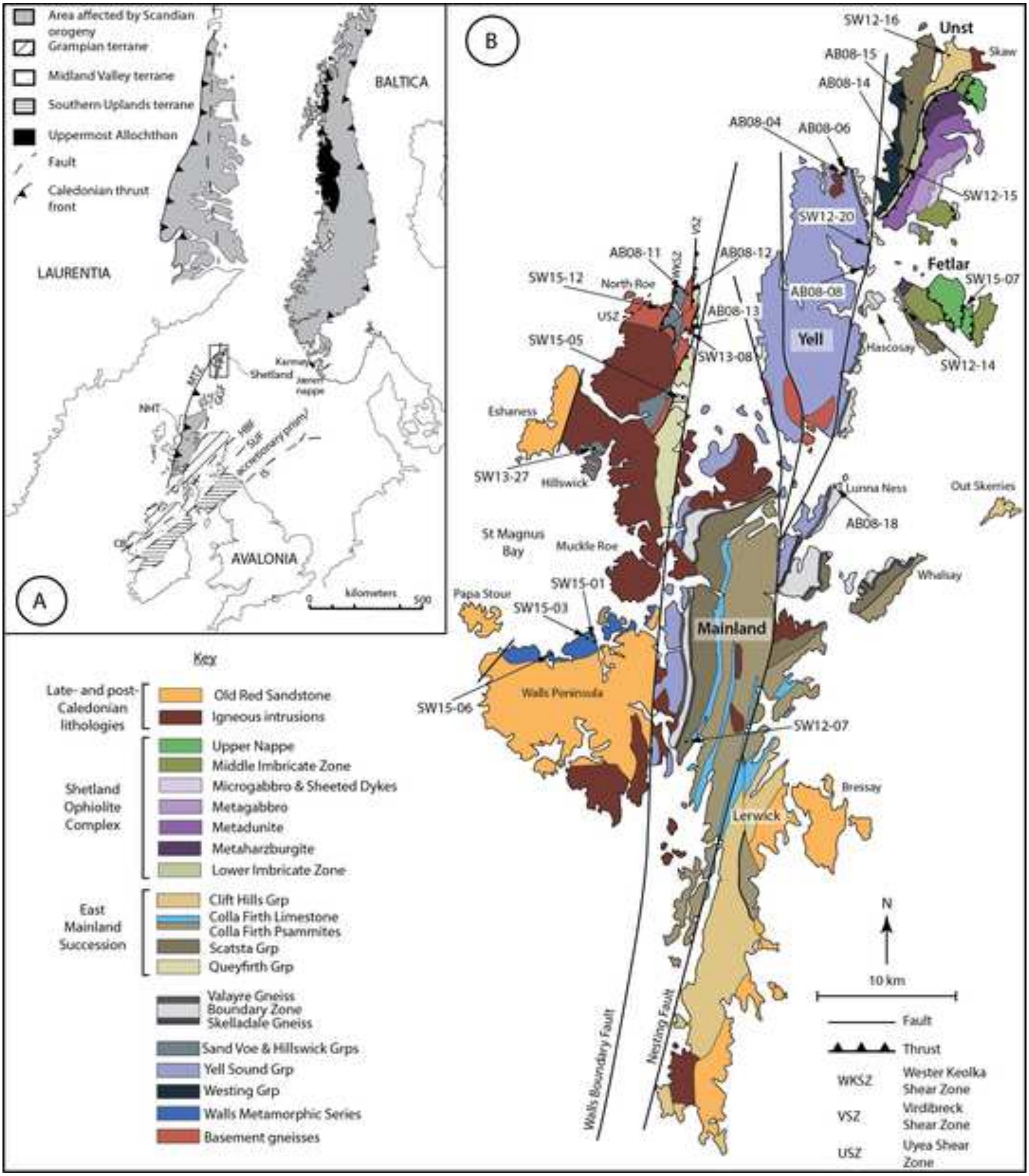
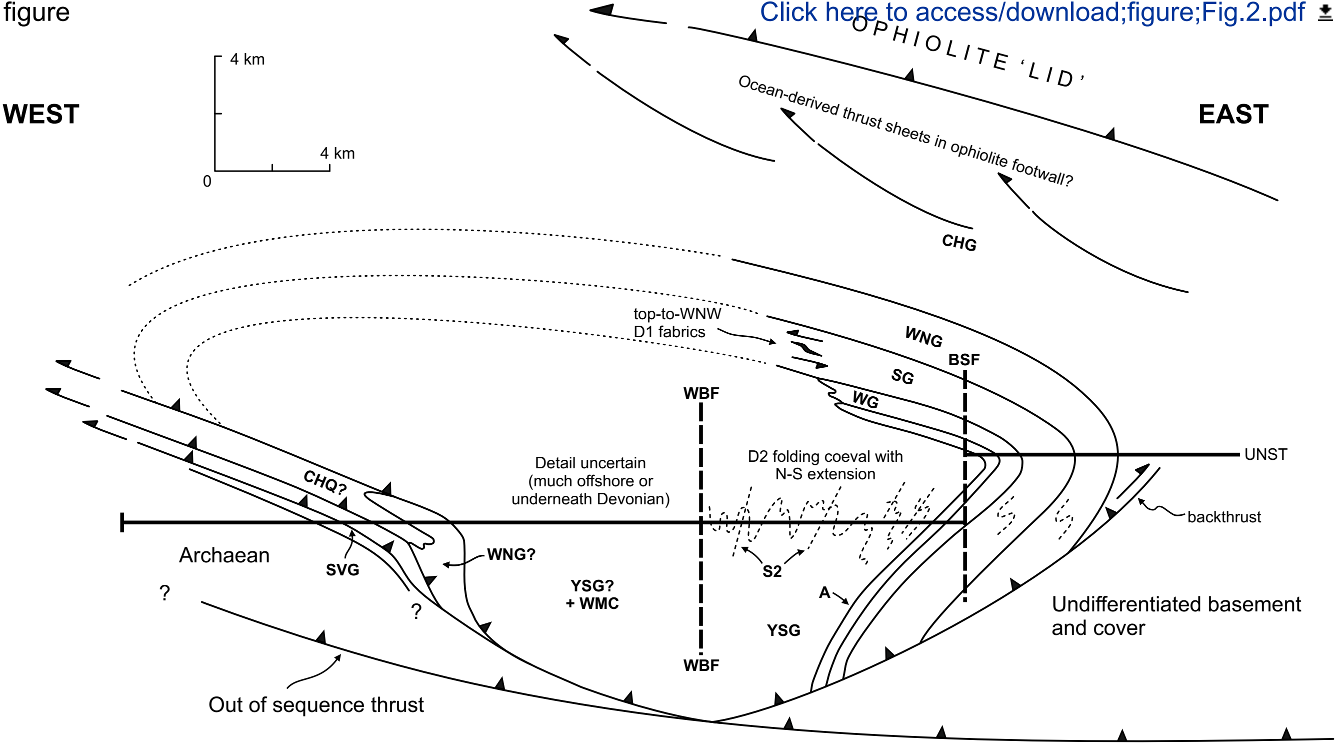
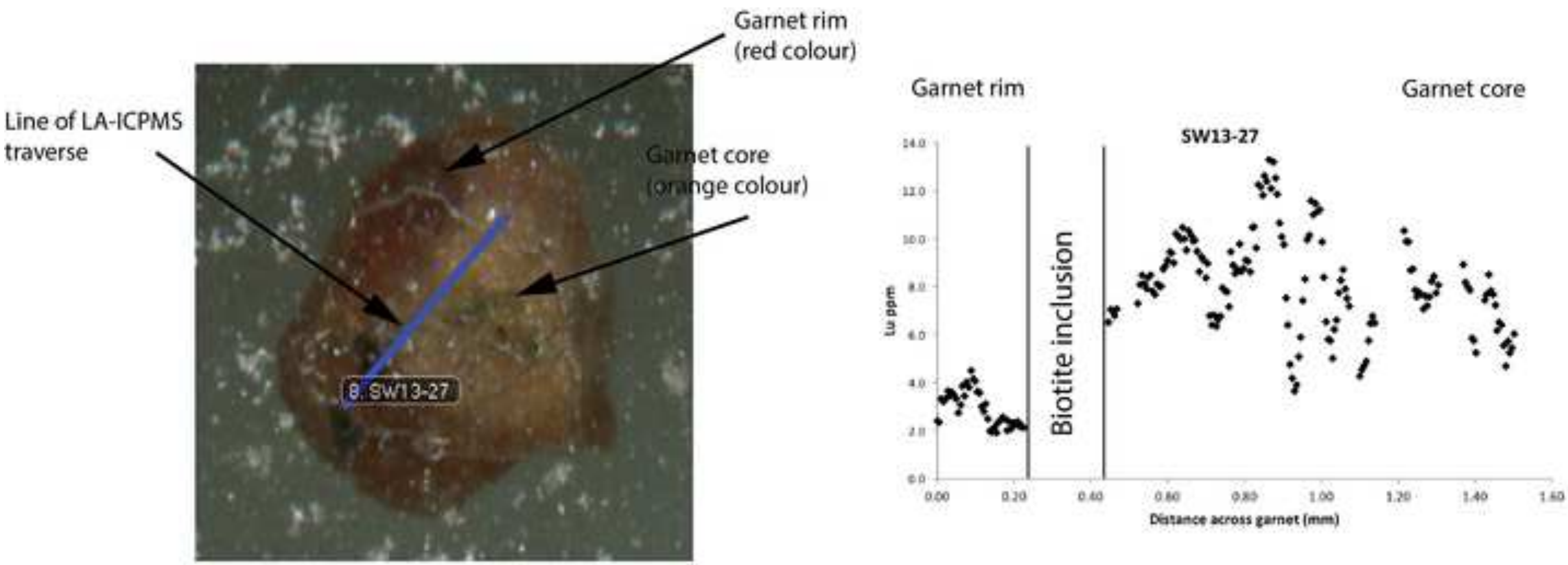


figure


WEST
EAST
4 km
4 km
0
OPHIOLITE 'LID'
Ocean-derived thrust sheets in ophiolite footwall?
CHG
top-to-WNW
D1 fabrics
WNG
BSF
SG
WG
WBF
UNST
Detail uncertain
(much offshore or
underneath Devonian)
D2 folding coeval with
N-S extension
CHQ?
backthrust
Archaean
SVG
WNG?
S2
YSG?
+ WMC
A
?
?
YSG
WBF
Undifferentiated basement
and cover
Out of sequence thrust



Garnet core (picked as 'orange') Lu-Hf age: 458.8 ± 2.3 Ma

Garnet rim (picked as 'red') Lu-Hf age: 453.0±2.3 Ma

figure

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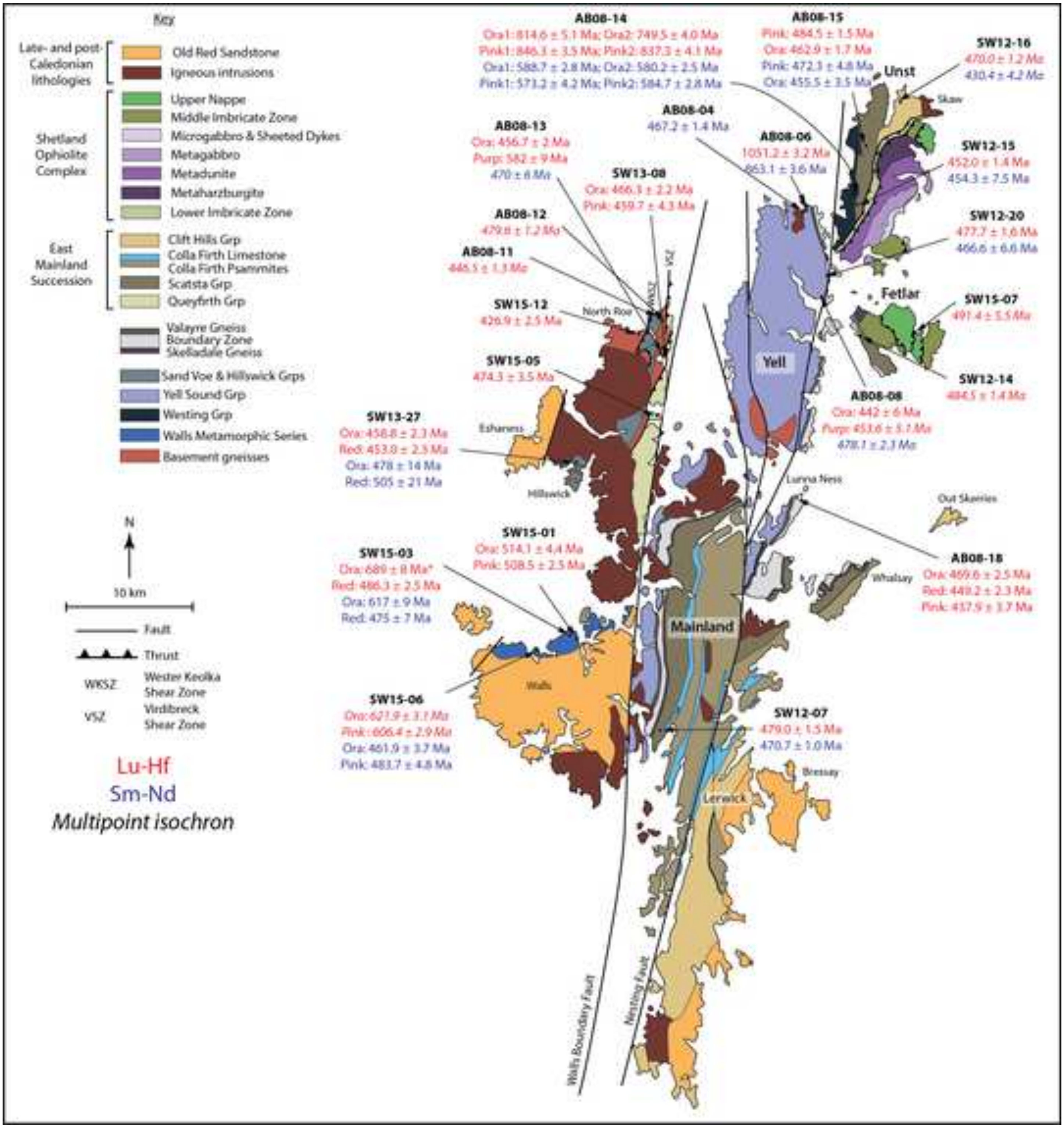
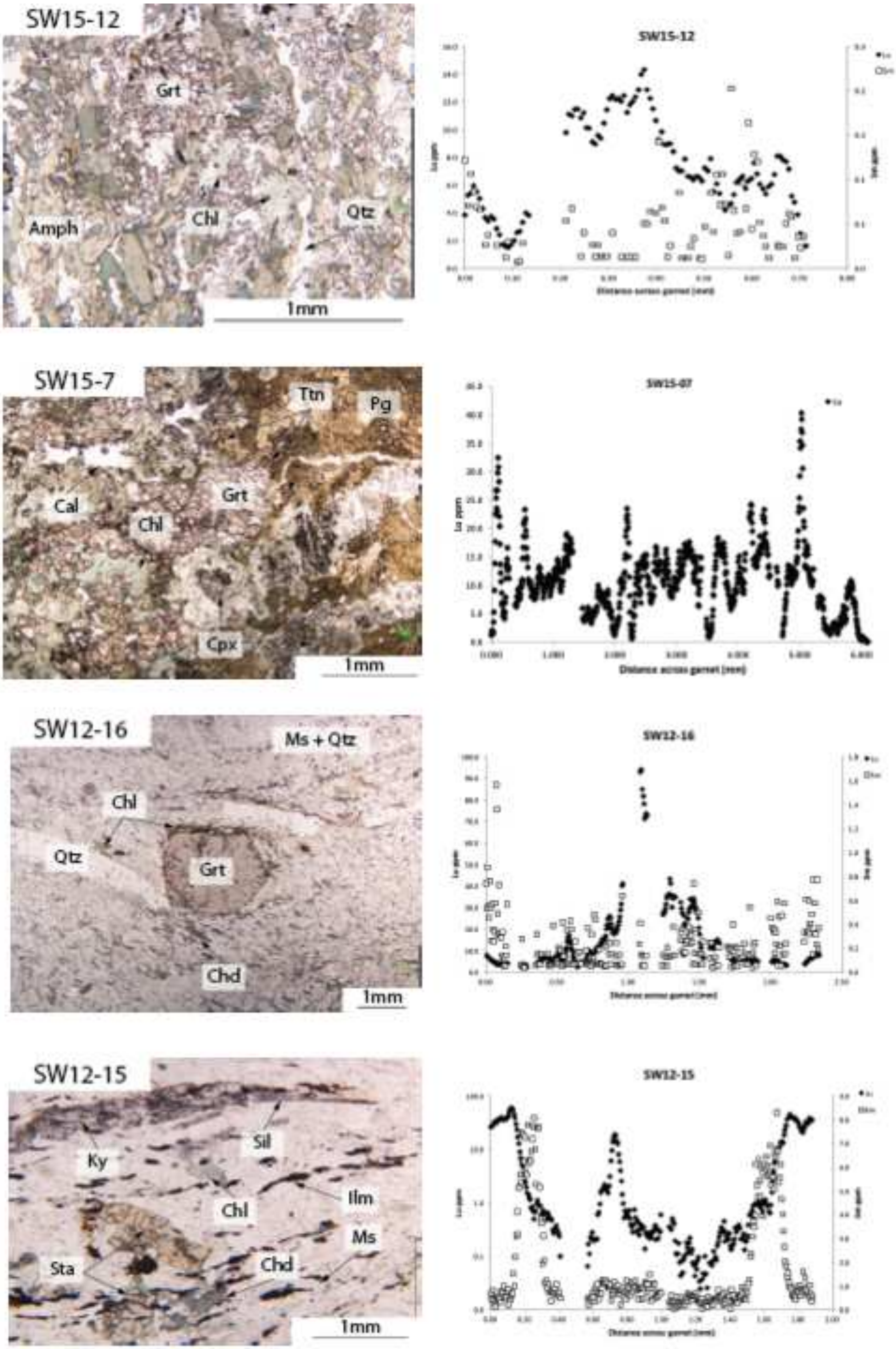


figure Click here to access/download;figure;Fig.5.png



figure

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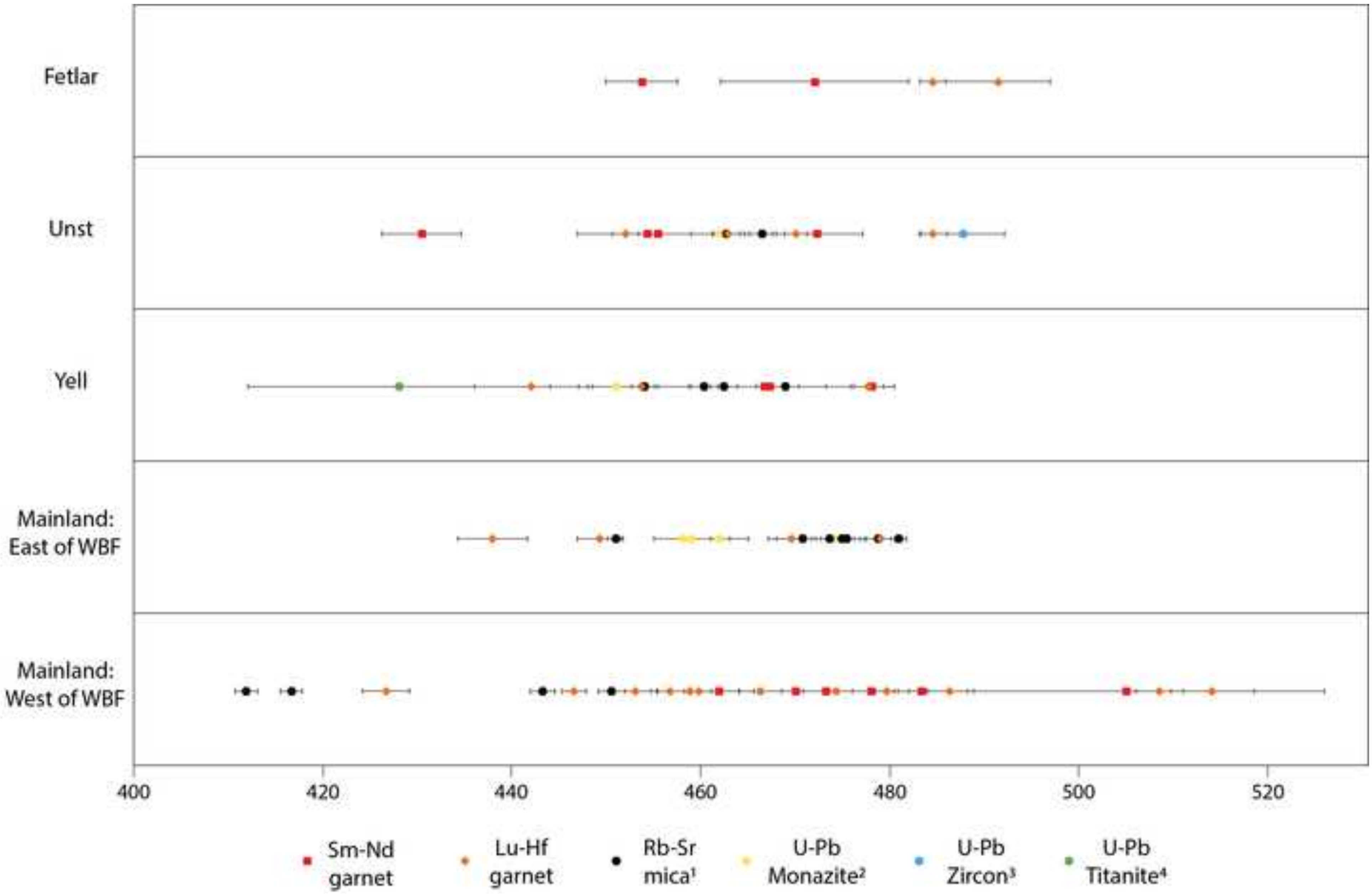

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supplementary material (not datasets)

SuppData1_XRF.xlsx

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SuppData2_LA-ICPMS.xlsx