On the track of a Scottish impact structure: a detrital zircon and apatite provenance study of the Stac Fada Member and wider Stoer Group, northwest Scotland

Gavin G. Kenny\textsuperscript{1,2*}, Gary J. O’Sullivan\textsuperscript{1}, Stephen Alexander\textsuperscript{1}, Michael J. Simms\textsuperscript{3}, David M. Chew\textsuperscript{1} and Balz S. Kamber\textsuperscript{1,4}

\textsuperscript{1}Department of Geology, School of Natural Sciences, Trinity College Dublin, Dublin 2, Ireland

\textsuperscript{2}Department of Geosciences, Swedish Museum of Natural History, SE-104 05 Stockholm, Sweden

\textsuperscript{3}Department of Natural Sciences, National Museums Northern Ireland, Cultra, BT18 0EU

\textsuperscript{4}School of Earth, Environmental and Biological Sciences, Queensland University of Technology, GPO Box 2434, Brisbane, QLD 4001, Australia

*gkennyire@gmail.com
Abstract

The Stac Fada Member of the Stoer Group, within the Torridonian succession of northwest Scotland, is a melt-rich, impact-related deposit that has not been conclusively correlated with any known impact structure. However, a gravity low approximately 50 km east of the preserved Stac Fada Member outcrops has recently been proposed as the associated impact site. Here we aimed to shed light on the location of the impact structure through a provenance study of detrital zircon and apatite in five samples from the Stoer Group. Our zircon U-Pb data is dominated by Archaean grains (>2.5 Ga), consistent with earlier interpretations that the detritus was derived largely from local Lewisian Gneiss Complex, whereas the apatite data (the first for the Stoer Group) display a single major peak at ca. 1.7 Ga, consistent with regional Laxfordian metamorphism. The almost complete absence of Archaean-aged apatite is best explained by later heating of the >2.5 Ga Lewisian basement (the likely source region) above the closure temperature of the apatite U-Pb system (~375-450°C). The U-Pb age distributions for zircon and apatite show no significant variation with stratigraphic height. This may be interpreted as evidence that there was no major change in provenance during the course of deposition of the Stoer Group or that, if there was any significant change, the different source regions were characterised by similar apatite and zircon U-Pb age populations. Consequently, the new data do not provide independent constraints on the location of the structure associated with the Stac Fada Member impact event.

Keywords: Stac Fada Member, impact structure, zircon, apatite, U-Pb, provenance, LA-ICPMS
1. Introduction

The geological record of Britain and Ireland records a rich history of events spanning almost 3 Gyr but no unequivocal impact structures have yet been identified. Evidence for impact events has been proposed at three stratigraphic levels: the Mesoproterozoic Stac Fada Member impact ejecta unit in the Stoer Group, northwestern Scotland (Amor et al., 2008), which contains, for example, the high-pressure polymorph of zircon, reidite (Reddy et al., 2015); a deposit of reworked microtektites in the late Triassic Mercia Mudstone Group of southwestern England, from which multiple orientation of planar deformation features (PDFs) in shocked quartz have been documented and measured (Walkden et al., 2002; Kirkham, 2003); and a purported Palaeogene impact ejecta layer on the Isle of Skye, Scotland (Drake et al., 2017) that awaits confirmation with unequivocal documentation of shock features. Only the microtektite-bearing Triassic deposit has been linked to a known impact structure – the approximately 100 km-in-diameter Manicouagan impact structure, Quebec, Canada (Thackrey et al., 2009). The impact structure associated with the Stac Fada Member has yet to be identified, but various lines of evidence have been used to suggest possible source locations for the material, even prior to its recognition as being impact-related. These include sedimentary features, thickness variations and an anisotropy of magnetic susceptibility study (Lawson, 1972; Stewart, 2002; Young, 2002; Amor et al., 2008, 2011; Simms, 2015). Most recently, Simms (2015) proposed that a geophysical anomaly known as the Lairg Gravity Low, which has a diameter of about 40 km and is centred approximately 50 km east of the Stac Fada Member outcrops, may indicate the location of the now-buried structure. Despite a lack of consensus on the likely location or size of the impact structure associated with the Stac Fada Member, it presently represents the best prospect for the first identification of an impact structure in Britain or Ireland. In this context, we
here report the results of a detrital zircon and apatite U-Pb provenance study of sedimentary rocks of the Stac Fada Member and wider Stoer Group with the aim to test if there was a change in sediment source contemporaneous with the impact that might shed light on the possible location of the impact structure.

1.a. Regional setting

The Stac Fada Member occurs within the ~2km-thick Stoer Group, the oldest of three groups of alluvial, lacustrine and aeolian sediments (Stoer, Sleat and Torridon Groups) that are collectively termed the ‘Torridonian.’ During the late Mesoproterozoic and early Neoproterozoic the Torridonian was deposited on the edge of the Laurentian Shield, near the approximately contemporaneous Grenville orogenic belt (Stewart, 2002). The sedimentary succession was deposited unconformably upon the high-grade metamorphic basement of the Lewisian Gneiss Complex. The Lewisian is composed of a number of Archaean terranes with differing protolith ages, which have experienced a range of metamorphic events. The polyphase metamorphic history is reflected in the complex pattern of Lewisian zircon U-Pb ages distributed along the concordia between \( \text{ca.} \ 3.0 \text{ Ga} \) and the time of granulite facies metamorphism at \( \text{ca.} \ 2.5 \text{ Ga} \) (Whitehouse & Kemp, 2010). Some zircon grains also record older Archaean events in the form of inherited cores dated to \( \text{ca.} \ 3.1 \text{ Ga} \) and \( \text{ca.} \ 3.5 \text{ Ga} \) (Kinny & Friend, 1997). The Proterozoic history of the Lewisian is dominated by \( \text{ca.} \ 1.9 \text{ Ga} \) felsic igneous activity in a magmatic arc setting – for example, the South Harris Complex of the Outer Hebrides (e.g., Whitehouse and Bridgwater, 2001; Mason et al., 2004), the Ben Stack granites near Loch Laxford, north of Stoer (Goodenough et al., 2013) and the Ard gneiss in the Gairloch area, south of Gruinard Bay (Park et al., 2001). The final assembly of various terranes composing the Lewisian is recorded by \( \text{ca.} \ 1.7 \text{ Ga} \) Laxfordian metamorphism (e.g., Heaman & Tarney, 1989; Waters et al., 1990; Corfu et
However, zircon of this age is relatively rare and mainly found in pegmatites (Park et al., 2001). Detrital zircon grains in sedimentary rocks of the Stoer Group have reported ages corresponding to those known from the Lewisian (Rainbird et al., 2001; Kinnaird et al., 2007). This is consistent with the original interpretation that detritus in the Stoer Group was primarily sourced from the Lewisian (e.g., Stewart, 1982, 1990, 2002; Van de Kamp & Leake, 1997). Later deformation in the region included the thrusting of younger Moine metamorphic rocks westward over the unmetamorphosed Torridonian during the Caledonian orogeny. However, the Torridonian escaped significant deformation and today the Stac Fada Member crops out approximately 20 km west of the Moine Thrust Zone (Fig. 1).

1.b. The Stac Fada Member

The Stac Fada Member, which is usually ~10 m thick and can be traced along strike for more than 50 km (Fig. 1), has a distinctive appearance with fragments of dark green, vesicular, devitrified glass accompanying mudstone, sandstone and gneiss clasts up to 0.5 m across in a poorly sorted sand matrix (Stewart, 2002). Sandstone rafts reach 15 m in length at the unit’s type locality at Stac Fada, near the village of Stoer (Stewart, 2002). The Stac Fada Member was previously interpreted as a mudflow, or series of mudflows, related to endogenic volcanic processes (e.g., Lawson, 1972; Sanders & Johnston, 1989; Stewart, 1990; Young, 2002) but the identification of PDFs in quartz led to its reinterpretation as an ejecta deposit associated with a bolide impact (Amor et al., 2008). Arguably the best evidence that the deposition of the Stac Fada Member was related to a hypervelocity impact is the presence of shock-metamorphosed zircon with lamellae of the high-pressure ZrSiO$_4$ polymorph, reidite (Reddy et al., 2015).
Following its reinterpretation as an impact-related deposit, the Stac Fada Member has been divided into three distinct units at the Enard Bay section (Branney & Brown, 2011). The lowermost stratigraphy, which varies from 4 to 10 m thick, comprises a massive suevite with matrix-supported devitrified melt fragments as well as gneiss and mudstone clasts. This grades into a similar unit, distinguished by its abundant matrix-supported whole and broken accretionary lapilli up to 15 mm in diameter and the onset of stratification near its top. The uppermost portion of the Stac Fada Member comprises a thin (≤3 cm) layer of clast-supported dust pellets (aggregates of ash which lack the distinct internal structure of accretionary lapilli) <5 mm in diameter. The two lower units are interpreted to have formed from a decelerating granular density current that rapidly waxed and then waned whereas the thin layer of pellets is interpreted to represent direct fallout from a residual atmospheric dust plume (Branney & Brown, 2011).

1.c. Locating the impact site

Various lines of evidence have been put forward in attempts to constrain the location and proximity of the source material for the Stac Fada Member but there is not currently any consensus. The most pertinent points are noted below.

Upon interpreting the Stac Fada Member as an impact-related unit, Amor et al. (2008) suggested that the relatively thick and distinctively continuous nature of the unit over tens of kilometres is indicative of quite a proximal source location, although no distance was specified. However, the lack of seismites or any significant soft-sediment deformation in the underlying succession has been interpreted as suggesting that the impact structure was still a significant distance away – “perhaps tens of kilometres” (Simms, 2015; p. 755).

Variations in thickness and lithology along the effectively linear outcrop trace of the Stac Fada Member (Fig. 1) have been cited as indicative of proximal-distal changes. The greater
thickness of the deposit in the more northerly outcrops (~10-15 m thick at Stoer and Enard Bay compared to 4-6 m thick further south; Simms, 2015) has been interpreted as tentative evidence that the southern sites may be more distal to the impact (Amor et al., 2008; Simms, 2015). The abundance of accretionary lapilli in the Stac Fada Member at Enard Bay (and their absence further south) has also been proposed as evidence that this is the most proximal presently exposed outcrop (e.g., Simms, 2015, and references therein).

The Stac Fada Member is largely massive and was emplaced without significant erosion of underlying material. This means that there is a paucity of sedimentary structures that could indicate the direction from which it was deposited. Wedge-shaped intrusions of melt-bearing breccia into the strata beneath the Stac Fada Member have been regarded as among the few potential indicators but different authors have interpreted them as indicating different directions of movement. Lawson (1972), working before the unit was recognised as an impact-related deposit, and Amor et al. (2008) proposed that material was moving from west to east, leading Amor et al. (2008) to suggest that the impact structure may be offshore beneath the Minch Basin. Conversely, Stewart (2002) interpreted the same folds and upturned beds as indicating movement from east to west. Sanders & Johnston (1989) described the wedge-shaped geometry of the base of the Stac Fada Member at Stoer and documented thinning to the north and west (their Figs 2 and 3). Young (2002) interpreted small-scale asymmetrical folds and flame structures in sandstones within the Stac Fada Member as evidence for movement of material from two opposing directions, one from the south-south-west and the other from the north-north-east.

With the recognition that the Stac Fada Member was impact-derived (Amor et al. 2008), it follows that the deposit must originate from a single location. Simms (2015) suggested that the
directional variability reported by Young (2002) may be due to rotation of the sandstone rafts during transportation, an interpretation supported by the rafts’ apparently random palaeomagnetic orientations (Irving & Runcorn, 1957; Stewart, 2002). Most recently, Simms (2015) has interpreted the wedge-shaped intrusions of melt-bearing breccia into the strata beneath the Stac Fada Member as evidence for emplacement from a source to the east (his Fig. 5) and argued that because the oversteepened sandstone beds above the intrusive wedges are anchored into the pre-impact stratigraphy they preserve a more robust record of the emplacement direction of the ejecta.

Other sedimentary features that may indicate transport directions have been documented at Enard Bay. These include planar cross beds and lapilli long axes in the upper part of the Stac Fada Member as well as gently plunging troughs subsequently incised into the lapilli beds. Simms (2015) interpreted all of these features to indicate that material was broadly moving from east to west during deposition. Further south, Simms (2015) documented curved fractures on the upper surface of the Stac Fada Member and suggested that these may be related to the transport direction, with their convex-westwards configuration indicating the direction of flow. Similarly, if the concave-up surfaces documented by Simms (2015) within the Stac Fada Member can be interpreted as thrust planes within a viscous flow, they would also be consistent with movement from the east.

Amor et al. (2011) reported, in a non-peer reviewed abstract, the results of an anisotropy of magnetic susceptibility study of the Stac Fada Member that supported an impact structure lying to the west of the present Stac Fada Member outcrops.

In light of the varying interpretations of the evidence within the Stac Fada Member itself, the overlying succession has also been studied with the aim of elucidating a possible source
location for the impact ejecta material. The Stac Fada Member is succeeded by up to 100 m of lacustrine, plane-beded sedimentary rocks (the Poll à Mhuilt Member; Fig. 2) at all but the most southerly sites (Stewart, 2002; Simms, 2015) before fluvial and aeolian deposition commences in the Meall Dearg Formation. These two lithostratigraphic units evidence a dramatic reconfiguration of the regional drainage pattern following deposition of the Stac Fada Member (Stewart, 2002). The Poll à Mhuilt Member was interpreted as a post-impact lake by Amor et al. (2008). Ripple cross lamination (Stewart, 2002) and cross bedding (Simms, 2015) indicate that flow into the lakes was broadly from the west, suggesting that eastward flowing rivers were dammed by debris located east of the present outcrops (Simms, 2015).

In contrast to the variable palaeocurrent azimuths of the pre-Stac Fada Member succession, fluvial sediments in the Meall Dearg Formation consistently record flow to the west (Stewart, 2002; Simms, 2015; Lebeau & Ielpi, 2017) but with evidence for a broadly radial drainage configuration centred on a focal point to the east (Simms, 2015; his Fig. 6). Stewart (2002) had interpreted this palaeoflow configuration as related to tectonic uplift on the eastern flank of the basin but, in light of the impact evidence, Simms (2015) reinterpreted the apparently radial drainage system of the Meall Dearg Formation as a consequence of post-impact regional doming.

Geophysical data can play a key role in the study of impact structures once unambiguous evidence for an impact has already been documented (such as the identification of shatter cones, PDFs in quartz, or shock microtwins or reidite in zircon). This is particularly relevant to structures that are not, or are only partially, exposed at the Earth’s surface (e.g., the Chicxulub structure buried on the Yucatán Peninsular, Mexico; Hildebrand et al., 1998). A common geophysical anomaly associated with impact structures is a broadly concentric gravity low which
in larger structures (D >30 km) is likely to contain a central gravity high (Grieve & Pilkington, 1996; Morgan & Rebolledo-Vieyra, 2013). Simms (2015) proposed that a significant gravity low centred near the village of Lairg in northern Scotland, approximately 50 km east of the Stac Fada Member outcrops, may represent the impact structure from which the Stac Fada Member material was derived, which is consistent with his interpretation of directional data from the Stac Fada Member and the overlying succession. Previous interpretations have ascribed this gravity low to a Caledonian granite pluton, an Archaean granite in the basement, a buried wedge of Torridonian sedimentary rocks, and/or a region of thickened Moine Supergroup rocks (see discussion in Leslie et al., 2010, and references therein). Arguably the most plausible explanation for the gravity low was offered by Leslie et al. (2010), who ascribed it a 5-6 km-thick package of Moine rocks on the basis of detailed mapping and modelling. There is also a conspicuous gravity low to the west of the Stac Fada Member outcrops – in the Minch Basin, which was proposed as the impact site by Amor et al. (2008, 2011). However, the thick post-Palaeozoic sediment fill there (Binns et al., 1975) provides the most plausible explanation of this feature.

Despite the numerous lines of investigation there is no consensus on the location of the impact structure associated with the Stac Fada Member.

1.d. A new approach

In this study we aimed to shed light on the possible location of the impact structure through a detrital zircon and apatite U-Pb provenance investigation of five samples from below, within and above the impact-related unit (Fig. 2). Zircon is a physically and chemically robust mineral that is readily dateable by the U-Pb method and is almost ubiquitous in clastic sediments; it is a well-established and powerful tool in provenance studies (e.g., Thomas, 2011). Recent advances in U-Pb dating of common Pb-bearing minerals (e.g., Chew et al., 2011;
Thomson et al., 2012; Chew et al., 2014) mean that it is now possible to complement detrital zircon analyses with data from other U-bearing heavy minerals. The utility of including apatite in detrital studies (e.g., O’Sullivan et al., 2016) stems from the fact that it crystallises in significant volumes in a much wider range of igneous rock types than zircon (as a result of the limited ability of rock-forming minerals to accept into their structure the amount of phosphorus that occurs in most rocks; Piccoli & Candela, 2002) and, unlike zircon, it crystallises in significant volumes in metamorphic rocks of all grades and most protolith types (Spear & Pyle, 2002). Secondly, apatite is more likely than zircon to represent first-cycle detritus as it is prone to dissolution at source by acidic meteoric and pedogenic waters (Morton & Hallsworth, 1999, and references therein). Despite being prone to dissolution at source (Joosu et al., 2016) apatite is found in non-trivial abundance in nearly all Quaternary sediments (Nechaev & Isphording, 1993) and, because it is stable during diagenesis (due to the liberation of organic-P and P adsorbed onto clay minerals surfaces; e.g., Bouch et al., 2002), the detrital apatite signal is likely to be preserved once buried. These factors result in detrital apatite U-Pb data (i) being able to record events such as magma-poor orogenesis that are not well represented in the detrital zircon record (O'Sullivan et al., 2016), and (ii) having a greater likelihood of recording relatively recent tectonic events than the detrital zircon U-Pb system, which is more likely to be dominated by plentiful polycyclic detritus. It is important to note that although apatite can record events not visible in the zircon record, oftentimes a single geological event can produce contrasting zircon and apatite age distributions. This is because the lower closure temperature of the U-Pb system in apatite (~375–450°C) compared to that of zircon (>900°C) means that the former may record prolonged cooling. Inversely, the disparity of the U-Pb closure temperatures of the two minerals
means that a relatively low-temperature event may reset apatite U-Pb ages without affecting the zircon ages in the same rock.

Although the Stoer Group has previously been studied in terms of detrital zircon U-Pb analysis (Rainbird et al., 2001; Kinnaird et al., 2007), we build on this work with a high-analysis-number, coupled zircon and apatite U-Pb study. Our specific aims were to understand:

(i) whether there are new U-Pb age populations in the succession overlying the impact-related unit that might reflect the presence of previously unexposed rocks brought to the Earth’s surface by the impact event;

(ii) whether there is an absence of any specific U-Pb age populations in the lacustrine sediments (Poll à Mhuilt Member) above the Stac Fada Member, which may reflect specific source terrain(s) being cut-off as a consequence of impact-related drainage reconfiguration;

(iii) whether there is any discernable difference between the heavy mineral assemblages of the fluvial sediments underlying the Stac Fada Member (which were sourced from multiple directions) and those of the fluvial sediments above the Stac Fada Member (which were sourced solely from the east) and whether this might indicate a possible location of the impact structure;

(iv) whether detrital apatite in the Stoer Group records different ages and events compared to detrital zircon, and if the former might have additional utility for recording stratigraphic changes through its ability to highlight a wide range of events and/or its increased likelihood of representing first-cycle detritus.
2. Materials and methods

2.a. Samples

Five samples were processed for zircon and apatite U-Pb analysis. Two were collected from stratigraphically beneath the Stac Fada Member, one from the Stac Fada Member itself, and two from stratigraphically above the impact-related layer (Fig. 2). The samples are listed below in stratigraphic order from lowest to highest, relative to the Stac Fada Member.

Sample 15BSK006 (Stoer; 58.20134°N, 5.34757°W; Fig. 1) is a well-bedded sandstone from the pre-impact fluvial succession. It was sampled approximately 10 m stratigraphically below the base of the Stac Fada Member at the Bay of Stoer in what is mapped as undivided Bay of Stoer Formation (British Geological Survey 2002).

Sample 15BSK008 (Second Coast, Gruinard Bay; 57.86136°N, 5.49697°W) is a sandstone similar to sample 15BSK006 and was collected immediately below the Stac Fada Member, where the sediment was disturbed by ballistically emplaced boulders of country rocks.

Sample 15BSK_X_SFM is composed of green, devitrified glass-bearing Stac Fada Member material from all three sample sites (Fig. 1). Collection from the Stac Fada Member primarily focussed on obtaining small hand specimens with the freshest possible vitric products for a petrological study. For heavy mineral separation, the leftovers of these hand specimens were later combined to provide sufficient material for a statistically meaningful number of analyses.

Sample 15BSK009 (Second Coast, Gruinard Bay; 57.86107°N, 5.49795°W) is a well-sorted, fine-grained sandstone of the Poll à Mhuilt Member lacustrine sequence immediately overlying the Stac Fada Member.
Sample 15BSK001 (Enard Bay; 58.07096°N, 5.35579°W) is a trough cross-bedded sandstone and is the stratigraphically highest sample. It was collected from the Meall Dearg Formation which represents a return to fluvial sedimentation above the Poll à Mhuillt Member of the Bay of Stoer Formation.

2.b. Analytical Methods

Zircon and apatite grains were separated from whole rock samples using crushing, milling, wet shaking table, heavy liquid and magnetic separation techniques at Trinity College Dublin. A selection of zircon grains from each sample were placed on conducting carbon tabs and their exteriors were imaged in backscatter electron (BSE) mode on a Tescan Mira XMU Field Emission Scanning Electron Microscope (SEM) at the Irish Centre for Research in Applied Geosciences (iCRAG) lab at Trinity College Dublin. A larger number of zircon and apatite grains were picked and were mounted in 2.5 cm-diameter epoxy mounts. The mounts were polished with 6 and 1 µm diamond polishing paste to reveal the grain midsections. After application of a ~10 nm-thick carbon coat to the mounts, all zircon grains were imaged in cathodoluminescence (CL) mode using a KE Developments Centaurus system attached to the SEM. An accelerating voltage of 10 kV and working distance of ~10 mm were used. Following removal of the carbon coat with a very brief (~30 s) polish using 1 µm diamond polishing paste, the zircon and apatite grains underwent laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) U-Th-Pb analysis.

All zircon analyses were conducted on a Photon Machines Analyte Excite 193 nm ArF Excimer laser coupled to a Thermo Scientific iCAP-Qc ICP-MS at the Department of Geology, Trinity College Dublin, in a single analytical period (December 2015). The methodology closely followed that of Rodrigues et al. (2015). The laser produced a circular spot 30 µm in diameter
and operated with a nominal fluence of 2.5 Jcm\(^{-2}\) for 180 shots at a 4 Hz laser repetition rate. Nine isotopes were measured during the analyses (\(^{88}\)Sr [3], \(^{91}\)Zr [3], \(^{202}\)Hg [2.5], \(^{204}\)Pb [50], \(^{206}\)Pb [50], \(^{207}\)Pb [70], \(^{208}\)Pb [50], \(^{232}\)Th [20], \(^{238}\)U [40]; the dwell time for each isotope is given in milliseconds in square brackets; total cycle time of 288.5 ms). 91500 standard zircon (\(^{206}\)Pb/\(^{238}\)U age isotope dilution thermal ionization mass spectrometry [ID-TIMS] age of 1062.4 ± 0.8 Ma [all uncertainties in the text are quoted at the 2\(\sigma\) level unless otherwise stated]; Wiedenbeck et al. 1995) was used as the calibration reference material (RM) and Temora 2 (\(^{206}\)Pb/\(^{238}\)U TIMS age of 416.78 ± 0.33 Ma; Black et al., 2004) was analysed as a quality control material (QCM). Zircon QCM data for all sessions are shown in Supplementary Appendix 1. The raw isotope data were reduced using the ‘VizualAge’ data reduction scheme (DRS; Paton et al., 2010; Petrus & Kamber, 2012) in the IOLITE package (v. 2.5) of Paton et al. (2011). Processed data were plotted in the Isoplot 4.15 add-in (Ludwig, 2012) for Microsoft Excel.

Apatite U-Pb analyses were conducted over two separate analytical periods (December 2015 and September 2016). The analyses performed during the first analytical period (on samples 15BSK001 and 15BSK009) were conducted on the same LA-ICPMS system as described above, following the procedure of Chew et al. (2014). A circular spot of 60 \(\mu\)m diameter was ablated for 225 shots at 5 Hz. The analyses performed during the second analytical period (on samples 15BSK006, 15BSK008 and 15BSK_X_SFM) were conducted on the same laser ablation system, which was on this occasion coupled to an Agilent 7900 ICP-MS. For these analyses, a circular spot 60 \(\mu\)m in diameter and operated with a fluence of 3.25 Jcm\(^{-2}\) for 280 shots at a 10 Hz laser repetition rate. During the first analytical period thirty-four isotopes were measured during the analyses (\(^{24}\)Mg [10], \(^{31}\)P [5], \(^{35}\)Cl [30], \(^{43}\)Ca [25], \(^{51}\)V [10], \(^{55}\)Mn [10], \(^{71}\)Ga [10], \(^{73}\)Ge [10], \(^{75}\)As [10], \(^{88}\)Sr [20], \(^{89}\)Y [5], \(^{90}\)Zr [10], \(^{139}\)La [5], \(^{140}\)Ce [5], \(^{141}\)Pr [5], \(^{146}\)Nd [5],
During the second analytical period twenty-nine isotopes were measured (as above but excluding $^{24}$Mg, $^{31}$P, $^{71}$Ga, $^{73}$Ge and $^{182}$W). Apatite rare earth element abundance data are provided alongside U-Pb data in Supplementary Appendix 1. For all apatite analyses, an approximately 1 cm-sized crystal of Madagascar apatite (Thomson et al., 2012; an in-house aliquot of fragments of this crystal has yielded a weighted average ID-TIMS concordia age of 473.5 ± 0.7 Ma) was used as the RM and McClure Mountain apatite ($^{207}$Pb/$^{235}$U TIMS age of 523.51 ± 1.53 Ma; Schoene & Bowring, 2006) was analysed as a QCM. Apatite QCM data for all sessions are shown in Supplementary Appendix 1. The raw isotope data were reduced using the ‘VizualAge_UcomPbine’ DRS (Chew et al., 2014) in Iolite (Paton et al., 2011).

Unlike zircon, which excludes common (i.e. initial or non-radiogenic) Pb ($^{\text{Pb}_c}$) during crystallisation, apatite often has considerable $^{\text{Pb}_c}$ contents that can result in significant discordance in the U-Pb system. This is coupled with generally low U-contents resulting in apparent lesser accumulation of radiogenic Pb ($^{\text{Pb}^\ast}$), hence resulting in high $^{\text{Pb}_c}$/$^{\text{Pb}^\ast}$ ratios that might hinder the dating of certain grains. $^{\text{Pb}_c}$ in the Madagascar apatite RM was corrected for using a $^{207}$Pb-based method employing the known $^{207}$Pb/$^{206}$Pb ratio (Chew et al., 2014). However, detrital apatite has by definition been isolated from co-genetic low-U phases that might have been used to estimate the grain’s initial Pb isotopic composition; hence the initial Pb isotopic composition must be estimated from Pb evolution models. In this study variable $^{\text{Pb}_c}$ in individual detrital apatite grains was corrected for by (i) using a starting estimate for the age of the grain, (ii) calculating its corresponding initial Pb isotopic composition in the model of Stacey
& Kramers (1975), and then (iii) adopting an iterative approach utilising on a $^{207}$Pb correction, based on the procedure of Chew et al. (2011).

3. Results

3.a. Shock features in zircon

External and internal imaging of zircon grains from all samples showed little evidence of potential shock features. A single grain in sample 15BSK001, stratigraphically above the Stac Fada Member, displayed planar microstructures that may be impact-related (Fig. 3a-c). In zircon, no neoblasts or granular textures, potentially related to impact-induced recrystallisation, were observed. Such features have been shown to record the impact age at a number of impact structures (e.g., Vredefort, South Africa – Moser, 1997; Moser et al., 2011; Cavosie et al., 2015; Sudbury, Canada – Kenny et al., 2017; Nicholson Lake, Canada – McGregor et al., 2018; Lappajärvi, Finland – Kenny et al., 2019) and would provide an opportunity to obtain the first direct U-Pb age for the impact event related to the Stac Fada Member deposits if they could be identified. The apparent rarity of shock features in zircon in the samples studied here is consistent with the observation of Osinski et al. (2011) that some samples of the Stac Fada Member contain no shocked quartz and, in general, the unit appears to contain an order of magnitude less shocked material than proximal impact melt-bearing ejecta layers (such as suevite from the Ries impact structure, Germany; e.g. Engelhardt, 1997).

3.b. Zircon U-Pb age data

All zircon and apatite U-Pb data from this study can be found in the Supplementary Appendix 1. Studies of detrital zircon generally exclude from consideration analyses with
discordance greater than an arbitrary cut-off value (e.g., Fedo et al., 2003); here, analyses that were >10 % discordant (grey ellipses in Fig. 4) were not considered further.

The five analysed samples of the Stoer Group display very similar zircon age distributions (Figs 4-6). Their age populations are all dominated by a major peak at 2.9-2.7 Ga with minor populations at ca. 3.2-3.1 Ga, ca. 2.5 Ga, ca. 2.4 Ga, ca. 1.9 Ga and ca. 1.75 Ga (Figs 4-5). The youngest concordant analyses are from two grains in sample 15BSK009, which have $^{206}\text{Pb} / ^{238}\text{U}$ ages of 1.43 ± 0.02 Ga and 1.23 ± 0.02 Ga, and a grain in sample 15BSK_X_SFM, which has a $^{206}\text{Pb} / ^{238}\text{U}$ age of 1.24 ± 0.01 Ga. Overall, the detrital zircon U-Pb distributions for the Stoer Group reported here are very similar to those reported by Rainbird et al. (2001) and Kinnaird et al. (2007) but the higher number of analyses here (a total of 553 analyses that were <10 % discordant, compared to 127 and 16, respectively, in the previous studies) has allowed additional insights. For example, the youngest detrital zircon ages encountered here are significantly younger than the >1.7 Ga ages reported previously. However, we note that caution should be applied when interpreting single detrital zircon analyses, particularly in the interpretation of youngest ages as, for example, post-sedimentation Pb loss may result in erroneously young ages (Nelson, 2001). Additionally, this study confirms the presence of a distinct ca. 3.2-3.1 Ga population (which was previously represented by only a single <10 % discordant analysis) and reports the first Palaeoarchaean age for a zircon grain from the Stoer Group – the oldest concordant analysis in this study has a $^{207}\text{Pb} / ^{206}\text{Pb}$ age of 3529 ± 30 Ma (Fig. 4d inset; Supplementary Appendix 1). With a total of 696 <10 % discordant zircon U-Pb analyses for the Stoer Group from this and previous studies (Rainbird et al., 2001; Kinnaird et al., 2007; Fig. 7), there is now 95 % confidence that no fractions of the zircon population composing ≥1.2 % of the total have been missed (cf. Vermeesch, 2004).
Visual comparison of the samples on histograms and kernel density estimates (Fig. 5), as well as cumulative distribution function (CDF) and quantile-quantile (QQ) plots (Fig. 6), shows that 15BSK006 (the stratigraphically lowest and geographically most northern sample) is the single sample with a noticeable, although still only slight, difference in zircon age distribution. This observation is supported by the results of a Kolmogorov-Smirnov (K-S) statistical test which demonstrates that only sample 15BSK006 is statistically likely (at a 95 % confidence level) to have been sourced from a different population to any of the other samples (Supplementary Appendix 2, Table 1A). We note that in this study the K-S test results support observations that were first made by visual inspection but that, in general, the p-value of the K-S test may be considered a poor measure of dissimilarity between samples due to the strong dependence of results on sample size (Vermeesch, 2013). The reason that sample 15BSK006 appears to be distinct is largely as a result of it lacking the ca. 1.9 Ga age population observed in all other samples.

3.c. Apatite U-Pb age data

Due to the nature of the $^{207}$Pb-based correction for common Pb, no apatite U-Pb age data can be excluded on the basis of discordance. Instead, grains with $^{207}$Pb-corrected 2σ age uncertainties above a certain threshold value (which may be absolute and/or a percentage) are not considered further (e.g., Zattin et al., 2012; Mark et al., 2016; O'Sullivan et al., 2016). Here, this value was set at 5 %. This corresponds to an absolute age threshold similar to that employed in studies of mostly Phanerozoic-aged apatite grains which are typically screened at 20 % (e.g., O'Sullivan et al., 2018).

Similar to the zircon data, the five samples all display quite similar apatite age distributions (Figs 4-6). Visual inspection of the data on histograms and kernel density plots (Fig.
5), as well as CDF and QQ plots (Fig. 6), is again supported by K-S test results indicating no statistically significant difference in age distributions between samples (Supplementary Appendix 2, Table 2). However, the age peaks are different to those in the zircon record; all samples display a range of ages between ca. 2.6 and ca. 2.15 Ga and a broad and dominant peak between ca. 1.8 and ca. 1.55 Ga, and most samples also have minor peaks centred at ca. 1.4 and ca. 1.15 Ga (Fig. 5). Sample 15BSK006, which appeared to be the most distinctive in terms of zircon U-Pb age distribution, is the only sample that lacks apatite grains younger than 1500 Ma.

Two apatite grains in the filtered dataset (339 grains in five samples) have $^{207}\text{Pb}$-corrected U-Pb ages (1101 ± 38 Ma and 1109 ± 40 Ma) that are younger than the current estimate for the deposition of the Stac Fada Member – a 1177 ± 5 Ma $^{40}\text{Ar}/^{39}\text{Ar}$ age for authigenic K-feldspar which precipitated in degassing structures in the Stac Fada Member itself (Parnell et al., 2011). Both of these grains are from sample 15BSK008, which was taken from stratigraphically below the Stac Fada Member (Fig. 2). The two grains which gave ages younger than the currently accepted age of deposition for the unit may be explained by, for example, a) subtle Pb loss from these two crystals, or b) inaccuracy in the $^{40}\text{Ar}/^{39}\text{Ar}$ age. The latter appears unlikely given the robust nature of the $^{40}\text{Ar}/^{39}\text{Ar}$ results from samples from a number of localities. Regardless, the presence of shock metamorphosed zircon in the unit (Reddy et al., 2015) suggests that there may also be the possibility for future studies to obtain a direct U-Pb age for the impact event through analysis of shocked accessory phases such as zircon (e.g., Bohor et al., 1993; Krogh et al., 1993a,b; Kamo et al., 1996; Moser, 1997; Moser et al., 2011; Cavosie et al., 2015; Kenny et al., 2017, 2019; McGregor et al., 2018), monazite (e.g., Erickson et al., 2017) or baddeleyite (e.g., White et al., 2017).
4. Discussion

4.a. Stratigraphic variation

The lack of significant stratigraphic variations in zircon or apatite U-Pb age distributions through the Stoer Group, northwest Scotland, may be interpreted as evidence that there was no major change in the source of detritus during Stoer Group deposition. Alternatively, there may have been a significant change in sediment source but it could not be detected as the different source regions shared similar apatite and zircon U-Pb age populations.

The polycyclic nature of zircon and the ability of intermediate repositories to overwhelm local provenance (e.g., Sircombe & Freeman, 1999) mean that changes in sedimentary provenance throughout a succession may not necessarily result in any major change in the detrital zircon age distribution. Apatite, by contrast, is more likely to represent first-cycle detritus (Morton & Hallsworth, 1999, and references therein) and may therefore be more likely than zircon to record major shifts in provenance throughout a succession. The relatively constant nature of detrital apatite U-Pb age distributions across the Stac Fada Member may therefore lend support to the first explanation – i.e. that there was not a major shift in drainage pattern.

Consistency in detrital zircon and apatite U-Pb age distributions throughout a stratigraphic section could conceivably be related to extensive reworking of underlying sediments. The lower part of the Stoer Group appears to have been deposited in a series of narrow, high-gradient bedrock and alluvial valleys that were only partially connected, whereas the younger parts of the Stoer Group appear to have been deposited in broader, low-gradient alluvial settings, with aeolian processes on-going in areas far from basement highs (Ielpi et al., 2016). It has been suggested that this transition in the Stoer Group led to more mature and hydrologically open drainage which was capable of remobilizing fine-grained detritus, with
“mobilization and reworking of sandy detritus in extra-channel areas also enhanced by the absence of plant rooting” (Ielpi et al., 2016, p. 309; Went, 2005).

The zircon and apatite U-Pb age results need to be considered in the context of palaeocurrent data for the Stoer Group. The well-documented changes in flow direction throughout the unit – from variable palaeocurrent directions below the Stac Fada Member, to broadly eastward movement in the up to 100 m thick lacustrine sedimentary rocks of the Poll à Mhuilt Member immediately overlying the Stac Fada Member, to broadly westward flow directions in the post-Poll à Mhuilt Member (Stewart, 2002; Simms, 2015) – indicate that there was at least some change in the regional drainage network coincident with the deposition of the Stac Fada Member.

Regardless of whether the relatively constant age distributions of heavy minerals in the Stoer Group can be interpreted as indicative of a lack of major shift in sediment source, they do not provide independent evidence that the impact associated with the Stac Fada Member: (i) brought previously unexposed rocks to the Earth’s surface, (ii) cut off specific source terrain(s), or (iii) resulted in any major change in the regional Stoer Group sedimentary system that might indicate a location of the impact structure.

The very minor differences between the U-Pb age spectra may be related to geographic or stratigraphic factors. For example, the lack of ca. 1.9 Ga zircon grains in sample 15BSK006 may be related to this sample’s northernmost location (Fig. 1) or its lowermost stratigraphic position of the five studied samples (Fig. 2). Interestingly, Rainbird et al. (2001) identified two ca. 1.9 Ga zircon grains (207Pb/206Pb ages of 1866 ± 62 and 1912 ± 30 Ma) in samples from even lower in the Stoer Group stratigraphy at the relatively southern location of Gruinard Bay. This may indicate that the absence of ca. 1.9 Ga zircon grains in sample 15BSK006 is not related to
stratigraphic position and may, more conceivably, be related to the sample’s geographic location. Additionally, intrusions of ca. 1.9 Ga age are mainly found close to Lewisian terrane boundaries – for example, the Ard gneiss in the Gairloch area to the south (Park et al., 2001) and the Ben Stack granites near Loch Laxford to the north (Goodenough et al., 2013). Sample 15BSK006 is the sample most distal to these known ca. 1.9 Ga intrusions and we suggest that this is the most likely reason for its lack of grains of this age.

4. Provenance

4.b. Detrital zircon

The new zircon U-Pb data for the Stoer Group are consistent with the U-Pb data of Rainbird et al. (2001) and Kinnaird et al. (2007) and earlier interpretations that the detritus was largely derived from local Lewisian Gneiss Complex basement (e.g., Stewart, 1982, 1990, 2002; Van de Kamp & Leake, 1997). Rainbird et al. (2001) noted that the major detrital zircon age peak at 2.9-2.7 Ga corresponds to protolith ages for rocks of the Lewisian Gneiss Complex in the Gruinard Bay area (Whitehouse et al., 1997; Corfu et al., 1998) as well as high grade metamorphic events in the north-central part of the Lewisian. However, recent work has shown that complex polyphase metamorphism of the Lewisian has resulted in zircon U-Pb ages distributed along the concordia between ca. 3.0 Ga and ca. 2.5 Ga and, thus, it is difficult to ascribe specific protolith ages within this time (Whitehouse and Kemp, 2010; MacDonald et al., 2015). We observe this broad spread of data in the Stoer Group (Figs 4-5). The zircon peak at ca. 2.5 Ga (Fig. 7b) corresponds to the 2490-2480 Ma Inverian event of the Lewisian central region (Humphries & Cliff, 1982; Corfu et al., 1994) and the peak at ca. 1.9 Ga corresponds to felsic magmatism and metamorphism at a number of localities in the Lewisian at approximately this time, including the South Harris Complex, the Ben Stack granites and the Ard gneiss (e.g.,
Whitehouse and Bridgwater, 2001; Park et al., 2001; Mason et al., 2004; Goodenough et al., 2013). Rare zircon grains with approximately 1.7 Ga ages are likely related to pegmatites which intruded into most of the Lewisian at this time (e.g., Park et al., 2001). It is also possible that there was a small contribution of material from distal sources to the west, which became more prevalent by the time of Sleat and Torridon Group deposition (Fig. 7a; Krabbendam et al., 2017).

The detrital populations in the Stoer Group not previously identified (including grains at ca. 3.5 Ga and ca. 3.2-3.1 Ga, as well as Mesoproterozoic ages) can also be attributed to sources in the Lewisian Gneiss Complex. The Palaeoarchaean ages reported from the Stoer Group (3529 ± 30 Ma) may be related to the ca. 3550 Ma inherited core found in a grain from the northern part of the Lewisian Gneiss Complex (Kinny & Friend, 1997). Similarly, the few ca. 3.2-3.1 Ga analyses may be related to the 3115 ± 18 Ma analysis on a zircon core from the central region of the Lewisian Gneiss Complex (Kinny & Friend, 1997).

4.2. Detrital apatite

The U-Pb age distribution of detrital apatite in the Stoer Group contrasts starkly with that of zircon (Fig. 7). Some of the apatite ages are likely to be related to rocks and events known from the zircon record (with the former potentially offset to younger ages due to the lower closure temperature of its U-Pb system), but others are likely related to previously unrepresented events.

The main apatite age peak, centred at ca. 1.7 Ga, represents cooling from amphibolite-facies metamorphism of the Laxfordian event, which is recorded in the Lewisian Gneiss Complex by titanite and rutile ages (Heaman & Tarney, 1989; Corfu et al., 1994; Kinny & Friend, 1997; Love et al., 2010), as well as rare zircon rims (Kinny & Friend, 1997). This event is not well-represented in zircon in the Stoer Group (Fig. 7), consistent with it being low-
temperature metamorphic event, but, as noted above, the few ca. 1.7 Ga zircon grains we observed may have been sourced from pegmatites associated with Laxfordian metamorphism (Park et al., 2001).

Considering the broad distribution of apatite ages between 2.6 and 2.1 Ga, it is noteworthy that zircon, by contrast, is relatively scarce between 2.4 and 2.1 Ga but represented by a clear peak at ca. 2.5 Ga (Fig. 7b). Some of the younger apatite ages may be related to discrete events not recorded by zircon (e.g., at ca. 2.15 Ga) but others most likely represent prolonged cooling and exhumation after the 2490-2480 Ma high-grade Inverian metamorphism in the central region of the Lewisian Gneiss Complex.

Finally, the almost complete absence of >2.5 Ga apatite ages in the Stoer Group, despite the abundance of zircon of this age, is most easily explained by resetting of the U-Pb system in apatite by relatively low-grade metamorphic events having affected the source rocks. Rocks with Archaean zircon U-Pb ages may yield Proterozoic apatite U-Pb ages if they are heated to temperatures above the partial retention window for Pb in apatite (~375-450°C) but not sufficiently high to reset the zircon U-Pb systematics.

4.b.3. Youngest detrital grains

Considering the youngest detrital mineral ages measured in the Stoer Group, the two zircon grains which gave ca. 1.25 Ga ages (and are within 2σ analytical uncertainty of the 1177 ± 5 Ma $^{40}$Ar/$^{39}$Ar age for authigenic K-feldspar in the Stac Fada Member; Parnell et al., 2011) are likely to represent the same source as the small number of apatite grains with ca. 1.2 Ga ages (Fig. 7b). The two youngest zircon grains lack any evidence for shock features typical of impact-induced age resetting (Fig. 3j-m), such as granular textures (e.g., Bohor et al., 1993; Krogh et al., 1993a,b; Kamo et al., 1996; Moser, 1997; Moser et al., 2011; Cavosie et al., 2015; Kenny et al.,
2017, 2019; McGregor et al., 2018). Together with the lack of evidence for impact-related U-Pb discordance in the dataset in general (Fig. 4), this suggests that these youngest ages are not related to Pb loss or recrystallisation associated with the Stac Fada Member impact event itself. In addition to inducing shock deformation and age resetting in zircon, medium to large impact events can also crystallise new igneous zircon and apatite in slowly cooled impact melts (e.g., at Vredefort, South Africa – Kamo et al., 1996; Sudbury, Canada – Davis, 2008; Manicouagan, Canada – Hodych & Dunning, 1992; Morokweng, South Africa – Hart et al., 1997; Koeberl et al., 1997; Mistastin Lake, Canada – Sylvester et al., 2013). However, to the best of our knowledge, zircon which crystallised from impact melt has not previously been reported in distal impact deposits and, given the time required for zircon to first crystallise from an impact melt, such an occurrence seems unlikely. Although it cannot be ruled out entirely, an impact melt origin appears similarly unlikely for the single ca. 1.25 Ga zircon grain in the overlying Poll à Mhuilt Member (Fig. 5d).

We note that the Stoer Group is generally considered to have been deposited prior to the Grenville Orogeny in Scotland (Stewart, 2002), which is dated to ca. 1.1 to 1.0 Ga (e.g., Sanders et al., 1984; Brewer et al., 2003), and the youngest detrital grains are therefore unlikely to be related to even very early Grenvillian orogenesis. However, ages of between 1.1 and 1.3 Ga have previously been reported from the Lewisian Gneiss Complex – early Rb-Sr and K-Ar biotite ages fall in the range of ca. 1148-1169 Ma (Giletti et al., 1961; Moorbath & Park, 1972) – and there are a number of more distal possible sources for the ca. 1.25 Ga grains (e.g., the Gardar Province of South Greenland; Upton et al., 2003). In conclusion, there is no single clear source for the youngest detrital grains in the Stoer Group.
5. Conclusions

Minimal evidence for shock metamorphism or associated Pb loss in zircon or apatite was encountered in this study. Despite extensive efforts at SEM imaging, potentially impact-related planar fractures (PFs) were only identified on the exterior of a single zircon grain. Although a number of zircon and apatite grains in the Stoer Group yielded U-Pb ages within uncertainty of the 1177 ± 5 Ma $^{40}$Ar/$^{39}$Ar depositional age constraint for the Stac Fada Member, neither of the two such zircon grains displayed textures indicative of shock metamorphism and overall there was no clear evidence for impact-induced Pb loss in the dataset.

The new zircon U-Pb data for the Stoer Group reported here are consistent with earlier interpretations that the detritus was derived largely from local Lewisian Gneiss Complex basement but the larger number of analyses in this study resulted in the identification of ages previously undocumented in the Stoer Group; these include grains at ca. 3.5 Ga (the first Palaeoarchaean ages reported from the Stoer Group) and ca. 3.2-3.1 Ga, as well as Mesoproterozoic ages.

Detrital zircon and apatite in the Stoer Group display contrasting age distributions. The first apatite age data for the Stoer Group highlights events either under-represented or absent in the zircon record, with the apatite record dominated by the ca. 1.7 Ga Laxfordian event. Conversely, detrital apatite U-Pb fails to record events older than ca. 2.5 Ga, indicating that all rocks in the sediment source regions older than 2.5 Ga have been heated above the closure temperature of the apatite U-Pb system (~375-450°C).

Neither zircon nor apatite recorded significant changes in U-Pb age distribution across the impact-related Stac Fada Member of the Stoer Group, northwest Scotland. The U-Pb systems in detrital apatite and zircon assemblages do not provide independent support for a major shift in
regional drainage patterns associated with the Stac Fada Member impact event and, as such, do not shed light on the likely location of the impact structure.
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Declaration of interest

None.
Figure 1. Regional geology of northwest Scotland with sample locations for this study. Map modified from Simms (2015). Note that the Torridonian is comprised of the Stoer and Torridon Groups, as well as the Sleat Group which is exposed south of this area. Sample 15BSK_X_SFM is a combination of rocks from the Stac Fada Member (SFM) at all three localities. The Minch basin, proposed as a possible location of the Stac Fada Member-related impact structure by Amor et al. (2008), lies offshore (i.e., where the legend is situated on the map) whereas the centre of the Lairg gravity low, suggested as a possible impact site by Simms (2015), lies approximately 30 km east of the Moine Thrust.
Figure 2. Generalised stratigraphic column for the Stoer Group at Stoer. Modified from Goodenough & Krabbendam (2011; their Fig. 32). Note that only sample 15BSK006 was taken at this locality and the stratigraphic location of the other samples are indicative on a relative time basis. There is significant lateral lithology variation within the Stoer Group (Stewart 2002). SFM – Stac Fada Member. PMM – Poll à Mhuilt Member.
Figure 3. Zircon imaging. (a-c) Zircon grain from sample 15BSK001 (taken from stratigraphically above the Stac Fada Member) which shows potentially impact-related planar microstructures on its exterior. (d-i) Two zircon grains that not did not display any potentially impact-related textures – typical of most grains in this study. Both are from the Stac Fada Member itself. (j-m) The two youngest detrital zircon grains in the Stoer Group – grain 15BSK009/Z/41 (j-k) and grain 15BSK_X_SFM/Z/82 (l-m). Circular features are laser ablation U-Pb analysis pits. BSE – backscattered electron; CL – cathodoluminescence; PFs – planar fractures
Figure 4. Concordia diagrams for detrital zircon (left panels) and apatite U-Pb data (right panels). For zircon data, grey ellipses represent analyses that are more than 10% discordant. For apatite data, grey ellipses represent analyses for which the 2σ uncertainty on the $^{207}$Pb-corrected age was greater than 5%. Number of concordant (for zircon) or low uncertainty (for apatite) analyses vs. total number of grains analysed given for each sample.
Figure 5. Detrital zircon and apatite U-Pb age distributions. Zircon data are $^{207}$Pb/$^{206}$Pb ages for analyses which were less than 10% discordant whereas apatite data are $^{207}$Pb-corrected apatite U-Pb ages which had 2$\sigma$ age uncertainties less than 5% (black ellipses in Fig. 4). Kernel density estimates were plotted in the ‘DensityPlotter’ program of Vermeesch (2012) in which the optimal bandwidth is calculated according to the method of Botev et al. (2010). SFM – Stac Fada Member.
Figure 6. Cumulative distribution function (CDF) and quantile-quantile (QQ) plots for detrital zircon $^{207}$Pb/$^{206}$Pb ages and detrital apatite $^{207}$Pb-corrected ages. (a) apt – apatite; zrc – zircon. (b) Dots represent the 0, 5, 10, ..., 95 and 100 percentiles (or ‘quantiles’) of the samples whose names are shown on the X- and Y-axis, respectively. A pair of samples have identical distributions if their percentiles fall on the 1:1-line (Vermeesch 2013).
Figure 7. Compiled detrital zircon, apatite and rutile U-Pb age distributions for the Stoer and Torridon Groups. Note that zircon and rutile data for the Torridon Group from Krabbendam et al. (2017) are only from sample ZY320 (which was taken at Grunard Bay, near Rainbird et al.’s [2001] sample GY96-56; Krabbendam et al. 2017; p. 76), and therefore does not include data for Krabbendam et al.’s sample ZY327, which was taken approximately 60 km further south. Zircon and rutile data are $^{207}\text{Pb}/^{206}\text{Pb}$ ages for analyses that were less than 10% discordant whereas apatite data are $^{207}\text{Pb}$-corrected apatite U-Pb ages that had 2σ age uncertainties less than 5%. KDE – kernel density estimate.
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Supplementary Appendix 2
Kolmogorov-Smirnoff (K-S) statistical test results

The numbers displayed in the tables below are P-values. Where these are less than 0.05, it is statistically likely (at a 95 % confidence level) that the two samples are from different populations. For example, for the zircon data and when the error in the CDF (Cumulative Distribution Function) is considered this is only the case for two pairs: 15BSK006-15BSK009 and 15BSK006-15BSK_X_SFM (not highlighted in orange).

Tests conducted using the Excel Macro made available by Guynn & Gehrels (2010). The algorithm for the test was adapted from Press et al. (1986) and has been used for detrital zircon analysis previously (e.g., Berry et al. 2001; DeGraaff-Surpless et al. 2003).

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Table 1. Results of K-S tests comparing detrital zircon $^{207}\text{Pb}/^{206}\text{Pb}$ age populations. Only for zircon analyses that were less than 10% discordant. A) Values that pass the test for a 95% confidence level and are not rejected are highlighted in orange. (Note that when all U-Pb data are
considered, i.e. when they are not screened for discordance, only the same two pairs of samples are rejected.) B) P-values for no consideration of uncertainty in the age measurements. Pairs that have different test conclusions to that reached in A are highlighted in red. These are pairs of samples that were statistically likely to be from the same source when the uncertainty in the age was considered (A) but do not appear to be statistically likely to be from the same source once the uncertainty in the age has been considered (B). C) Average K-S P-values using Monte-Carlo (with 2σ of the P-value using Monte-Carlo shown in parentheses). For these results, values are highlighted in blue if the P-value range defined by two standard deviations (95% confidence level) overlaps the 0.05 P-value. This means that some of the synthetic distributions passed the test and some failed, at the 95% confidence level. It shows us that for the two sample pairs that failed in the test in A, neither of them had a significant number of synthetic distributions pass the test, i.e. had P-values greater than 0.05.
A) K-S P-values using error in the CDF

| apatite       | 15BSK001 | 15BSK006 | 15BSK008 | 15BSK009 | 15BSK_X_SFM |
|---------------|----------|----------|----------|----------|-------------|
| 15BSK001      | 1.000    | 0.733    | 0.675    | 0.735    |             |
| 15BSK006      | 0.411    | 0.733    | 0.421    | 0.602    |             |
| 15BSK008      | 0.675    | 0.411    | 0.622    | 0.547    |             |
| 15BSK009      | 0.735    | 0.602    | 0.547    | 0.952    |             |
| 15BSK_X_SFM   | 0.735    | 0.602    | 0.547    | 0.952    |             |

B) K-S P-values using no error

| apatite       | 15BSK001 | 15BSK006 | 15BSK008 | 15BSK009 | 15BSK_X_SFM |
|---------------|----------|----------|----------|----------|-------------|
| 15BSK001      | 0.865    | 0.531    | 0.391    | 0.516    |             |
| 15BSK006      | 0.124    | 0.100    | 0.463    |          |             |
| 15BSK008      | 0.350    | 0.257    | 0.808    |          |             |
| 15BSK009      | 0.183    | 0.364    | 0.742    |          |             |
| 15BSK_X_SFM   | 0.248    | 0.248    | 0.742    |          |             |

C) Average K-S P-values using Monte-Carlo

| apatite       | 15BSK001 | 15BSK006 | 15BSK008 | 15BSK009 | 15BSK_X_SFM |
|---------------|----------|----------|----------|----------|-------------|
| 15BSK001      | 0.797(0.351) | 0.336(0.283) | 0.339(0.270) | 0.424(0.229) |
| 15BSK006      | 0.164(0.187) | 0.183(0.215) | 0.383(0.237) |
| 15BSK008      | 0.364(0.249) | 0.248(0.210) |          |          |
| 15BSK009      | 0.742(0.307) |          |          |          |
| 15BSK_X_SFM   | 0.248(0.210) | 0.742(0.307) |          |          |

Table 2. Results of K-S tests comparing detrital apatite $^{207}$Pb-corrected age populations. Only for apatite analyses that had $2\sigma$ age uncertainties less than 5%. Colours as in Table 1. Note that
using populations with less strict rejection criteria produces very similar results. For example, including data that had $2\sigma$ age uncertainties up to 10% also results in no sample pairs appearing, at a 95% confidence level, to be sourced from different populations.