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Title	K-feldspar sand-grain provenance in the Triassic, west of Shetland : distinguishing first-cycle and recycled sediment sources?
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Publication date	2009-11
Publication information	Tyrrell, Shane, Sophie Leleu, A. Kate Souders, Peter D. W. Haughton, and J. Stephen Daly. "K-Feldspar Sand-Grain Provenance in the Triassic, West of Shetland : Distinguishing First-Cycle and Recycled Sediment Sources?" 44, no. 6 (November, 2009).
Publisher	John Wiley and Sons
Item record/more information	http://hdl.handle.net/10197/3056
Publisher's statement	This is the authors' version of the following article: "K-feldspar sand-grain provenance in the Triassic, west of Shetland: distinguishing first-cycle and recycled sediment sources?" (2009) published in Geological Journal, 44 : 692-710. It is available in its final form at http://dx.doi.org/10.1002/gj.1185
Publisher's version (DOI)	10.1002/gj.1185

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**K-feldspar sand-grain provenance in the Triassic, west of Shetland:
distinguishing first-cycle and recycled sediment sources?**

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Abstract:

Sandstone provenance studies can help constrain palaeogeographic reconstructions and ancient drainage system scales and pathways. However, these insights can be obscured by difficulties in geochemically distinguishing or adequately characterising potential sourcelands, or by failure to identify sedimentary recycling. Triassic basins west of Shetland accumulated ~2.5 km of sand-rich sediment. The Middle-Upper Triassic Foula Formation represents fluvial, aeolian and sabkha facies deposited in the northern interior of the Pangean supercontinent. Published U-Pb zircon geochronology and heavy mineral analysis suggest that these sandstones were derived from East Greenland. They contain significant fresh K-feldspar which is likely to be first-cycle and derived directly from its source. Pb isotopic analyses of individual K-feldspar sand-grains show a single, unradiogenic Pb population, consistent with the provenance indicated by U-Pb zircon geochronology. Archaean and Palaeo-Mesoproterozoic rocks – the Nagssugtoqidian Mobile Belt, the Lewisian Complex or equivalents - are the likely source, with terranes south of the Moine Thrust (Grampian, Caledonian and Variscan) ruled out by both the Pb and U-Pb data. However, it is not possible to distinguish between rift flank sources to the east and west, as both areas have similar crustal affinity and/or share the same tectonic history.

It is possible that the sediment was derived from the West Shetland Platform and not from Greenland. The comparison of provenance signals from robust and less stable mineral phases provides a means of recognising sedimentary recycling. Robust zircon populations and less stable feldspar in Foula Formation sandstones concur in indicating the same source, suggesting that they are likely to be first-cycle. The Triassic sand supply can be contrasted with that in Upper Carboniferous (Namurian) basins in the north of England where a significant zircon population has no corresponding K-feldspar component. This zircon population is likely to have been recycled from Lower Palaeozoic greywackes from the Southern Uplands Belt or its along strike extension.

Keywords: Provenance, Pb isotopes, K-feldspar, Triassic, recycling.

1: Introduction:

Determining the provenance of sands and sandstones is a vital tool in reconstructing palaeogeography (e.g., Haverkamp *et al.* 1992; Cawood *et al.* 2004). Provenance studies offer important constraints on drainage scales and sediment pathways in ancient depositional systems (Cliff *et al.*, 1991; Hallsworth and Chisholm, 2008) and on the evolution of modern large rivers (Morton and Johnsson 1993; Clift *et al.* 2001; Najman *et al.* 2008). An understanding of drainage scales and routeways can help in the prediction of sandstone distribution and reservoir quality in the subsurface (Tyrrell *et al.* 2007). However, provenance studies can have some inherent and critical shortcomings. They are limited by the ability to identify, characterise and geochemically distinguish potential sourcelands. Often, the detrital grains end up being far better characterised than the full range of potential sourcelands. Additionally, the use of provenance studies in reconstructing palaeodrainage is hampered by difficulties in recognising sedimentary recycling and mixing. Seemingly far-travelled grains may have been delivered close to the basin during a previous erosion and transport cycle.

With the advent of *in-situ* micro-analytical methods, provenance studies increasingly exploit geochemical and/or isotopic signals in single mineral grains. This helps avoid

some of the mixing or ‘averaging’ issues associated with analysis of bulk samples. However, although these techniques enable the likely sourcelands to be determined, the transport history experienced by individual framework components remains unconstrained. Robust minerals such as zircon can be recycled through one or more intermediary sediments or sedimentary rock (Dickinson *et al.*, 2009), thus introducing a natural bias, which is difficult to quantify. Feldspar is prone to mechanical and chemical breakdown, especially in humid climates (Tucker, 2001), and can undergo albitisation and partial/dissolution during burial diagenesis (Wilkinson *et al.* 2001). Previous studies which have utilised the Pb-in-K-feldspar tool have demonstrated that K-feldspar in Upper Jurassic sandstones in the Porcupine Basin, west of Ireland, cannot have been reworked from Lower Triassic sandstones in the nearby Slyne Basin (Tyrrell *et al.*, 2007). Although it remains to be more thoroughly tested, this evidence suggests that K-feldspar is less likely to survive sedimentary recycling. Therefore, if present, it can be regarded as first-cycle detritus (Tucker, 2001). In this way, careful integration of complementary provenance tools can offer more precise source identification and can facilitate the recognition of recycled detrital signals. U-Pb zircon geochronology provides information on the age range of the detritus, which may be first or multi-cycle, whereas the Pb isotopic composition of K-feldspar sand grains is more likely to preserve a first-cycle signal derived directly from the source (Tyrrell *et al.*, 2007).

Recent studies have demonstrated the utility of the Pb isotopic composition of detrital K-feldspar as a sand provenance tool, particularly when applied on a regional scale (Hemming *et al.* 1996, Tyrrell *et al.* 2006, 2007; Clift *et al.* 2008). Pb isotopes vary in the crust on a sub-orogenic scale and it has been shown that detrital K-feldspar can retain the signature of its source despite erosion and transport (Tyrrell *et al.* 2006). It has also been demonstrated for two source-sediment pairs, that diagenesis, even that involving recrystallisation of K-feldspar grains, has not altered the Pb isotopic composition (Tyrrell *et al.* 2006). As K-feldspar normally has low contents of the radioactive isotopes of U and Th, the Pb isotopic signature is conservative over time. Moreover Pb isotopic analysis of individual K-feldspar sand grains can be carried out *in-situ* using laser ablation multiple collector inductively coupled plasma mass spectrometry (LA-MC-ICPMS). Imaging prior to analysis allows intra-grain heterogeneities (albitised or altered areas, inclusions, authigenetic features), which

have the potential to compromise the Pb isotopic signal, to be avoided during laser ablation.

This paper, forming part of a wider study dealing with Triassic provenance in Atlantic margin basins (e.g., Tyrrell *et al.* 2007), presents new K-feldspar Pb data from Middle-Upper Triassic Foula Formation sandstones from west of Shetland, and compares these with published U-Pb zircon provenance datasets from these rocks. The aim is to further constrain Triassic sand provenance west of Shetland, and relate it with other basins along the Atlantic margins, while also advocating the use of an integrated approach to provenance, utilising signals in both the more robust and less stable component of the sandstone. This study demonstrates how sedimentary recycling may be identified by integrating Pb in K-feldspar and U-Pb zircon datasets. The utility of this approach is further illustrated by comparing the Triassic results with an analogous dataset from older Namurian sandstones from northern England.

2: Geological Background:

2.1 Triassic sand dispersal on the NW European Margin:

Triassic rocks of northwest Europe comprise two regionally extensive red-bed sedimentary packages – the Lower Triassic Sherwood Sandstone Group (SSG) and equivalents and the Middle-Upper Triassic Mercia Mudstone Group (MMG), which is only locally sand-prone (Warrington *et al.* 1980; Figure 1; Figure 2). The SSG was deposited in the arid to semi-arid interior of the Pangaeon Supercontinent and represents large-scale fluvial and alluvial systems with subordinate ephemeral fluvial and aeolian deposits (Warrington *et al.* 1980). This package evolves upwards into a fine-grained dominantly playa sequence with subordinate fluvial, aeolian and sabkha facies (the MMG). Both groups are encountered in a number of NW European sedimentary basins where they locally form important hydrocarbon reservoirs and aquifers. Their distribution and depositional style are well understood in the Paris and North Sea basins and onshore Britain. The Variscan Uplands of central Europe appear to have exerted a strong control on drainage into these basins, resulting in large-scale, south-to-north flowing rivers (i.e., the ‘Budleighensis’ river system; Audley-Charles 1970; Warrington and Ivimey-Cooke, 1992). Although the Triassic succession further

to the west and north is known to host hydrocarbon reservoirs (e.g., the Corrib and Strathmore fields), the nature, origin and pattern of Triassic drainage in the peripheral and under-explored NE Atlantic basins remain poorly constrained.

Recently published provenance studies have shed new light on the nature and origin of Triassic sandstones in the NE Atlantic margin basins. K-feldspar in Lower Triassic sandstones of the Corrib gasfield, Slyne Basin, offshore west of Ireland (Figure 1) was probably sourced from Archaean and Proterozoic rocks (Tyrrell *et al.* 2007), indicating derivation from the north and west. These data preclude the Irish Mainland to the east or the remnant Variscan Uplands to the south as a sand source, indicating no linkage between the drainage systems operating in the NE Atlantic margin and those onshore Britain. Further to the north, in the Foula Formation (Middle-Upper Triassic) of the Faeroe-Shetland and West Shetland basins (Figure 1), U-Pb zircon geochronology and heavy mineral analysis (Morton *et al.* 2007) indicate a composite Archaean-Palaeoproterozoic sand source, which the authors interpret to have been derived from east Greenland.

2.2 Triassic development west of Shetland

The major Triassic basins west of Shetland have trends varying between NE-SW and NNE-SSW (Hitchen *et al.* 1995). Originally forming a single depocentre, the Triassic basins were subsequently dissected, and currently comprise a series of basins divided by ~N-S trending ridges (Figure 3). A >2.5 km thick Triassic succession is inferred in the West Shetland Basin, but appears to thin in the Faeroe-Shetland Basin, west of the Rona Ridge (Figure 3). The Triassic succession in these basins consists of the Lower Triassic Otter Bank Formation (equivalent to the SSG) and the Middle-Upper Triassic Foula Formation (a sand-rich equivalent of the MMG; Figure 2). The Otter Bank Formation is envisaged as being derived transversely from the uplifted eastern and western rift-flanks during a major phase of early Triassic rifting. Foula Formation sandstones are interpreted as marking the establishment of a southward propagating axial braidplain system, deposited during a period of minor and intermittent tectonism (Swiecicki *et al.* 1995). The Foula Formation, reaching a maximum thickness of ~1.1 km in well 205/27-1, comprises mineralogically immature medium to fine-grained sandstones with subordinate silt and mudstones.

The lower part of the Foula Formation has been interpreted as an interbedded sequence of fluvial and aeolian sabkha deposits, with fluvial facies dominating at higher levels in the formation (Swiecicki *et al.* 1995; Herries *et al.*, 1999). Palynology suggests that deposition of this unit commenced during the Ladinian (Swiecicki *et al.* 1995). Petrography indicates derivation from a high grade metamorphic terrane (Herries *et al.* 1999). Palaeocurrents, inferred from high resolution dipmeter logs (Herries *et al.*, 1999), are variable, but dominantly suggest sediment transport along-east-west axes and from the north.

High detrital garnet and rutile abundances in the Foula Formation sandstones were interpreted to indicate a high-grade, possibly granulite-facies, metamorphic source terrane (Morton *et al.* 2007). High-Mg, low-Ca garnets are dominant, and because these are uncommon in rocks onshore Scotland, Morton *et al.* (2007) suggested a source in East Greenland. Detrital zircon U-Pb geochronology revealed a strong ~1880 Ma signal, which Morton *et al.* (2007) linked to the Nagssugtoqidian Mobile Belt of Eastern Greenland, arguing that this age is uncommon on the eastern margin (i.e., in Scotland including the Lewisian Complex). There is also a relatively minor Permian acidic igneous zircon component, which cannot be linked to a known source on either side of the rift, though Morton *et al.* speculate that this is derived from the Greenland margin. Although derivation from Rockall Bank cannot be ruled out, Morton *et al.* (2007) argue that this area is an unlikely source as the Rockall Bank is considered contiguous with the Ketilidian Belt of southern Greenland (see below), from which ages ~1750 Ma would be anticipated (Daly *et al.* 1995).

2.3: Source areas for west of Shetland Triassic?

Triassic sediments record the early break-up of Pangaea, but the major rifting which culminated in the opening of the North Atlantic between the European and Greenland margins did not commence until the late Cretaceous (Roberts *et al.* 1999). The area to the immediate east and south of the studied wells comprises an assembly of high-grade metamorphic terranes, many with Archaean protoliths (~2.65 – 3.15 Ga), which have been extensively reworked and intruded during the Palaeoproterozoic (1.75 – 1.9

Ga). These rocks – the Lewisian Complex (Figure 3) – are well studied onshore, where they occur west of the Moine Thrust, and though their occurrence is well constrained (i.e. the West Shetland Platform), less is known about the precise affinities of the offshore equivalents. The Lewisian Complex is partially covered by Neoproterozoic sedimentary Torridonian Supergroup, which comprises an older Stoer Group sequence of fluvial and lacustrine red sandstones and mudstones deposited directly on the Lewisian. These are overlain unconformably by ~7 km of dominantly fluvial Torridon Group sandstones which are the youngest and most volumetrically significant part of the sequence (Stewart 2002). Locally, fluvial and lacustrine sandstones form a third component, the Sleat Group, which was deposited directly on Lewisian Complex rocks, but is conformably overlain by the Torridon Group. The relationship between the Stoer and Sleat Group is never observed (Stewart 2002).

Palaeogeographic reconstructions indicate that during the Triassic the southeast Greenland margin lay immediately to the west of the studied basins (Figure 3). The modern geology of this region comprises a series of east-west trending tectonic belts. The far south of Greenland is composed of the c. 1.85 – 1.75 Ga Ketilidian orogen (Garde *et al.* 2002). To the north, the North Atlantic Craton is comprised of Archaean rocks, which have experienced minimal Proterozoic reworking. Further north, the Nagssugtoqidian Mobile Belt consists of the Isertoq and Tasilaq blocks with Archaean protolith ages (~3.0 – 2.6 Ga), which have been extensively reworked and intruded during the Palaeoproterozoic (1.8 – 1.9 Ga). The intervening c. 1.9 Ga Ammassalik Block is a linear belt of juvenile Palaeoproterozoic crust.

Correlations between southeast Greenland and NW Scotland are tentative, but recent revaluations of Lewisian terranes have suggested links with the Nagssugtoqidian Mobile Belt of east Greenland (Friend and Kinny 2001; Kinny *et al.* 2005). These potential links are highlighted in the palaeogeographic reconstruction shown in Figure 3.

Although the distribution of the Lewisian Complex offshore is generally well known (Figure 3) and U-Pb zircon geochronology has confirmed Archaean protolith ages in at least three wells west of Shetland (F. Darbyshire, pers. comm., 2004), detailed studies on the nature and geological history of the Precambrian basement, especially

on the West Shetland Platform and Rona Ridge are lacking, hampering efforts to construct a more rigorous correlation with eastern Greenland. This also impacts on provenance studies in younger basin fills, as potentially important sources remain poorly characterised.

U-Pb geochronological and Sm-Nd isotopic data from the Stanton Banks (Figure 3) suggest that this basement high represents a juvenile Palaeoproterozoic terrane within the Lewisian Complex (Scanlon *et al.*, 2003). The southern portion of the Rockall Bank has been correlated with the Ketilidian mobile belt on the basis of geochronology (Morton and Taylor 1991), but isotopic data from Cenozoic basalts on the northern bank (Hitchen *et al.* 1997) suggest the basement here has an Archaean affinity, likely correlated with the North Atlantic Craton of Eastern Greenland. Recently, Cretaceous sandstones in the Hatton Basin, interpreted as being derived from local basement, have yielded zircon geochronological data which suggests that the Edoras and Hatton Banks have a Ketilidian affinity (Morton *et al.*, 2009).

In provenance studies generally, there are inherent difficulties in constraining potential source areas because of erosion level differences between the contemporary and modern surfaces. Potential source rocks, available in the past, may have been completely eroded from the geological record. The geology of the modern hinterland may not accurately reflect the nature and distribution of potential sources in the geological past. However, it may be possible, through indirect means, to place some constraints on the likely exposure of potential sediment sources in the past.

Though there are difficulties constraining the Triassic erosion level in the study area, recent provenance work has indicated that the onshore Lewisian Complex, or its offshore equivalents, was already available as a source for sandstones in the Pennine Basin, onshore Britain during the Upper Carboniferous (Tyrrell *et al.* 2006). This would suggest that if the Lewisian Complex was buried during the Triassic, the age of its cover would have to be of Uppermost Carboniferous (Westphalian, Stephanian), Permian or earliest Triassic age. In some basins, thick Permian sedimentary sequences have been interpreted to lie unconformably on Lewisian basement, for example in the West Orkney Basin (Hitchen *et al.* 1995), but elsewhere Triassic sandstones were deposited directly on Proterozoic basement, e.g., in well 156/17-1 (Figure 3) and on

Raasay, inner Hebrides. Early Permian volcanics have also been recorded (Hitchen *et al.* 1995) in some offshore wells (i.e. in well 205/27a-1). The evidence, therefore, suggests that Lewisian Complex rocks cropped out during the Triassic, perhaps with a partial cover of Permian sedimentary rocks.

3: Methods:

3.1 Sampling, imaging and EMPA analysis

Cores from two wells (204/29-1 and 205/27a-1) were logged and sampled. Well 204/29-1 penetrates the Foula Formation within the Færoe-Shetland Basin and well 205/27a-1 was drilled on the western margins of the West Shetland Basin (Figure 3). A single core (core 1) of Upper Foula Formation sandstones was sampled from well 204/29-1. Seven cores of Permo-Triassic sedimentary rocks were recovered from well 205/27a-1, of which three were sampled in this study. These comprised samples from Foula Formation sandstones from cores 1 and 2, and Upper Permian sandstones from core 5. Upper Permian sandstones were sampled in order to compare their detrital populations with those from the Triassic.

The logged Triassic cores dominantly comprise fluvial deposits with a stacked succession of channel fills intercalated by levee and highly-bioturbated overbank sediments. Channel facies typically comprise cross-bedded, well-sorted, medium sandstones, forming units ~2.5 m thick, and often have coarse basal lags containing mudclasts. In well 205/27a-1, cores 1 and 2, channel fills are commonly stacked into >6m thick packages, with bed thickness up to 3.5 m. They contain cross-stratified units with conglomeratic lags at the base, passing to planar low angle cross-stratified medium-grained sandstones. Levees consist of stacked ripple-laminated medium to very fine-grained sandstones (0.5 - 1.5 m thick), while overbank deposits comprise mudstones and siltstone beds, (typically 0.1 – 0.5 m thick, but can be up to 3 m) showing horizontal fine lamination or ripple lamination. Overbank facies are often burrowed and contain abundant calcrete nodules, which are often reworked into overlying channel fills. In order to investigate possible links between facies and

detrital grain populations, sandstones from both channel fill and levee deposits were sampled.

The petrography of individual samples was assessed using standard optical microscopy. The sampled sandstones range from well-sorted to poorly sorted, with sub-angular grain shapes prevalent. Mineralogically, the sandstones are quartzose, varying from sub-arkosic to arkosic, with some sub-lithic compositions. Lithics are predominantly metamorphic, comprising quartzite, gneissic and granitic rock fragments. Garnet occurs as a relatively common accessory phase. Cements vary from dominantly carbonate (including dolomite) to patchy carbonates with minor clays. Porosities range up to ~15%.

Thin sections of ~300µm thickness were prepared in which K-feldspar grains were imaged using backscatter electron (BSE) and cathodoluminescence (CL) at the Electron Microprobe Laboratory, Geowissenschaftliches Zentrum, Göttingen, Germany. A subset of imaged target grains was analysed quantitatively by electron microprobe to determine their bulk compositions.

3.2 Pb analysis:

Pb isotopic analyses were carried at the Microanalysis Facility, InCo Innovation Centre, Memorial University, Newfoundland using a Neptune MC-ICPMS coupled to a Geolas 193nm Excimer laser. The use of LA-MC-ICPMS to analyse the Pb isotopic signal offers advantages over other analytical techniques. The data can be acquired rapidly *in situ*, thereby retaining the grain context within the sample. Previous studies have used multiple- and single-grain leaching techniques coupled with thermal ionisation mass spectrometry (TIMS; Hemming *et al.* 1996), but this approach does not allow potential intra-grain heterogeneities to be avoided during analysis. *In-situ* analysis by ion microprobe (Clift *et al.* 2001; 2008) provides high spatial resolution (~20µm spot sizes), but produces consistently larger errors on ^{204}Pb dependent ratios than LA-MC-ICPMS analysis. In previous LA-MC-ICPMS Pb K-feldspar work (Tyrrell *et al.* 2006, 2007), data could only be retrieved from grains larger than ~300µm long axis, but refinement of the technique (detailed below) permits Pb

isotopic analysis of finer-grained material and with similar levels of spatial resolution ($\sim 20\mu\text{m}$ laser spot sizes) to those obtained using the ion microprobe.

Two different collector array configurations were employed during the acquisition of the isotopic data. The initial analyses were carried out using Faraday cups, similar to the technique detailed in Tyrrell *et al.* (2006). For this configuration, the laser was operated at 7 Joules/cm^3 , with a repetition rate of 20 Hz and spot sizes between 99 and $158\mu\text{m}$. The stage was rastered at $3\mu\text{m/s}$ producing a track length of $\sim 300\mu\text{m}$ per analysis. It was necessary to ablate in this manner in order to produce a sufficiently strong ^{204}Pb ion beam (the least abundant isotope Pb isotope) in order to achieve acceptable errors in ^{204}Pb dependent isotopic ratios. This approach limited the minimum size of target grains to greater than $300\mu\text{m}$ long axis (medium-grained and coarse sand).

The concentration of Pb in individual K-feldspar grains also limited the use of the Faraday collector array. Grains with low Pb concentration ($<30\text{ ppm}$) produced weak Pb ion beams, resulting in unacceptably poor errors ($2\text{SE} > 1\%$) in Pb isotopic ratios. In order to analyse Pb-poor and finer sand grains, analyses were carried out using an ion counter collector array, largely following the procedure outlined in Souders and Sylvester (2008). This configuration enabled precise analysis of grains with low Pb concentration and using lower ablation volumes (i.e. use of small spot sizes instead of tracks). Prior to Pb isotopic analysis, Pb concentrations (along with U and Th concentrations) of individual grains were determined using the laser coupled to an Element ICPMS. These data allowed for the adjustment of laser spot sizes according to the Pb concentration of each grain, thus avoiding detector damage due to strong ion beams.

Though much useful data was obtained using the Faraday collector configuration, the ion counter method represented a significant improvement. The laser was operated at 5 joules with a repetition rate of 10 Hz, and spot size varied between $69\mu\text{m}$ (for grains $<5\text{ ppm Pb}$) and $20\mu\text{m}$ (for grains $>140\text{ ppm Pb}$). The use of single small spots instead of tracks enabled the analysis of grains with long axes $<100\mu\text{m}$ (very fine-

grained sand). Analytical uncertainties (2SE on $^{206}\text{Pb}/^{204}\text{Pb}$) are typically <0.5% for the Faraday configuration and typically <0.25% with the ion counter array.

For both configurations, ^{204}Pb , ^{206}Pb , ^{207}Pb and ^{208}Pb as well ^{202}Hg , to correct for isobaric interference of ^{204}Hg on ^{204}Pb . Standard-sample bracketing, using standard glass BCR2g, was employed to correct for instrumental mass bias. The analytical sequence comprised repetitions of three standards and three unknowns. In addition, to test for internal consistency during analytical sessions, Shap Granite K-feldspar was also analysed periodically. 49 analyses of Shap K-feldspar using the ion counter configuration were carried out, yielding a mean $^{206}\text{Pb}/^{204}\text{Pb}$ composition of 18.286 (standard deviation = 0.10), which is within error of previous LA-MC-ICPMS analyses (mean = 18.245, n = 60, standard deviation = 0.023; Tyrrell *et al.* 2006).

4 Results:

K-feldspar Pb data from the Foula Formation sandstones are shown in Table 1. The data comprise Pb isotopic analyses of 53 K-feldspar grains from nine samples of Foula Formation sandstone and six K-feldspar grains from one sample of Late Permian sandstone from core 5, well 205/27a-1. Of these, 38 were analysed using the ion counters after first determining their Pb, U and Th concentrations. Pb concentrations varied significantly – from 5.5 ppm to 63.7 ppm (mean = 34.07 ppm Pb). U and Th concentrations are typically very low (<0.001 ppm), with 4 grains exhibiting outlying compositions (highest U = 1.7 ppm, highest Th = 1.34 ppm). The Pb isotopic composition of the remaining 15 grains was measured using the Faraday cup configuration (see above).

Pb isotopic analysis of detrital K-feldspar grains from Foula Formation sandstones reveal a radiogenic composition with mean $^{206}\text{Pb}/^{204}\text{Pb}$ = 13.87, mean $^{207}\text{Pb}/^{204}\text{Pb}$ = 14.8 and mean $^{208}\text{Pb}/^{204}\text{Pb}$ = 34.5. There are no discernable differences between Pb analyses carried out using the Faraday cups and ion counters.

When plotted (Figure 4), the Foula Formation data form a broadly linear array typical of that observed in Palaeoproterozoic and older K-feldspars, with a few outlying

compositions. The dispersal of Pb isotopic ratios, a phenomenon not observed in younger K-feldspars, is likely the result of variable radiogenic growth. K-feldspars with a common initial isotopic composition will generate such arrays as a result of even small variations in U and Th concentration. Further complications arise from the fact that K-feldspars of the same age can exhibit significant variations in initial isotopic composition. Consequently the characteristics of the resulting ‘pseudo-growth curves’ are very difficult to constrain.

In this study, Pb data are plotted in $^{206}\text{Pb}/^{204}\text{Pb}$ - $^{208}\text{Pb}/^{204}\text{Pb}$ lead space. This appears to provide the optimum spatial pattern for comparing potential source and detrital data. On the $^{206}\text{Pb}/^{204}\text{Pb}$ - $^{207}\text{Pb}/^{204}\text{Pb}$ diagram the data tend to collapse into overlapping linear arrays (Figure 4). This linearity can be ascribed to radiogenic growth of uranogenic lead alone, whereas the combination of uranogenic and thorogenic lead (i.e., in the $^{206}\text{Pb}/^{204}\text{Pb}$ - $^{208}\text{Pb}/^{204}\text{Pb}$ diagram) results in broad fields of less constrained geometry, more amenable to comparing data sets.

BSE and CL imaging of K-feldspar grains reveal a variety of grain morphologies, inclusions and perthite types. K-feldspars are generally sub-angular to sub-rounded, occasionally lath-like, and are dominantly perthitic, commonly showing thin (> 5), and occasionally pseudo-ellipsoidal, albitic lamellae. Inclusions dominantly comprises rounded albites and quartz, and, more rarely, apatite and zircon. The grains generally have a fresh, unaltered appearance, but very occasionally show areally restricted albitisation, often as ~ 20 - 50 μm thick veins. Thin authigenic overgrowths are sometimes observed, but are rare. Electron microprobe analysis of a subset of the K-feldspar grains show a very restricted range of bulk K-feldspar composition (Or : Ab : An) between $83.58 : 14.95 : 1.47$ and $96.58 : 3.35 : 0.07$, with mean composition of $92.53 : 7.29 : 0.18$. No correlation was observed between bulk feldspar and Pb isotopic composition.

5 Discussion:

5.1 Foula Formation provenance

There is no correlation with depth over a range of 600m in well 205/27a-1, and though the sampling was concentrated in the upper parts of the formation, this suggests that the source area remained broadly similar at least for the sampled succession. K-feldspar grains from Upper Permian sandstone in well 205/27a-1 indicate the same Pb isotopic composition as that in the Foula Formation, though the Permian dataset is currently too small to draw any firm provenance conclusions. There is no discernable correspondence between detrital K-feldspar Pb population and sandstone facies type, although higher resolution sampling of the stratigraphy would be required in order to verify this statistically.

Data from Foula Formation K-feldspars are compared with published and new Pb isotopic data from potential sources (Figure 5). The unradiogenic Pb isotopic composition of the Foula Formation detritus indicates that more radiogenic Pb domains (Figure 7C), including potential sources south of the Moine Thrust (i.e., NW Highlands, Grampian Terrane, Midland Valley etc.) can be ruled out as sources for K-feldspar in the Foula Formation sandstones.

The Foula Formation data correspond well to those of basement rocks in the Lewisian Complex of NW Scotland and the Nagssugtoqidian Mobile Belt of Eastern Greenland – two crustal domains, which have been previously correlated with one another (Kalsbeek *et al*, 1993, Kinny *et al*, 2005). Detrital K-feldspar Pb data from Foula Formation sandstones partially overlap those from the Palaeoproterozoic Lewisian on the Stanton Banks and whole-rock Pb data from the Uist Block and Rhiconich Terrane Gneisses, both Archaean components of the Lewisian Complex (Figure 5). There is poor correspondence with the Nis Terrane anorthosites and with Palaeoproterozoic rocks from the Rockall Bank. The Ketilidian of southern Greenland is likely isotopically contiguous with the Rockall Bank and therefore, although it cannot be ruled out, seems unlikely to provide a source for K-feldspar in the Foula Formation.

Detrital K-feldspar Pb data from Foula Formation sandstones also correspond well with certain elements from Greenland, specifically with K-feldspar data from the Nagssugtoqidian Mobile Belt in western Greenland, and whole-rock Pb data from the Kangertigtivatsiaq granulites of eastern Greenland). There is poor correspondence

with the Rinkian Domain of western Greenland, and the Ammassalik Intrusive Complex, and its associated gneisses, from eastern Greenland.

A small subset of data (6 grains), appearing to correspond with gneissic complexes from eastern Greenland (Blokken gneiss and Smalsund gneiss; Figure 5), do not correspond with any Pb domains from Lewisian Complex rocks. This evidence suggests a unique East Greenland source for the Foula Formation detrital K-feldspars. However, given that many elements of the Lewisian Complex, particularly the volumetrically significant portion occurring as offshore basement highs, remains poorly characterised, the Pb evidence alone is not considered sufficient to argue the case strongly for a unique East Greenland source.

The data were compared with a small dataset from Torridonian Supergroup sandstones in order to investigate potential recycling from these sedimentary rocks. There is good correlation between detrital K-feldspar Pb data from Foula Formation sandstones and from specific stratigraphic elements from the Torridonian Supergroup (Figure 5). The Foula Formation data overlap with K-feldspar Pb isotopic compositions from the Stac Fada Member of the older Stoer Group and correspond very well with similar data from Diabaig Formation sandstones from the Torridon Group. There is no correlation with K-feldspar data from the volumetrically significant Applecross Formation sandstones of the Torridon Group. However, it is considered highly improbable that recycled Torridonian K-feldspar sandstones could contribute significantly to Foula Formation sandstones. If K-feldspar were to be derived from the Torridonian in this manner, it would be expected that the youngest and most voluminous formation, i.e., the Applecross Formation, would contribute the most detritus. However this is clearly not the case (Figure 5). At the very least it might be anticipated that derivation from the Torridonian would produce a mixed population of grains, with contributions from different parts of the Torridonian stratigraphy, but this is clearly not observed either. It would take a very special set of circumstances to derive K-feldspar into the Foula Formation entirely from the lower parts of the Torridonian stratigraphy, without deriving any detritus from the overlying rocks. Therefore, the overlap in Pb isotopic data between Foula Formation K-feldspars and those from the Diabaig Formation and Stac Fada Member of the Torridonian are better explained by all three units sharing the same provenance.

Morton *et al.* (2007) argued that the strong 1880 Ma signal in U-Pb detrital zircon in the Foula Formation supports a source in East Greenland. However, the compilation of geochronological data from both the Lewisian Complex and the Nagssugtoqidian Mobile Belt (Figure 6) illustrates that the 1880 Ma detrital zircon peak from the Foula Formation is not unique to Greenland. This age occurs widely within the Lewisian Complex, but often in terranes which are in area terms, relatively minor (e.g., the Nis, Roineabheal and Rhiconich terranes). However, more significant areas of crust with similar affinities and age ranges could occur offshore to the north (i.e. on the Solan Bank, Sula Sgeir highs and on the Rona Ridge), and therefore, it is difficult to reject these areas as sources while they remain poorly characterised. Similarly, though Morton *et al.* (2007) speculate that the Permian aged zircons recovered from Foula Formation sandstones were more likely derived from the Greenland margin, the extent and geographical distribution of Permian acidic volcanic activity is not definitively known on either margin.

Essentially, the Nagssugtoqidian Mobile Belt of East Greenland and the Lewisian Complex appear indistinguishable in terms of both their zircon geochronology and Pb isotopic composition, pointing towards very similar or shared tectonic/metamorphic histories and supporting the idea that these domains are directly correlated. However, this implies easterly and westerly rift flank sources for sandstones in the developing Triassic basins cannot be distinguished by single grain isotopic techniques.

5.1 Wider implications for sediment recycling

In the case of Foula Formation sandstones, it appears that the K-feldspar Pb populations can be linked to the detrital zircon age data. It follows that if the K-feldspar is first-cycle detritus then zircon is less likely to have been recycled. However, it is important to highlight that this integrated dataset represents one possible end-member – i.e., close correspondence between the sources implied by the stable (zircon) and labile (K-feldspar) components. In other cases, the stable (zircon) and labile (K-feldspar) may be uncoupled, as for example in Upper Carboniferous of the Pennine Basin, northern England. This is one of the few other basins where both stable and labile grain provenance datasets are available. Namurian sandstones in the

Pennine Basin have been the subject of several detailed provenance studies. It has long been established, from petrological observations (Gilligan 1920), heavy mineral analysis, including garnet chemistry (Hallsworth and Chisholm, 2008), and isotopic techniques (Drewery *et al.* 1987; Cliff *et al.* 1991; Evans *et al.* 2001), that these sandstones are northern-derived, from a terrane comprising high-grade (granulite facies) metamorphic rocks and granites. Equivalents to the Lewisian Complex rocks, from offshore NW Scotland, have long been considered an appropriate source.

More recent studies, including detailed U-Pb zircon geochronological (Hallsworth *et al.* 2000) and K-feldspar Pb isotopic analysis (Tyrrell *et al.* 2006), have largely supported the initial provenance work carried out by Gilligan (1920).

The K-feldspar Pb isotopic studies of northern-derived Namurian sandstones in the Pennine Basin (Tyrrell *et al.* 2006) indicate a bimodal distribution of detrital K-feldspar grains – comprising an unradiogenic population - envisaged as being derived from Lewisian Complex rocks or an equivalent (Figure 7B) - and a radiogenic population apparently sourced from Caledonian granites in the Southern Uplands Belt and its along strike equivalents (Figure 7C). The U-Pb zircon geochronological data from the same northerly-derived rock units are not entirely consistent with this model for provenance (Figure 7D). There is some correspondence - U-Pb zircon age data show a peak at ~420 Ma, concurrent with the age range for Caledonian granites. However, major age peaks occur between 1.0 and 1.8 Ga. Moine and Dalradian metasediments within the Northwest Highland and Grampian terranes in Scotland contain 1.0 – 1.8 Ga zircons. These terranes have a distinctive Pb isotopic signature, defining a range in $^{206}\text{Pb}/^{204}\text{Pb}$ - $^{207}\text{Pb}/^{204}\text{Pb}$ lead space between the unradiogenic Archaean Pb and that associated with younger Caledonian granites (Figure 7C). This signature has not been recorded in K-feldspar from Upper Carboniferous sandstones. Despite abundant Lewisian-derived K-feldspar, there is a relatively minor zircon component which could have been derived from Lewisian Complex lithologies (age range between 1.8 and 3.0 Ga). This may be because there are issues with the persistence of old, radiation damaged, zircons.

However, if it is assumed that K-feldspar represents first cycle detritus, then zircon that does not match a K-feldspar population (e.g. the zircons with ages ranging

between 1.0 and 1.8 Ga) can be interpreted as poly-cyclic, derived indirectly from its source via an intermediary sedimentary rock. In terms of potential sources of second cycle detritus, it is logical to suggest, given that the Southern Upland granites or their along strike equivalents provided a source of K-feldspar, that the metasedimentary successions into which those granites intruded must also have supplied detritus. U-Pb zircon geochronology from Ordovician metasedimentary rocks from the Southern Uplands Belt (Waldron *et al.* 2008) demonstrate the presence of a clear 1.0 – 1.8 Ga detrital zircon population, which correlates well with that in the Namurian of the Pennine Basin (Figure 7D). It therefore seems plausible that the 1.0 to 1.8 Ga zircon population in the Namurian sandstones has been recycled through the Southern Upland Belt metasedimentary rocks. In this way, through careful integration of the datasets, the Pb-K-feldspar and zircon data can be better reconciled and poly-cyclic detrital components can be identified. Failure to recognise the recycled component could lead to misinterpretation of sandstone provenance, and ultimately the palaeodrainage, in the Pennine Basin.

6 Conclusions:

The use of an ion-counter collection configuration during ICPMS analysis of Pb isotopic composition allows data to be obtained from feldspars with low Pb (<30 ppm) concentration. This technique allows accurate Pb analysis from smaller volumes of ablated material, thereby, reducing the necessary laser spot sizes. This, in turn, allows grains below 100 μm long axis to be analysed precisely, which cannot be achieved using the Faraday cup configuration.

Pb isotopic data indicate that detrital K-feldspar in Middle-Upper Triassic Foula Formation sandstones from basins west of Shetland are likely derived from gneisses, granulites or intrusive rocks from the Nagssugtoqidian Mobile Belt of eastern Greenland, from elements of the Lewisian Complex of NW Scotland, or from areally significant, though poorly characterised, Lewisian equivalents on the West Shetland Platform and Rona Ridge. Rocks from south of the Moine Thrust and the Rockall Bank are ruled out as sources. This implies that drainage in these areas was controlled by uplifted Archaen-Proterozoic basement, and that the remnant Variscan Uplands to

the south exerted no influence, a conclusion similar to that reached for Corrib gas field sandstones in the Slyne Basin (Tyrrell *et al.* 2007).

It can be argued that K-feldspar is a likely first cycle component. Therefore, agreement between provenance signals from K-feldspar Pb isotopic data and detrital zircon U-Pb ages suggests that the zircon component is also likely to be first cycle. However, in contrast to previous interpretations, this study hints that an eastern or western rift flank source for Foula Formation sandstones cannot be distinguished, because the potential sourcelands lie along strike from one another and exhibit similar tectonic histories. Thus, they are not distinguishable in terms of their geochronology (U-Pb zircon), nor do they display significant variation in their Pb isotopic composition.

Many of the potential source areas, particularly the submarine basement highs remain poorly characterised, and although these are likely to have broadly similar geochemical character to their better-studied equivalents, specific lithological elements within these offshore basement highs may offer improved correspondence with detrital geochemical data.

These studies help constrain likely first-cycle provenance of Triassic sandstones in basins west of Shetland and have, in the case of Namurian sandstones in the Pennine Basin, highlighted how sedimentary recycling may manifest in provenance analysis. They have also shown the outstanding difficulties in distinguishing different source terranes with similar aged rocks and geological histories, and clearly demonstrate the need for an integrated approach to single grain provenance determination, specifically one which utilises signals in both robust and less stable components of the sandstone.

Acknowledgements:

This research forms part of a larger study funded by a Science Foundation Ireland Research Frontier Programme grant (RFP06/GEO029) awarded to PDWH. Mike Tubrett and Paul Sylvester (Microanalysis Facility, Memorial University, Newfoundland, Canada) are thanked for assistance with ICPMS. Dick Sutherland (DTI core store, Edinburgh, UK) is acknowledged for facilitating access to and sampling of core. Andreas Kronz (Electron Microprobe Laboratory,

Geowissenschaftliches Zentrum, Göttingen, Germany) is thanked for assistance with BSE and CL imaging. Martin Lee and an anonymous referee are acknowledged for constructive reviews which improved the manuscript. Tom McKie is thanked for his detailed editorial input.

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Figure Captions:

Figure 1: Map of the North Atlantic region, showing the position of the study area and the broad area of continental crust on the NW European Margin. The map was constructed using a Europe-centred Lambert Conformal Conic projection, such that scale is invariant. Numbers 1-5 refer to the lithostratigraphic columns in Figure 2.

Figure 2: Schematic Triassic lithostratigraphy in basins from the NW European margin (after Tate *et al.* 1999; Scotchman and Carr 2005; Meadows 2006). Lithostratigraphic columns 1-5 correspond to geographic positions on Figure 1.

Figure 3: Triassic plate tectonic reconstruction of the NE Atlantic region (derived from Ziegler 1991; Scotese 2002; Eide 2002; Torsvik *et al.* 2001; Roberts *et al.* 1999) showing the relative positions of Greenland and NW Europe. Coastlines are projected using a Europe-centred Lambert Conformal Conic projection. The distribution of Precambrian basement domains is also shown, highlighting potential correlation between the Lewisian Complex and the Nagssugtoqidian Mobile Belt (adapted from Morton *et al.* 2007; Kinny *et al.* 2005; Friend and Kinny 2001; Watt and Thrane 2001; Kalsbeek *et al.* 1993; Srivastava and Verhof, 1992). Phanerozoic geology has been removed for simplicity. The positions of the sampled wells (204/29-1 and 205/27a-1) and well 156/17-1, discussed in the text, are also shown.

Figure 4: Example of the contrast between linear arrays on the $^{206}\text{Pb}/^{204}\text{Pb}$ - $^{207}\text{Pb}/^{204}\text{Pb}$ diagram (uranogenic Pb) and broad spatial fields in the $^{206}\text{Pb}/^{204}\text{Pb}$ - $^{208}\text{Pb}/^{204}\text{Pb}$ diagram (function of uranogenic and thorogenic Pb). The data plotted included basement source Pb K-feldspar data from western Greenland (Connolly and Thrane 2005) and detrital Pb K-feldspar data from this study. In this study, data re-plotted on $^{206}\text{Pb}/^{204}\text{Pb}$ - $^{208}\text{Pb}/^{204}\text{Pb}$ lead space, optimising the potential for assessing source – detrital Pb spatial correlation.

Figure 5: $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{208}\text{Pb}/^{204}\text{Pb}$ lead data (with 2σ errors) for detrital K-feldspar grains from Foula Formation sandstones from wells 205/27a-1 and 204/29-1 and Permian sandstones from 205/27a-1 compared with data from potential basement sources, (A) on the NW European Margin - Lewisian Complex and equivalents,

Torridonian Supergroup sandstones (S_{sf} = Stoer Group, Stac Fada Member; T_{df} = Torridon Group, Diabaig Formation; T_{af} = Torridon Group, Applecross Formation) and Rockall Bank; and (B), in Greenland - Nagssugtoqidian orogen from East and West Greenland and the Rinkian orogen from West Greenland. Pb basement data (KF = K-feldspar; WR = whole rock) are from Kalsbeek *et al.* 1993; Connolly and Thrane 2005; Whitehouse and Moorbath 1986; Whitehouse 1990; Whitehouse 1993 and Tyrrell *et al.* 2007, except Stanton Bank and Torridonian, which are unpublished.

Figure 6: Probability density plot for U-Pb ages (<10% discordant analyses) of detrital zircon in Foula Formation sandstones from 2454m, well 205/26a-3, replotted from data in Morton *et al.* (2007) compared with U-Pb geochronology (Watt and Thrane 2001; Connolly and Thrane 2005; Friend and Kinny 2001; Kinny *et al.* 2005; Morton and Taylor 1991; Kalsbeek *et al.* 1993) from potential zircon sources on the NW European Margin and Greenland. Grey bands highlight major age peaks to facilitate comparison. Check marks highlight correspondence or lack of correspondence between potential sources and the Foula Formation using the K-feldspar provenance indicator.

Figure 7: A) Pb isotopic data (with 2σ errors) for detrital K-feldspar data from Namurian sandstones in the Pennine basin, adapted from Tyrrell *et al.* (2006), showing the bimodal distribution of grains. K-feldspars appear to have been derived from B) Lewisian Complex rocks (or equivalents) and C) from Southern Uplands Granites. D) U-Pb detrital zircon data (<10% discordant analyses) from i) Ordovician Southern Upland metasedimentary rocks (from Waldron *et al.* 2008) and ii) ‘northern sourced’ Namurian sandstones from the Pennine Basin (from Hallsworth *et al.* 2000).

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Table 1: Sample descriptions, Pb isotopic data, Pb, U and Th concentrations data and bulk feldspar composition data of detrital K-feldspars from Foula Formation and Upper Permian sandstones in wells 204/29-1 and 205/27a-1

Sample No.	Well	Core	Depth (m)	Depth (ft)	Stratigraphy	Sample Description	Feldspar grain	Collection method*	Or:Ab:An [†]	Pb ppm [†]	U ppm [†]	Th ppm [†]	²⁰⁶ Pb/ ²⁰⁴ Pb	2SE	²⁰⁷ Pb/ ²⁰⁴ Pb	2SE	²⁰⁸ Pb/ ²⁰⁴ Pb	2SE
9	204/29-1	1	1834.53	6018.80	Upper Foula Fm.	Medium- to coarse-grained sandstone, near top of core. Poorly-sorted, v. angular, arkosic, sub-lithic, carbonate cement	1	F	88.60 : 11.24 : 0.16	-	-	-	13.519	0.062	14.362	0.079	33.390	0.153
							2	F	94.83 : 5.17 : 0	-	-	-	13.911	0.035	14.866	0.022	33.479	0.060
							3	F	-	-	-	-	13.978	0.102	14.893	0.032	33.735	0.123
							4	F	87.94 : 11.68 : 0.38	-	-	-	13.516	0.039	14.572	0.043	33.212	0.101
							5	F	-	-	-	-	13.609	0.029	14.660	0.031	33.559	0.073
							6	F	91.22 : 8.65 : 0.13	-	-	-	14.012	0.040	14.995	0.043	33.899	0.098
							7	F	92.43 : 7.5 : 0.03	-	-	-	13.901	0.075	14.886	0.044	33.557	0.123
							8	F	94.14 : 5.86 : 0	-	-	-	13.670	0.055	14.669	0.041	33.374	0.105
8	204/29-1	1	1835.38	6021.60	Upper Foula Fm.	Medium- to coarse-grained, massive sandstone, near base of pebbly bed; Poorly-sorted, v. angular, sub-arkosic, sub-lithic, carbonate cement	2	IC	-	50.3	<0.01	<0.01	14.084	0.029	15.027	0.015	34.059	0.095
							3	IC	-	22.9	0.32	0.14	14.137	0.029	15.027	0.015	40.747	0.113
							4	IC	-	25.1	<0.01	<0.01	13.872	0.028	14.817	0.015	34.781	0.093
							5	IC	-	25.5	<0.01	<0.01	13.649	0.028	14.714	0.015	33.321	0.099
							5	IC	-	-	-	-	14.232	0.023	14.918	0.024	35.385	0.057
4	204/29-1	1	1852.04	6076.25	Upper Foula Fm.	Medium to coarse grained, cross-bedded sandstone. Poorly-sorted, v. angular, sub-arkosic, sub-lithic (carbonate intraclasts), carbonate cement (incl. dolomite)	2	F	83.59 : 14.95 : 1.47	-	-	-	13.555	0.036	14.485	0.039	32.850	0.091
							4	F	93.92 : 6.08 : 0	-	-	-	13.918	0.089	14.875	0.032	33.536	0.119
							5	F	92.75 : 7.07 : 0.17	-	-	-	13.266	0.035	14.315	0.039	32.617	0.090
							6	F	-	-	-	-	13.986	0.021	14.700	0.020	34.117	0.086
							7	F	-	-	-	-	13.807	0.026	14.699	0.029	33.736	0.067
							8	F	-	-	-	-	13.266	0.035	14.314	0.039	32.616	0.090
							9	F	-	-	-	-	13.986	0.021	14.699	0.020	34.116	0.086
							10	F	-	-	-	-	13.806	0.026	14.698	0.029	33.734	0.067
							12	IC	-	42.9	0.04	<0.01	13.767	0.040	14.908	0.022	33.617	0.121
							12	IC	-	-	-	-	14.198	0.013	14.824	0.012	34.286	0.069
38	205/27a-1	1	457.43	1500.75	Upper Foula Fm.	Medium-grained, parallel laminated sandstone; Well sorted, angular to sub-rounded, sub-arkosic, minor carbonate, ~10% porosity	2	IC	-	30.4	<0.01	<0.01	14.182	0.042	15.092	0.022	33.862	0.128
							3	IC	-	39.1	<0.01	<0.01	12.866	0.038	14.258	0.021	32.756	0.117
							5	IC	-	39.8	0.56	<0.01	14.381	0.042	15.241	0.022	34.296	0.122
							6	IC	-	40.9	<0.01	<0.01	14.240	0.042	15.031	0.022	37.392	0.137
							7	IC	-	9.7	<0.01	0.04	15.479	0.045	15.588	0.023	40.228	0.145
							8	IC	-	36.7	<0.01	<0.01	14.228	0.042	15.113	0.022	34.280	0.122
							12	IC	-	-	-	-	13.767	0.040	14.908	0.022	33.617	0.121
							12	IC	-	-	-	-	14.198	0.013	14.824	0.012	34.286	0.069
37	205/27a-1	1	460.76	1511.67	Upper Foula Fm.	Medium-grained, parallel laminated sandstone; Well sorted, angular to sub-rounded, sub-arkosic, minor carbonate, ~15% porosity	2	IC	-	21.9	<0.01	<0.01	13.784	0.013	14.716	0.011	33.672	0.062
							3	IC	-	5.5	<0.01	<0.01	14.044	0.014	14.528	0.012	42.443	0.143
							4	IC	-	30.4	<0.01	<0.01	14.225	0.013	15.181	0.012	34.446	0.062
							5	IC	-	63.8	<0.01	<0.01	12.970	0.012	14.328	0.011	33.071	0.060
							6	IC	-	32.1	<0.01	<0.01	13.232	0.012	14.554	0.011	33.372	0.061
							6	IC	-	-	-	-	14.236	0.031	15.057	0.027	35.701	0.156
36	205/27a-1	1	466.62	1530.92	Upper Foula Fm.	Medium-grained, parallel laminated sandstone; Well sorted, angular to sub-rounded, sub-arkosic, minor carbonate, minor clay ~10% porosity	2	IC	-	59.2	<0.01	<0.01	14.739	0.032	15.356	0.027	34.755	0.152
							3	IC	-	56.8	<0.01	<0.01	13.421	0.029	14.640	0.026	33.687	0.150
							4	IC	-	32.0	<0.01	<0.01	13.888	0.030	14.996	0.026	33.653	0.147
							5	IC	-	7.5	0.06	<0.01	13.752	0.030	14.524	0.026	33.658	0.152
33	205/27a-1	2	1082.04	3550.00	Mid Foula Fm.	Coarse-grained sandstone, near top of core; Poorly sorted, sub-angular to sub-rounded, sub-arkosic, sub-lithic, minor carbonate, ~15%	6	IC	-	39.0	<0.01	<0.01	16.224	0.036	15.674	0.028	43.403	0.195
							7	IC	-	37.3	0.59	1.71	13.994	0.031	14.915	0.026	33.768	0.149
							8	IC	-	56.7	0.32	0.05	14.236	0.031	15.057	0.027	35.701	0.156
							3	F	95.35 : 4.65 : 0	-	-	-	13.771	0.031	14.746	0.034	33.837	0.078
							4	F	94.96 : 5.04 : 0	-	-	-	13.824	0.045	14.753	0.045	33.993	0.112
							5	F	96.40 : 3.60 : 0	-	-	-	13.066	0.210	14.158	0.337	32.622	0.694
31	205/27a-1	2	1085.95	3562.83	Mid Foula Fm.	Medium-grained, trough cross-bedded sandstone; Well sorted, sub-angular to sub-rounded, sub-arkosic, sub-lithic, patchy carbonate cement, ~10% porosity	1	IC	-	26.7	<0.01	<0.01	14.513	0.028	15.397	0.026	34.990	0.157
							2	IC	-	30.6	1.34	0.36	14.375	0.027	15.119	0.026	36.862	0.174
							3	IC	-	43.0	<0.01	<0.01	14.882	0.028	15.349	0.026	38.157	0.173
							5	IC	-	40.5	<0.01	<0.01	13.338	0.025	14.514	0.024	34.865	0.157
							6	IC	-	63.7	<0.01	<0.01	13.012	0.025	14.342	0.024	33.161	0.149
							7	IC	-	19.0	<0.01	<0.01	13.448	0.026	14.623	0.025	33.383	0.151
30	205/27a-1	2	1088.06	3569.75	Mid Foula Fm.	Medium-grained sandstones; Well sorted, angular to sub-rounded, sub-arkosic, sub-lithic, patchy carbonate cement, ~10% porosity	4	F	86.55 : 0.04 : 0.04	-	-	-	14.263	0.031	14.807	0.022	38.481	0.058
							5	F	93.90 : 6.10 : 0	-	-	-	12.926	0.024	14.284	0.017	32.674	0.043
27	205/27a-1	5	1997.96	6555.00	Top Permian	Medium-grained, parallel laminated sandstones; Well sorted, angular, sub-arkosic, carbonate cement	1	IC	-	32.0	<0.01	<0.01	13.689	0.027	14.741	0.025	34.023	0.159
							2	IC	-	19.0	<0.01	<0.01	13.915	0.027	14.866	0.025	34.164	0.161
							3	IC	-	36.7	<0.01	<0.01	14.075	0.027	14.909	0.025	33.692	0.157
							4	IC	-	49.3	<0.01	1.07	14.479	0.028	14.945	0.025	37.181	0.174
							5	IC	-	11.1	<0.01	<0.01	13.596	0.026	14.635	0.024	34.949	0.165
							6	IC	-	51.8	<0.01	0.66	14.110	0.027	14.789	0.025	34.092	0.159

* Calculated from Electron Microprobe Analysis (EMPA) data

* Data collected using Faraday cup (F) or ion counter (IC) configuration on Neptune LA-MC-ICPMS (see text for details)

[†] Concentrations determined using Element LA ICPMS