Heavy mineral constraints on Paleocene-Eocene sand transport routes in the Faroe-Shetland Basin

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SUMMARY

- Heavy mineral and garnet geochemical data enable differentiation of six sandstone types (I-VI), derived from different source rocks, in the Paleocene-Eocene of the Faroe-Shetland Basin. The key parameters are garnet geochemistry, ATi, GZi, RuZi, CZi and clinopyroxene contents.

- Sandstone type I has low abundances of type A garnet and relatively high RuZi, and was mainly derived from basement lithologies (Lewisian and/or Moine/Dalradian) on the Orkney-Shetland Platform, either directly or indirectly through recycling. Sandstone type I is seen at T10 level in 204/19-3A and 204/24a-7, at T22-28 level in 204/19-3A, at T31-32 level in 204/24a-7, at T35 level in 204/19-3A, 205/14-2 and 6005/15-1, at T36 level in 204/19-3A, 205/14-2, 214/27-2, 6004/16-1z and 6005/15-1, and at T38 level in 206/2-1A, 208/17-2, 208/19-1, 214/27-2, 6004/16-1z and 6005/15-1.

- Sandstone type II is characterised by abundant type Ai garnet and relatively high RuZi, and was derived principally through recycling of the Triassic on the Orkney-Shetland Platform, together with basement and Old Red Sandstone. Sandstone type II is found at T10 level in 204/20-1z, 205/9-1 and 204/24a-7, at T22-28 level in 204/24a-7, 204/19-3A, 204/20-1Z, 214/19-1 and in the lower part of 214/27-1, at T31-32 level in 204/19-3A and 204/20-1Z, at T34 level in 204/19-3A, 204/20-1Z, 204/24a-7 and 214/27-2, at T35 level in 204/20-1Z, and at T36 level in 204/19-3A and 205/12-1.

- Sandstone type III is diagnosed by low RuZi, and is frequently associated with the volcaniclastic sandstone type (V). Input from the west is considered most likely, but local sourcing (for example, from the Corona Ridge) is considered more likely than derivation from East Greenland. Sandstone type III is seen in at T10 and T22-28 levels in 6004/16-1z, at T31-32 and T34 levels in 6004/16-1z and 6005/15-1, at T35 level in 205/9-1, and at T36 level in 205/9-1 and 214/27-2.

- Sandstone type IV is diagnosed by the abundance of type Aii garnets. Recycling from Carboniferous (Namurian-Westphalian) sandstones on the Orkney-Shetland Platform is considered the most likely origin of sandstone type IV. Sandstone type IV is seen at T22-28 level in 208/19-1, 214/27-2 and the upper part of 214/27-1, at T31 level in 214/27-1, and at T34 level in 214/19-1, 214/27-1, 214/27-2 and 214/29-1.

- Sandstone type V represents volcaniclastic material derived from basaltic sources, and is primarily recognized on the basis of the abundance of clinopyroxene. It may be present at T31-32 and T34 levels in 6005/15-1, at T35 level in 205/9-1, at T36 level in 205/9-1 and 214/27-2.

- Sandstone type VI is present only in the Eocene (post T50) of 214/10-1 and 214/26-1. It has low ATi, low GZi and high CZi. The provenance of this sandstone type is enigmatic, but given the seismic evidence for transport from the south, involvement of Tertiary ultramafic rocks similar to those found in Rum (Inner Hebrides) is considered likely. The most likely location of these igneous centres are the Wyville-Thomson Ridge to the southwest (Fig. 1).

- During T10-T38, there are distinct lateral and stratigraphic differences in mineralogy resulting from interplay between different submarine fan systems sourced from both east and west. In T40-T45, sediment compositions become more homogeneous, causing difficulty in categorizing samples into the distinct sandstone types seen in T10-T38. This change coincides with a change in depositional environment, from deep water submarine fans to shallow water and fluvial facies, a result of a regional transient uplift phase related to the Icelandic Plume (Rudge et al., 2008). This change in depositional setting allows greater mixing of sediment from different sources through coalescence of individual fluvial systems and homogenisation in shallow marine settings.

- The change in mineralogy in the post-T50 sandstones coincides with a return to deep water conditions following the end of the transient uplift phase. The appearance of a new sandstone type (VI) at this time suggests that there was a reorganisation of drainage patterns compared with the pre-T50 succession.

- The pilot study of rutile geochemistry has shown that this technique provides valuable additional information, being particularly useful in identifying sandstone type II and showing the variable involvement of metamafic rocks across the basin.

INTRODUCTION

This report discusses the implications of heavy mineral data collected during the SINDRI project ‘Sand Transport Routes in the Faroe-Shetland Basin: A Heavy Mineral Provenance Project’. The report is based on data previously reported by HM Research Associates (2007a,b), together with data presented by Morton et al. (2002), Morton et al. (2005) and Jolley and Morton (2007). Heavy mineral data are available from Paleocene-Eocene sandstones in twenty-five wells west of Shetland (204/10-1, 204/19-3a, 204/20-1z, 204/24a-7, 205/9-1, 205/12-1, 205/14-1, 205/17b-2, 206/1-1a, 206/1-3, 206/2-1, 208/17-2, 208/19-1, 208/22-1, 213/23-1, 214/9-1, 214/19-1, 214/24-1, 214/26-1, 214/27-1, 214/27-2, 214/29-1, 6004/16-1z and 6005/15-1). Well locations are shown in Fig. 1. A stratigraphic breakdown has been provided for most of these wells by Statoil and BP, but this information is confidential to these companies and is therefore not included in the accompanying GIS database. Stratigraphic information has not been supplied for 206/1-3 and 214/24-1. For instructions concerning the GIS database, see the end of this report.

The heavy mineral data provide evidence for both stratigraphic and regional differences in provenance. In this report, we describe the principles behind the use of heavy mineral analysis as a provenance tool and the analytical methods used. We then describe the different provenance groups, their distribution in the analysed wells, and the regional patterns of sand supply to the Faroe-Shetland Basin area. Finally, we discuss the implications of data acquired during rutile geochemical analysis, a technique that has not been previously used in this region.

PROVENANCE DETERMINATION USING HEAVY MINERALS: BASIC PRINCIPLES

Heavy mineral assemblages are sensitive indicators of sediment provenance. A large number of species have been found in sandstones, many of which have restricted parageneses that provide a positive indication of the mineralogical composition of the source region (Mange and Maurer, 1992). Differences in heavy mineral assemblages facilitate the discrimination of sand bodies derived from different sources via different sediment transport pathways. Stratigraphic changes in heavy mineral assemblages provide a basis for correlation, independent of traditional biostratigraphic or log correlation methods.

The composition of heavy mineral assemblages is not, however, entirely controlled by source rock mineralogy, because there are several processes that operate during the sedimentary cycle that alter the original provenance signal (Morton and Hallsworth, 1999). These processes can introduce a large degree of heterogeneity to assemblages that were derived from the same source and were therefore originally homogeneous. It is crucial for accurate provenance and correlation studies that these factors are fully appreciated and accounted for.

The processes are:

1. **Weathering**, which causes modification of source rock mineralogy both at source (prior to incorporation into the transport system) and during periods of exposure on the floodplain during transport (alluvial storage).

2. **Abrasion**, which may reduce proportions of mechanically unstable minerals. Mechanically-induced depletion of minerals may occur through abrasion during transport. Assemblages recovered from ditch cuttings samples may also be affected by abrasion through the aggressive action of the drill bit.

3. **Hydraulic processes** during transport and deposition, which strongly affect relative abundances of minerals with different hydraulic behaviour (controlled by grain size, density and shape).

4. **Diagenesis**, which selectively removes unstable minerals during burial diagenesis through circulation of elevated temperature pore waters.

5. **Sampling and laboratory procedures**, which can also influence the mineralogy, particularly if chemical pretreatment is used.

Source rock mineralogy is undoubtedly altered during weathering process, but the extent to which this affects the detrital mineralogy has not been comprehensively evaluated. However, qualitative studies of modern river sediments indicate that there is little or no actual reduction in mineral diversity between source rock and transport system. In any case, the extent of source-area weathering can be justifiably viewed as a provenance-related feature that might have potential value in correlation studies (for example, in sequences deposited during periods of climate change).

It is a common misconception that abrasion during transport is an important factor in controlling heavy mineral assemblages. Although experimental work has shown that some loss of minerals does occur with prolonged simulated transport, case studies have failed to demonstrate that it occurs to any appreciable extent in natural systems (see Morton and

Smale, 1990, for example). By contrast, there is evidence that minerals may be depleted through the action of the drill bit, as core and cuttings samples over equivalent sections commonly have slightly different mineralogical compositions. The most severely affected mineral appears to be apatite, presumably because of its relatively low hardness.

The other three processes (weathering on the floodplain during periods of exposure or at the site of deposition, hydraulic conditions during deposition, and burial diagenesis) are potentially significant factors. Both weathering and burial diagenesis cause reductions in detrital mineral diversity, as a result of dissolution of unstable species. The effects of burial diagenesis are particularly significant and pervasive, being marked by a clear and well-defined progressive reduction in mineral diversity with increasing depth. This decrease in diversity is caused by increased dissolution rates resulting from the higher pore fluid temperatures that occur with increasing depth. The relative stability of heavy minerals under both deep burial and weathering are relatively well known (Morton and Hallsworth, 1999; Morton and Hallsworth, 2007), the most significant difference between the two processes being that apatite is unstable during weathering but stable in deep burial. Thus, absence or reduced contents of apatite suggest that acidic groundwaters may have influenced heavy mineral suites.

Variations in hydraulic conditions during deposition affect the relative proportions of minerals with different hydraulic behaviour. The principal factors influencing hydraulic behaviour are grain size and density. Therefore, the main effect that hydraulic variations have on heavy mineral suites is to vary the ratio of the more dense minerals, such as zircon, garnet or rutile, to the less dense minerals, such as apatite and tourmaline. Grain shape also influences hydraulic behaviour, but this is generally a less important factor, the most obvious exception being mica, which behaves as a light mineral even though it has the density of a heavy mineral.

The above guidelines serve to indicate how variations in weathering, diagenesis and depositional processes may be detected, but do not indicate how their effects can be minimised, allowing variations in provenance to be detected. There are two approaches to this problem. The first is to utilise the **conventional heavy mineral data**. Identification of variations in sediment source from the conventional data is best made by determining ratios of stable minerals with similar densities, as these are not affected by changes in hydraulic conditions during sedimentation or by diagenetic processes (Morton and Hallsworth, 1994). Ratios that are recommended to best reflect provenance characteristics are apatite:tourmaline, garnet:zircon, rutile:zircon, chrome spinel:zircon and monazite:zircon. Indices are expressed as index values (ATi, GZi, RuZi, MZi, CZi) as defined in Table 1. In some circumstances, ATi and GZi may not provide a true reflection of the source composition. For example, ATi may be reduced during weathering, and GZi may be lowered during burial diagenesis.

Table 1. Definition of provenance-sensitive ratio parameters (from Morton and Hallsworth, 1994).

Index	Mineral pair	Definition
ATi	apatite-tourmaline index	% apatite in total apatite plus tourmaline
GZi	garnet-zircon index	% garnet in total garnet plus zircon
RuZi	rutile-zircon index	% rutile in total rutile plus zircon
MZi	monazite-zircon index	% monazite in total monazite plus zircon
CZi	chrome spinel-zircon index	% chrome spinel in total chrome spinel plus zircon

The alternative approach is to undertake **varietal studies**. These are studies that concentrate on variations seen within one mineral group. By concentrating on a single mineral phase, the range of density and stability within the data set is strongly diminished, thus minimising the effects of varying hydrodynamic conditions and diagenesis. The classical approach to varietal studies is to distinguish types on the basis of their optical properties, such as crystal form or colour, but this approach is commonly subjective and class distinctions tend to be arbitrary. Nevertheless, this approach can provide useful information on sedimentary processes, for example in Devonian-Carboniferous sandstones of the Clair Field (west of Shetland), where variations in apatite roundness reflect the interplay between fluvial and aeolian transport (Allen and Mange-Rajetzky, 1992; Morton et al., in press). A more objective approach is to determine the geochemical characteristics of a mineral population using single-grain mineral chemical analysis, for example energy-dispersive x-ray analysis by electron microprobe (suitable for major elements) or laser-ablation inductively-coupled plasma mass spectrometry (suitable for trace elements). Mineral chemical analysis has the advantage of generating data sets that can be readily compared with those generated by other analysts.

In this study, provenance discrimination has been achieved using variations in provenance-sensitive heavy mineral ratios (principally ATi, GZi and RuZi), together with variations in garnet geochemistry. In addition, variations in the abundance of clinopyroxene (an indicator of supply from basic igneous rocks) have also proved useful, although this parameter is less reliable owing to the highly unstable nature of clinopyroxene during burial diagenesis.

ANALYTICAL METHODS

Sample preparation

Core samples were gently disaggregated by use of a pestle and mortar, avoiding grinding action. This was not necessary for the cuttings samples, which were already disaggregated through the action of the drill bit. Chemical pretreatment was not used, thereby avoiding the possibility of modifying assemblages in the laboratory. Following disaggregation, the samples were immersed in water and cleaned by ultrasonic probe to removed and disperse any clay that was adhering to grain surfaces. The samples were then washed through a 63 μm sieve and resubjected to ultrasonic treatment until no more clay passed into suspension. Following this, the samples were wet sieved through the 125 and 63 μm sieves, and the resulting >125 μm and 63-125 μm fractions were dried in an oven at 80^{o}C. The 63-125 μm fraction was placed in bromoform with a measured specific gravity of 2.8. Heavy minerals were allowed to separate under gravity, with frequent stirring to ensure complete separation. The heavy mineral residues were mounted under Canada Balsam for optical study using a polarising microscope. Where possible, a split was retained for mineral chemical analysis.

Conventional analysis and ratio determination

Heavy mineral proportions were estimated by counting 200 non-opaque detrital grains using the ribbon method described by Galehouse (1971). Identification was made on the basis of optical properties, as described for grain mounts by Mange and Maurer (1992). A qualitative assessment was also made of other components, such as diagenetic minerals, opaques and mica. Provenance-sensitive mineral ratios were also determined using the ribbon counting method, ideally on the basis of a 200 grain count. However, it was not always possible to achieve the optimum 200 grain count because of the scarcity of some of the mineral phases or because of small sample sizes.

Garnet geochemical analysis

Samples for garnet geochemical analysis using the microprobe were selected on the basis of the results of the conventional optical analysis. Grains were picked with a needle from the dry residues during optical examination under the polarising microscope, in a manner analogous to the ribbon method of Galehouse (1971). The grains were placed on double sided adhesive tape, coated with carbon, and analysed using a Link Systems AN 10/55S energy-dispersive x-ray analyser attached to a Cambridge Instruments Microscan V electron microprobe at the University of Aberdeen. The count time was 30 seconds for each grain. Data reduction used the ZAF4 programme. Results from poorly-oriented or rough grain surfaces were identified by low analytical totals and/or deviations from ideal stoichiometry, and were discarded. Garnet compositions are expressed in terms of the molecular proportions of Mg, Fe^{2+}, Ca and Mn, calculated on the basis of 24 oxygens, and normalised to total Fe+Mg+Ca+Mn, with all Fe calculated as Fe^{2+}, as recommended by Droop and Harte (1995).

Differences in garnet assemblages in Paleocene-Eocene sandstones in the Faroe-Shetland Basin are manifested by changes in the relative proportions of low-Ca, high-Mg garnets compared with low-Mg garnets containing variable amounts of Ca and Mn (respectively, types A and B in the terminology of Morton et al., 2004). High-Ca, high-Mg garnets (type C) form a minor component of the garnet populations and show no discernible regional or stratigraphic pattern. As noted by Jolley and Morton (2007), there are distinct variations within the type A group, with some sandstones being dominated by type Ai garnets (those with molecular proportions of Mg > 30%), whereas others are dominated by type Aii (garnets with molecular proportions of Mg between 20% and 30%). Representative ternary diagrams illustrating the variations in type Ai, type Aii and type B garnets within the data set are shown in Fig. 2.

DISCRIMINATION OF PROVENANCE TYPES

Provenance-sensitive parameters

Discrimination of provenance has been made on the basis of variations in the provenance-sensitive heavy mineral ratios GZi, ATi and RuZi, on variations in garnet geochemistry, and on the abundance of clinopyroxene. Variations in mineralogy are shown in a series of crossplots and maps for a number of stratigraphic time-slices (Figs 3-49). The time-slices are T10, T22-28, T31-32, T34, T35, T36, T38, T40, T45-50 and post-T50. The stratigraphic information used to compile these crossplots was provided by Statoil and BP. Data from two wells (206/1-3 and 214/24-1) have not been included in these diagrams because of the lack of stratigraphic information and, in the case of 214/24-1, because of the lack of garnet geochemical data.

On GZi-ATi plots, the vast majority of samples have high ATi and high GZi. However, there are deviations both towards lower ATi and towards lower GZi. Low ATi is particularly well-marked in T10 samples from 204/19-3A, T36 sands from 205/12-1, T38 sands from 208/17-2, 208/19-1 and 6005/15-1, in scattered samples at T40 and T45-50 level, and in post-T50 sands from both analysed wells (204/10-1 and 214/26-1). In most cases, the low ATi values are considered to diagnose weathering. Those found in the T10 interval from 204/19-3a and

204/24a-7 are believed to be related to weathering of the Late Cretaceous land surface (Morton et al., 2002). Low ATi values at subsequent levels either relate to weathering during the sedimentary cycle or to the composition of the source.

In most cases, samples with low GZi are interpreted as having undergone partial or complete loss of garnet as a result of burial diagenesis. As shown in Fig. 50, the most deeply-buried sandstones in the data set have the lowest GZi, which, together with surface textural evidence for increasing corrosion with depth, provides strong evidence for burial-depth related garnet dissolution. However, some sandstones have low GZi at comparatively shallow depths. These samples tend to also have relatively low ATi, such as the T10 sandstones from 204/19-3A (Fig. 3) and the post-Eocene sandstones from 204/10-1 and 214/26-1 (Fig. 46), and modification of the GZi value by weathering-related garnet dissolution is considered likely.

On RuZi-ATi plots, most of the samples form a single cluster with high GZi and RuZi between 20 and 40, occasionally reaching 50. Deviations towards lower GZi values are mainly due to garnet dissolution, as described above. However, samples in a number of wells have RuZi below 20, and in some cases, notably T10 in 6004/16-1z and T35-T36 in 205/9-1, have very low RuZi (<10). The variations in RuZi are considered to be significant in terms of provenance, since rutile and zircon are both ultrastable and their relative abundances cannot be modified during weathering or diagenesis.

The most useful provenance-sensitive information in the data set is provided by the garnet geochemistry. There are major variations in abundance of type A garnet relative to types B and C, and furthermore, sandstones with high contents of type A garnet can be further discriminated on the basis of variations in the Ai/Aii ratio (Fig. 2). However, the application of garnet geochemistry is limited by the extent of burial diagenesis, since (as discussed above), the most deeply-buried samples have undergone partial or complete garnet dissolution.

A further useful provenance feature is the abundance of clinopyroxene, which is the key indicator for the presence of basaltic volcaniclastic sediment. Samples with common clinopyroxene are therefore likely to have a significant volcaniclastic component. However, clinopyroxene is one of the least stable heavy mineral phases during burial diagenesis (Morton and Hallsworth, 2007), and hence it is possible that some of the samples in the data set have a volcaniclastic component that cannot be recognised using the heavy mineral data. In addition, some of the clinopyroxene found in cuttings samples could be from interbedded basalt flows or basic intrusions, rather than being of volcaniclastic origin. This is believed to be a significant problem in only one well in the data set, 6005/15-1.

Sandstone types

Five sandstone types, each with a different provenance, have been identified in the T10-T50 interval. For the most part, these follow previous discriminations of provenance. Four sandstone types (I, II, III and IV) were identified by Jolley and Morton (2007) on the basis of variations in garnet geochemistry and RuZi values. This scheme has been modified by the addition of a fifth source (V), by the differentiation of two subtypes in IV (IVa and IVb), and by the recognition of subtypes within the type I group. Furthermore, the post-T50 sandstones define a sixth sandstone type (VI).

Sandstone type I

The key features of sandstone type I are the low abundances of type A garnet in conjunction with relatively high RuZi. The high abundance of type B garnet indicates that a large proportion of the detritus was supplied from metamorphic basement, probably including Lewisian Gneiss and Moine/Dalradian metasediments, both of which are present on the western margin of the Shetland Platform and are known to have predominantly type B garnet populations (Morton et al., 2004). There are large variations in the Ai/Aii ratio in type I sandstones, but these are not considered significant because the parameter has been determined on a very small number of type A garnets. A variable, but minor, contribution from the Triassic Foula Formation (present in the southern part of the study area, notably the Solan Basin) is inferred, in order to explain the presence of type A garnets, which are abundant in the Foula Formation (Morton et al., 2007). Alternatively some or all of the type A garnets in sandstone type I may be from small-scale high-grade metasedimentary units within the Lewisian, as seen onshore, for example in South Harris (Morton et al., 2004) and Tiree (Cartwright, 1992). Some input from the Old Red Sandstone is possible, but available in-house HM Research data indicate that most of the Old Red Sandstone in the Orcadian Basin is devoid of garnet due to burial-related dissolution.

Low ATi values are seen in sandstone type I in the T10 and T22-T28 intervals in wells from the Foinaven Sub-Basin, such as 204/19-3a and 204/24a-7 in the present data set, and 204/24-1A and 204/24a-5 in the data set described by Morton et al. (2002). These low ATi values are believed to represent weathered basement material derived from the weathering profile on the Late Cretaceous land surface (Morton et al., 2002; Jolley and Morton, 2007) uplifted at the start of the Paleocene. Such sandstones gradually grade upwards into the typical sandstone type I present in younger sediments, indicating that weathered material has been stripped off leading to erosion of fresh basement material.

Type I sandstones with low ATi are also present higher in the succession, in some cases on a sporadic basis, suggesting local modification through weathering processes. However, T38-T45 sandstones in two adjacent wells in the Flett Sub-basin (208/17-2 and 208/19-1) have uniformly low ATi, suggesting they form the products of a separate depositional system. It is possible that these low ATi values also result from weathering, either at source or during periods of alluvial storage, but it is also possible that they represent derivation from more tourmaline-rich basement (most likely to occur in Dalradian metasediments). These sandstones also tend to have higher RuZi than other Type I sandstones. The T38 sandstones in 208/17-2 and the T38-T45 sandstones of 208/19-1 are therefore distinguished as a separate sandstone subtype (type Ia).

Sandstone type II

Sandstone type II is characterised by abundant type A garnet together with relatively high RuZi. The sandstone type is distinguished from sandstone type IV by having high abundances of Ai garnets relative to Aii. The abundance of type Ai garnet indicates that the Triassic Foula Formation was widespread in the source region. Sandstone type II has lower GZi than typical Foula Fm, therefore requiring additional input from a low-garnet source, such as Lewisian acidic gneisses or the Old Red Sandstone. It is also possible that some type II sandstones could be derived directly from suitable basement lithologies (candidates being high-grade granulite facies metasedimentary rocks or charnockites). Suitable lithologies are scarce in the basement complexes of the UK landmass: although small enclaves are present within the Lewisian, these are of insufficient lateral extent to provide undiluted type A garnet suites to the Paleocene. The ultimate source of sediment with high type A garnet contents is believed to lie outside the UK, probably in East Greenland (Morton et al., 2007). There is little evidence for weathering of type II sandstones, but those at the base of T10 in 204/24a-7 have low ATi values, and are ascribed to sandstone type IIw. As with sandstone type Iw, the low ATi is believed to be related to weathering of the Late Cretaceous land surface.

Sandstone type III

Sandstone type III is distinguished by the presence of low RuZi values, which are comparatively scarce in Paleocene sandstones along the Faroe-Shetland Basin margin. The abundance of type B garnet is relatively high, but overlaps with both sandstone types I and II, and is therefore not diagnostic. The combination of low RuZi and high type B garnet suggests derivation from predominantly gneissic basement, with the subordinate type A garnet probably being sourced from high-grade metasedimentary units within the gneissic basement. Sandstone type III is commonly found in association with volcaniclastic sand (sandstone type

V), for example in 205/9-1 and 214/27-2. Although some basement rocks on the UK landmass (most notably the Lewisian) could provide assemblages with low RuZi values, the co-occurrence of sandstone type III with volcaniclastic material (sandstone type V) suggests that the source lay to the west, where exposed basaltic lava fields were present (Kiørboe, 1999). Furthermore, there is no obvious sand entry point on the West Shetland Platform margin for the sandstone with type III mineralogy in 205/9-1 (Smallwood et al., 2004). Finally, sandstone type III is found in association with a distinctive palynoflora indicating transport from the western (Greenland) margin of the basin (Jolley et al., 2005; Jolley and Morton, 2007). Low-RuZi sandstones have also been found in the Paleogene of the Kangerlussuaq area of East Greenland (Whitham et al., 2004), although there is no evidence to suggest sandstone type III was derived directly from the Kangerlussuaq area. Local structural highs such as the Corona Ridge, which may include high-grade gneissic basement rocks that were exposed during the Paleocene, are another potential source for type III detritus (Jolley and Morton, 2007).

Sandstone type IV

Sandstone type IV is characterised by high abundances of type A garnet and low-moderate RuZi, similar to sandstone type II, although RuZi values tend to be slightly lower. It is distinguished from sandstone type II in that it has Aii garnets > Ai garnets. Sandstone type IV can be subdivided on the basis of variations in the Ai/Aii ratio, with very low values (<25) being characteristic of type IVa, and intermediate values (25-50) being typical of type IVb (Fig. 2). Garnets similar to those characterising sandstone type IV occur in parts of the Devonian-Visean Clair Group of the Clair Field, located on the Rona Ridge to the southeast (Jolley and Morton, 2007). Sandstone type IV also contains recycled Namurian-Westphalian miospores (Jolley and Morton, 2007). Reconciliation of the age disparity between these two pieces of evidence is possible, if it is accepted that Namurian-Westphalian sands (now eroded from the Hebrides-Shetland landmass) represent continued supply from the area supplying the Upper Clair Group. Regional evidence supports this hypothesis, since Namurian sandstones in the Pennine Basin, which were derived from a source area to the north of the British Isles, have similar garnet assemblages to those found in parts of the Clair Group (Hallsworth et al., 2000).

Sandstone type IVa is interpreted as representing relatively pure recycled Carboniferous sediment from the Shetland Platform, whereas sandstone type IVb is interpreted as including a type II (recycled Triassic) component to account for the increased Ai/Aii ratio.

Sandstone type V

The presence of clinopyroxene is believed to diagnose input from basaltic volcanics or associated basic intrusive rocks. This interpretation is supported by the presence of basaltic lithoclasts in clinopyroxene-bearing sandstones (Lamers and Carmichael, 1999). The volcaniclastic component is here termed sandstone type V. Due to the instability of clinopyroxene, it is possible that the influence of this source in the sample set has been underestimated. In most cases, sandstone type V occurs in association with sandstone type III.

Sandstone type VI

The post-T50 sandstones in the two analysed wells (204/10-1 and 214/26-1) have closely comparable assemblages that do not correspond with any seen in the T10-T50 interval. They have relatively low GZi and ATi (Fig. 46) and relatively low RuZi (Fig. 47). A distinctive feature is the presence of relatively high CZi values (7-19), significantly higher than in any of the sandstone types in the T10-T50 interval, in which CZi usually lies between 0 and 2, and rarely exceeds 5. Garnet assemblages are dominated by the type B component (Fig. 48).

The provenance of sandstone type VI is enigmatic at this stage. The presence of high CZi values suggest that recycling of earlier Tertiary sandstones is unlikely, and requires the presence of ultramafic or mafic rocks in the source area. Derivation from ophiolitic rocks on the Shetland Isles (such as the Unst ophiolite) seems unlikely, since chloritoid, which is abundant in sediment derived from the Shetland Isles (Morton et al., 2004), is scarce in sandstone type VI. Furthermore, the post-T50 sandstones are considered to represent submarine fans sourced from the south (Davies et al., 2004). Derivation from the south may indicate that the chrome spinel was sourced from ultramafic complexes within the Tertiary Igneous province. One such complex lies on the Isle of Rum, although this is at a considerable distance from the Faroe-Shetland Basin; a more likely possibility would be from one or more centres on the Wyville-Thomson Ridge.

STRATIGRAPHIC VARIATIONS IN HEAVY MINERAL PROVENANCE

In this section, we examine the variations in sandstone mineralogy within individual time slices (T10, T22-28, T31-T32, T34, T35, T36, T38, T40, T45-50 and post-T50), in order to build up a picture of evolving provenance within the basin during the Paleocene and Eocene.

T10

Data are available for six wells at T10 level (204/19-3A, 204/20-1z, 204/24a-7, 205/9-1, 214/19-1 and 6004/16-1z). There are significant variations in mineralogy within the T10 sandstones (Figs 3-7). The sandstones in 204/19-3A and some of those in 204/24a-7 have garnet assemblages typical of sandstone type 1, whereas those in 204/20-1z, 205/9-1 and the remaining 204/24a-7 have type II characteristics. There is evidence for weathering in 204/19-3a and 204/24a-7. The effects of weathering diminish higher in T10 and into T22-28.

By contrast, the sandstones in 6004/16-1z have very low RuZi and are interpreted as representing sandstone type III. Garnet data are unavailable from these sandstones because of near-complete garnet dissolution.

There is insufficient information from 214/19-1 to determine the affinity of the single T10 sample in this well. The relatively high RuZi rules out sandstone type III, but due to the lack of garnet data, the sample could belong to any of type I, type II or type IV. It seems most likely that the sample belongs to type II, on the basis of similarities with the overlying T22-28 sandstones in the same well (see below).

T22-28

Data are available for eight wells (204/19-3A, 204/20-1z, 204/24a-7, 208/19-1, 214/19-1, 214/27-1, 214/27-2 and 6004/16-1z) at T22-28 level (Figs 8-12). Four sources appear to have operated at this level.

Sandstone type I is seen in only one sample (from 204/19-3A), although another sample from this well has a garnet population that is intermediate between type I and type II (Fig. 11).

Sandstone type II is seen in 204/24a-7, 204/19-3A and 204/20-1Z in the Foinaven Sub-basin, and in 214/19-1 and the lower part of T22 in 214/27-1 in the Flett Sub-basin.

Sandstone type IV is seen in 208/19-1, 214/27-2 and the upper part of 214/27-1 (all from the Flett Sub-basin). The samples from 208/19-1 differ from those of 214/27-1 and 214/27-2 by having lower low Ai/Aii ratios and lower RuZi. These sandstones are therefore ascribed to type IVa, whereas those from 214/27-1 and 214/27-2 have type IVb mineralogy.

In 6004/16-1z, the sandstones have comparatively low RuZi, although values are slightly higher than in T10. On the GZi-RuZi plot (Fig. 9), they overlap with the samples from

208/19-1, but garnet geochemistry (Fig. 11) rules out the possibility of IVa mineralogy. On the basis of their low RuZi and garnet compositions, therefore, it is considered most likely that these sandstones have type III mineralogy. Their relatively low ATi suggests they may have undergone weathering during the sedimentary cycle.

T31-32

Data are available for six wells (204/19-3A, 204/20-1z, 204/24a-7, 214/27-1, 6004/16-1z and 6005/15-1) at T31-32 level (Figs 13-17).

Sandstone type II dominates the Foinaven Sub-basin, the sandstones in 204/19-3A and 204/20-1Z being exclusively of this type. Most samples from 204/24a-7 are also sandstone type II, but a small number have type I mineralogy (Fig. 17). Other wells in the Foinaven area (such as 204/24a-3) are dominated by sandstone type I (Morton et al., 2002).

The single T31 sample from 214/27-1 in the Flett Sub-basin has similar mineralogy to the underlying T22-28 (type IVb).

Wells 6004/16-1z and 6005/15-1 have similar sandstone compositions, the only significant difference being that GZi values tend to be reduced in 6005/15-1, owing to more advanced garnet dissolution. The sandstones in these two wells have relatively low RuZi (Fig. 14), suggesting they have type III affinities. This is supported by the presence of Greenland floras in 6005/15-1 (Jolley et al., 2005). Garnet assemblages are compatible with type III mineralogy (Fig. 16), the one sample with much higher and apparent aberrant type A contents being the most deeply-buried, with a comparatively low GZi. This sample may therefore have undergone greater garnet dissolution, which tends to cause type A contents to increase because Ca-rich garnets are preferentially dissolved relative to Ca-poor types (Morton and Hallsworth, 2007).

The T31-32 interval in 6005/15-1 is rich in clinopyroxene, but as the samples are from cuttings it is not possible to judge whether the clinopyroxene is from the sandstones, the basalts or the intrusive rocks, all of which are believed to be present in the interval in question. The presence of sandstone type V is therefore open to question. There is little evidence for the presence of type V detritus in the adjacent well, 6004/16-1z.

T34

Data are available for ten wells (204/19-3A, 204/20-1z, 204/24a-7, 206/2-1A, 214/19-1, 214/27-1, 214/27-2, 6004/16-1z and 6005/15-1) at T34 level (Figs 18-22).

Sandstone type I appears to be absent during this interval, but types II, III and IV have all been recognised. Type II sandstones occur in 204/19-3A, 204/20-1Z and 204/24a-7, and are also seen at the top of T34 in 214/27-2. Type IVa sandstones occur in 214/29-1, with type IVb in 214/19-1, 214/27-1 and the lower part of 214/27-2. The affinity of the samples in 206/2-1A is difficult to judge since burial diagenesis has caused garnet dissolution, precluding analysis of garnet populations.

The sandstones in 6004/16-1z and 6005/15-1 are distinguished from the other T34 sandstones on the basis of their lower RuZi (Fig. 19). This feature suggests they have type III characteristics, similar to the sandstones in T31-32. This interpretation is supported by the continued presence of Greenland floras (Jolley et al., 2005). The T34 interval in 6005/15-1 is rich in clinopyroxene, but the highest clinopyroxene contents are found in cuttings samples, and it is therefore difficult to judge whether the clinopyroxene is from the sandstones, the basalts or the intrusive rocks, all of which are believed to be present in the interval in question. However, clinopyroxene does occur in the one core sample from this well, and although the abundance is much lower than in the cuttings, its presence diagnoses the involvement of type V material. There is little evidence to suggest that type V detritus is present in the adjacent well, 6004/16-1z.

T35

Data are available for six wells (204/19-3A, 204/20-1z, 205/9-1, 205/14-2, 206/2-1A and 6005/15-1) at T35 level (Figs 23-27).

There is a distinct change in provenance at T35 level. In the Foinaven Sub-basin, sandstone type II is much less common, being found in just one sample from 204/20-1Z (Fig. 26). The other samples from this area (from 204/19-3A and 205/14-2) fall either in the type I field, or close to the boundary between type I and type II, indicating a reappearance of basement-derived sediment and a decrease in Triassic recycling. These samples are classed as type I on Fig. 27, although they contain a small but significant type II component. The affinity of sandstones in 206/2-1A is uncertain because burial diagenesis has caused garnet dissolution, thereby precluding analysis of garnet populations.

In 6005/15-1, there is an increase in RuZi, implying a shift away from western (type III) sourcing towards type I (similar to the Foinaven Sub-basin). This coincides with a marked reduction in the proportion of Greenland floras (Jolley et al., 2005).

By contrast, sandstone type III makes an appearance further north, in 205/9-1, where it is associated in some samples with sandstone type V (common clinopyroxene).

T36

Data are available for seven wells (204/19-3A, 205/9-1, 205/12-1, 205/14-2, 214/27-2, 6004/16-1z and 6005/15-1) at T36 level (Figs 28-32).

The trend seen in T35 continued during T36, with the influence of sandstone type II continuing to wane. Samples from 205/12-1 fall in or close to the type II field, and one sample from 204/19-3A also has type II features. However, the remaining 204/19-3A samples, plus all samples from 205/14-2, 6004/16-1z and 6005/15-1, and samples from the upper part of T36 in 214/27-2 have sandstone type I characteristics

Sandstone type III continues to be present in 205/9-1, and is also found in the basal two T36 samples from 214/27-2. Many of the samples with type III characteristics also contain clinopyroxene, indicating the additional presence of sandstone type V.

T38

Data are available for six wells (206/2-1A, 208/17-2, 208/19-1, 214/27-2, 6004/16-1z and 6005/15-1) at T38 level (Figs 33-37).

Virtually all the T38 samples have sandstone type I characteristics. However there is evidence for two different sandstone subtypes. The two wells in Quadrant 208 (208/17-2 and 208/19-1) have lower ATi, lower type A garnet abundances and higher RuZi values than most of the other wells, and the sandstones in this area appear to have been derived from different basement source to those found further to the south and west. The lower ATi in these sandstones could be due to weathering, but another possibility is that they were derived from tourmaline-rich basement lithologies (such as the Dalradian).

The T38 sandstones in 6004/16-1z have relatively low RuZi values, but these are based on poor grains counts, and it is considered more likely that these are type I sandstones rather than type III. In the adjacent well (6005/15-1) RuZi values are typical of type I, but ATi values are low. The reason for the lower ATi is not certain in this case: possibilities include a slight difference in provenance or surficial weathering causing apatite depletion.

T40 and younger sandstones

In T40 and T45 (Figs 38-45), regional differences in sandstone characteristics become less distinct. The majority of samples fall in a cluster on the garnet plot (especially well-defined in T40) that overlaps sandstones types I, II and IV, and the range in RuZi implies involvement of type III. There are some samples with distinctive and diagnostic parameters, notably the T40 sandstones in 208/19-1 and 214/29-1 and T45 sandstones in 214/29-1, which have type I characteristics, and the T40 sandstones in 213/26-1 and 214/4-1, which have low RuZi and are probably type III.

The sandstones that fall into the cluster overlapping with type I, II and IV may represent mixed provenances, involving all these three sources, and probably also detritus with type III characteristics. The change from well-defined regional differences in provenance to more homogenised populations coincides with a change from predominantly deep water sedimentation to shallow water and paralic depositional environments (Mudge and Bujak, 2001). This is related to regional plate uplift associated with the Icelandic plume (Mudge and Jones, 2004; Rudge et al., 2008). The change in mineralogy between the T10-T38 and T40-T45 intervals is inferred to reflect this regional plate uplift, with the paralic depositional setting allowing greater mixing of sediment from different sources through coalescence of individual fluvial systems and through homogenisation in shallow marine settings. Provenance patterns at T40-T45 level require further investigation through acquisition of more data across the area.

The post-T50 sandstones (sampled in 214/10-1 and 214/26-1) have markedly different provenance characteristics compared with those from the T10-T45 interval (Figs 46-49). These sandstones are categorised as type VI. As discussed above, the provenance of sandstone type VI remains enigmatic. The high CZi requires the presence of ultramafic or mafic rocks in the source area. Derivation from ophiolitic rocks on the Shetland Isles (such as the Unst ophiolite) seems unlikely, since chloritoid, which is abundant in sediment derived from the Shetland Isles (Morton et al., 2004), is scarce in sandstone type VI. Furthermore, the post-T50 sandstones are considered to represent submarine fans sourced from the south (Davies et al., 2004). Derivation from the south may indicate that the chrome spinel was sourced from ultramafic complexes within the Tertiary Igneous province. One such complex lies on the Isle of Rum, although this is at a considerable distance from the Faroe-Shetland Basin: a more likely possibility would be from one or more centres on the Wyville-Thomson

Ridge to the southwest (Fig. 1). The low GZi and ATi suggest that the source area also included sandstones that had undergone weathering, and may indicate a significant degree of recycling from earlier Tertiary sandstones.

The marked change in provenance between the pre-T50 and post-T50 sandstones corresponds to a return to deep water conditions (Smallwood and Gill, 2002) following the transient phase of regional uplift related to the Icelandic Plume (Rudge et al., 2008). The appearance of a different sandstone type, unlike those found in the pre-T50 succession, implies reorganisation of sediment source areas and transport paths, rather than a reversion to the drainage systems operative prior to the transient uplift phase.

RUTILE GEOCHEMICAL CONSTRAINTS ON PROVENANCE

Arguably the most exciting recent development in the field of mineral-chemical provenance studies concerns the geochemistry of rutile. Rutile (TiO_2) predominantly forms in medium to high grade (greenschist-granulite facies) metamorphic rocks, and is scarce or absent in magmatic and low grade metamorphic rocks (Force, 1980, 1991). The lack of variation in major element composition has, until recently, precluded the application of rutile geochemistry in provenance studies. For example, Preston et al. (1998, 2002) demonstrated that detrital rutile in Triassic continental red-beds in the Beryl Field, North Sea, comprises almost pure TiO_2, with only a small proportion containing appreciable Nb_2O_5 or FeO.

The recognition that a large number of trace elements (V, Cr, Fe, Al, Nb, Sn, Sb, Ta, W, Zr, Mo, Hf, Th and U) may substitute for Ti in the rutile lattice led Zack et al. (2002, 2004a, 2004b) to undertake electron microprobe and laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) analyses on rutile in order to develop a useful provenance tracer. This work had two significant conclusions. Firstly, they showed that the two principal rutile hosts (metapelitic and metamafic rocks) can be distinguished on the basis of Nb and Cr contents in rutile. Secondly, they showed that the Zr content of metapelitic rutile is dependent on temperature of formation, indicating that Zr in rutile can be used to measure maximum metamorphic temperatures. This single-grain Zr-in-rutile geothermometer is believed to be the first of its kind to be used in provenance studies. The Zack et al. (2004a) Zr-in-rutile geothermometric calculation, which was based on data from rutile-, quartz- and zircon-bearing metamorphic rocks formed at temperatures between 430°C and 1100°C, calculates temperature as

$T\ (^{o}C) = 127.8 \times \ln(Zr\ ppm) - 10$

with an error of ±50°C.

Watson et al. (2006) presented an alternative thermometric calculation based largely on experimental data, with additional constraints provided by rutiles from metamorphic rocks, which expresses temperature as:

$T\ (^{o}C) = 4470/(7.36 - \log_{10}[Zr\ ppm]) - 273$
with an error of ±20°C.

Meinhold et al. (2008) and Morton and Chenery (in press) present data that show the Watson et al. geothermometer gives a more realistic measure of metamorphic temperature, and therefore, in the following discussion, only temperatures derived using the Watson et al. formula are discussed.

Applications of detrital rutile geochemistry by Stendal et al. (2006), Triebold et al. (2007), Meinhold et al. (2008) and Morton and Chenery (in press) have demonstrated the effectiveness of the method in identifying sources and constraining the metamorphic evolution of the hinterland. Meinhold et al. (2008) suggest that the Zr-in-rutile thermometer may be applicable not only to metapelitic rutiles but also to those of metamafic origin, a view supported by Morton and Chenery (in press). Triebold et al. (2007) showed that high-grade metamorphic rutile survives metamorphic conditions on a retrograde path below 550°C, thereby preserving its chemical signature to much lower temperatures, and Stendal et al. (2006) showed that rutile does not always break down during low-grade (greenschist facies) metamorphism, as was previously thought (Force, 1980; Zack et al., 2004b).

The recognition that mineral-chemical analysis of detrital rutile may yield significant provenance information is of particular importance because of the stability of rutile under both burial diagenetic and surficial weathering conditions (Hubert, 1962; Morton and Hallsworth, 1999, 2007). The ultrastable nature of rutile means that crucial provenance information can be gathered from highly modified heavy mineral assemblages that may have lost considerable amounts of provenance information.

Given the evidence for significant differences in provenance in the Paleocene-Eocene of the Faroe-Shetland Basin, and for loss of crucial garnet provenance information in the most deeply-buried parts of the succession, rutile geochemical analysis was carried out on a subset of samples. These analyses were undertaken to assess if differences in provenance interpreted using conventional and garnet geochemical data are supported by rutile data, and to place further constraints on the nature of the sediment sources. In addition, rutiles were analysed from a small number of Paleozoic and Mesozoic sandstones on the Shetland Platform margin in order to determine their potential as sediment sources for the Paleocene-Eocene. Data acquired and analytical methods used are described by HM Research Associates (2007b).

Rutile compositions

Rutile compositions reflect both the composition of their host rock (principally metapelitic or metamafic) and the temperatures at which they formed during metamorphism. The relative abundance of metapelitic and metamafic rutiles and their inferred temperature distributions in each sample are shown in Figs 51-77. The samples analysed in this study cover all the sandstone types with the exclusion of the volcaniclastic source (type V).

Sandstone type I

Five samples interpreted as having sandstone type I mineralogy were included in the rutile geochemistry data set. These samples are 204/19-3a, 1948.48 m (Fig. 51); 206/2-1a, 2270.18 m (Fig. 52); 208/17-2, 2404.60 m (Fig. 53); 208/19-1, 1865.40 m (Fig. 54); and 214/29-1, 1904.50 m (Fig. 55). The five samples have closely comparable rutile temperature distributions, all being dominated by amphibolite/eclogite facies grains. The four samples from the northern part of the study area (206/2-1a, 208/17-2, 208/19-1 and 214/29-1) have maximum metamorphic temperatures between 550-650^{o}C, whereas the sample from the Foinaven sub-basin (204/19-3a) has slightly higher temperature rutiles (600-750 ^{o}C).

Three of the five samples have metapelitic rutiles (62-64%) dominant over metamafic types (36-38%), but the samples from 208/17-2 and 208/19-1 have higher proportions of metamafic rutile (52-59%). These two samples are from T38, and were identified as having a different source on the basis of their lower ATi, lower type A garnet abundances and higher RuZi values than other sandstones of this age.

These results suggest that it may be possible to recognise subtle differences in basement sourcing across the area, and that a number of different basement sources on the Orkney-Shetland Platform may have sourced sandstone type I. However, the data set clearly needs substantiating, particularly from samples in the Foinaven sub-basin.

Sandstone type II

Four samples interpreted as having sandstone type II mineralogy were included in the rutile geochemical data set: 204/20-1z, 2673.15 m (Fig. 56), 206/1-3, 4289.00 m (Fig. 57), 214/19-

1, 4140 m (Fig. 58) and 214/27-1, 4179.47 m (Fig. 59). These samples are all characterised by having bimodal rutile temperature distributions, all containing a distinctive group of granulite-facies rutiles (750-900^{o}C) in addition to amphibolite-facies grains similar to those found in sandstone type I. Sandstone type II is characterised by the abundance of type Ai garnets, which are believed to diagnose granulite facies metasedimentary or charnockitic sources (Sabeen et al., 2003; Mange and Morton, 2007). The direct relationship between abundance of type Ai garnet and granulite-facies rutile in sediments of the Faroe-Shetland Basin (Fig. 78) provides strong support for this view.

All samples have higher contents of metapelitic rutiles compared with metamafic types, but the sample from the Foinaven Sub-basin (204/20-1z) has lower metamafic rutile contents (28%) than samples from further north (35-43%). This mirrors the pattern seen in sandstone type I and suggests that amphibolite-facies metamafic rocks were more widespread in the northern part of the Orkney-Shetland Platform than they were in the south. This in turn suggests that sandstone type II may have been derived from at least two sources, one in the south (where metamafic rutiles are less abundant) and one further north (where such rocks are more widely distributed). Again, more data are needed to substantiate this suggestion.

Sandstones with mixed type I/type II mineralogy

A relatively large number of samples in the study have type I mineralogy with a small type II component. Four such samples were included in the rutile data set (204/24a-7, 2214.90 m, Fig. 60; 206/2-1a, 2478.51 m, Fig. 61; 206/2-1a, 3381.40 m, Fig. 62; and 214/27-2, 3118.29 m, Fig. 63) in order to determine whether the subsidiary type II component, as identified by the presence of type Ai garnet, is supported by the presence of small numbers of granulitic rutiles. All the samples contain small numbers of granulitic rutiles, and in three cases the assemblages are distinctly bimodal, with a subordinate granulite-facies group and a major amphibolite/eclogite-facies group.

The north-south difference in abundance of metamafic rutiles seen for sandstones type I and II is substantiated by the sandstones with mixed characteristics, with the sample from the Foinaven sub-basin having fewer metamafic types (35%) compared with those from the Flett sub-basin (39-44%).

Sandstone type IV

Four sandstones with type IV mineralogy have been included in the rutile data set: 208/19-1, 2458.55 m (Fig. 64), 208/19-1, 2649 m (Fig. 65), 214/29-1, 2578.60 m (Fig. 66) and 206/1-3, 4000.60 m (Fig. 67). The samples from 208/19-1 and 214/29-1 have type IVa mineralogy, whereas that from 206/1-3 has type IVb mineralogy. The four samples have rutile populations dominated by amphibolite-facies grains with most temperatures between 550-650^{o}C, with metapelitic grains (57-65%) being more common than metamafic types (35-43%). These compositions are not dissimilar to those seen in sandstone type I from the Flett sub-basin, and it would be difficult to discriminate these two provenance types on the basis of rutile data alone.

Sandstone type IV is characterised by abundant type Aii garnet. Previous work has suggested that such garnets are derived from granulite-facies rocks (Sabeen et al., 2003; Mange and Morton, 2007), but the rutile data indicate that in this case, granulites were not involved. It seems likely that in the Faroe-Shetland Basin, most type Aii garnets were ultimately derived from igneous rocks sourced from deep crustal levels, which is the other known provenance of such garnets (Hamar and Moyes, 1982; Mange and Morton, 2007).

Sandstone type III

The key feature of sandstone type III is relatively low RuZi, and hence rutile is not a major component of type III assemblages. Therefore, only two samples with type III mineralogy were included in the rutile data set, both from 6004/16-1z (3453.15 m, Fig. 68, and 4203.35 m, Fig. 69). The two assemblages are similar in terms of source rock composition, having higher abundances of metapelitic types (57-71%) compared with metamafic types (29-43%). Both have a wide range of metamorphic temperatures, although amphibolite-facies grains are more common than granulite-facies grains. Garnets are present only in the shallower sample, and indicate the presence of type B with subordinate type A. The rutile assemblage is therefore compatible with the garnet data. The rutile assemblage in sandstone type III cannot be readily discriminated from sandstones of mixed type I/II mineralogy.

Sandstone type VI

One sample with type VI mineralogy (214/26-1, 2292.73 m) has been included in the rutile study (Fig. 70). The temperature distribution in the sample is relatively structureless and wide-ranging, although rutiles formed in the 600-650^{o}C bracket are the most common. Metapelitic rutiles are more common than metamafic types (59% compared with 41%). The population is not especially distinctive, and rutile data alone would not be sufficient to recognize this sample has having a different provenance to others in the data set.

Paleozoic and Mesozoic sandstones

Samples from the Triassic succession in the Strathmore Field (Foula and Otter Bank formations), from the Devonian-Carboniferous Clair Group succession in the Clair Field, and from the Old Red Sandstone of Caithness and Orkney were included in the study to determine the possible roles these sandstones may have had in sourcing the Paleocene-Eocene.

The rutile population in the Foula Formation sample from 205/26a-4, 2534.44 m (Fig. 71) is distinctive, in that it is dominated by granulite-facies rutiles. As previously suggested on the basis of garnet geochemical data, the Foula Formation is likely to have been the main source for sandstone type II, since both contain large numbers of type Ai garnets (Morton et al., 2002; Jolley and Morton, 2007). The rutile data provide strong support for this suggestion, since, as discussed above, granulite-facies rutiles make up a large proportion of the rutile population in sandstone type II. However, it is noteworthy that the Foula Formation contains significantly fewer metamafic rutiles (18%) than sandstone type II, implying an additional supply from amphibolite-facies metamafic rocks, both in the Foinaven sub-basin and especially in the Flett sub-basin.

The rutile population from the underlying Otter Bank Formation in 205/26a-4 (2723.12 m) is markedly different to that of the Foula Formation (Fig. 72), being dominated by amphibolite-facies grains peaking in the 600-650^{o}C range. There is a subordinate granulite facies group, consistent with the presence of small numbers of type Ai garnets. Metamafic rutiles are more common than in the Foula Fm (29%), although they remain subordinate to metapelitic rutiles. The difference in rutile assemblages confirms previous evidence from conventional heavy mineral data, garnet geochemistry and zircon age dating for a major change in provenance between the Otter Bank and Foula formations (Morton et al., 2007). The rutile assemblage in the Otter Bank bears some similarities with sandstones of mixed type I/II origin, and may have been involved in their provenance.

Rutile populations in three samples from the Clair Group succession are shown in Figs 73-75. One of these samples is from the Upper Clair (206/8-2, 1426.70 m), whereas the other two (206/8-8, 2004.65 m, Unit IV and 2111.70 m, Unit III) are from the Lower Clair. Despite the samples having markedly different garnet assemblages, rutile compositions are closely comparable, all being dominated by amphibolite-facies grains, with metapelitic rutiles forming 73-75% of the populations. The sample from 2004.65 m is slightly different in that the main peak (600-650^{o}C) is more well-defined, whereas the other two have more diffuse patterns. The garnet assemblage in the sample from 2004.65 m is comparable to that found in sandstone type IV, and the rutile temperatures in this sample support this similarity. Jolley and Morton (2007) suggested that sandstone type IV was derived from Carboniferous sandstones with similar garnet assemblages to those found in parts of the Clair Group. The rutile data supports this view, although there must have been additional supply from metamafic rocks in order to generate the rutile compositions in sandstone type IV.

The rutile population in the Hoy Sandstone (Middle Old Red Sandstone on Hoy, Orkney Isles), is closely comparable to those found in the Clair Group (Fig. 76), having predominantly amphibolite facies temperatures and containing 75% metapelitic types. Rutile data therefore support the view that the Clair Group had a similar source to the ORS of Orkney. The other ORS sample, from the Dunnet Head Sandstone, is also dominated by amphibolite-facies rutiles (Fig. 77), but metamafic types are much less common (forming only 12% of the population).

CONCLUSIONS

Heavy mineral and garnet geochemical data differentiate six sandstone types (I-VI), derived from different source rocks, in the Paleocene-Eocene of the Faroe-Shetland Basin. The key parameters are garnet geochemistry (notably the abundance of type Ai and Aii garnets), ATi, GZi, RuZi, CZi and clinopyroxene contents. Rutile geochemistry provides valuable additional information, being particularly useful in identifying sandstone type II and showing the variable involvement of metamafic rocks across the basin.

The key features of sandstone type I are low abundances of type A garnet in conjunction with relatively high RuZi. Sandstone type I was derived from basement lithologies (Lewisian and/or Moine/Dalradian) on the Orkney-Shetland Platform, either directly or indirectly through recycling. Rutile data indicate that amphibolite-facies rocks were widespread. It appears that at least two different basement areas were involved, since type I sandstones in the Foinaven sub-basin have lower contents of metamafic rutiles compared with those in the Flett sub-basin.

Sandstone type II is characterised by abundant type Ai garnet and relatively high RuZi. The garnet geochemistry and presence of granulite-facies rutile indicate that the ultimate source of sandstone type II included high-grade granulite facies basement rocks. The presence of similar garnet and rutile assemblages in the Foula Fm (Triassic) indicates that sandstone type II was probably recycled from the Triassic on the Orkney-Shetland Platform. Sandstone type II has lower GZi than typical Foula Fm, therefore requiring additional input from a low-garnet source, such as Lewisian acidic gneisses or the Old Red Sandstone. Additional sources are also required to account for the presence of amphibolite facies rutile and of metamafic rutile. The metamafic component probably represents basement material. The increased content of metamafic rutile in the Flett sub-basin compared with the Foinaven sub-basin suggests that at least two sediment transport systems operated in the Faroe-Shetland Basin, one in the Foinaven area and one in the Flett area. Both tapped Triassic rocks similar to those found in the Foula Formation, plus other sources, including metamafic basement that was more widespread in the northern part of the Orkney-Shetland Platform. This mirrors the evidence shown by sandstone type I. Sandstone type II is most widespread in the earlier parts of the succession, becoming less important after T34.

Sandstone type III is diagnosed by low RuZi, and is frequently associated with the volcaniclastic sandstone type (V). Input from the west is considered most likely, but local sourcing (for example, from the Corona Ridge) is considered more likely than derivation from East Greenland.

Sandstone type IV is diagnosed by the abundance of type Aii garnets. Rutile data suggest that these garnets were not supplied from granulite facies rocks, and ultimate derivation from igneous rocks sourced from deep crustal levels seems a more likely explanation. Similar garnet and rutile populations have been identified in the Devonian-Carboniferous Clair Group, and recycling from younger Carboniferous (Namurian-Westphalian) sandstones on the Orkney-Shetland Platform is considered the most likely origin of sandstone type IV (Jolley and Morton, 2007).

Sandstone type VI is present only in the Eocene (post T50). It has markedly different characteristics to earlier Tertiary sandstones, with lower ATi and GZi in conjunction with higher CZi. The relatively high abundance of chrome spinel indicates that ultramafic rocks were involved, but the low GZi and ATi suggests that recycled sandstones were also a major component of the source area. The provenance of this sandstone type is enigmatic, but given the seismic evidence for transport from the south, involvement of Tertiary ultramafic rocks similar to those found in Rum (Inner Hebrides) is considered likely. The most likely location of these igneous centres are the Wyville-Thomson Ridge to the southwest (Fig. 1).

During T10-T38, there are distinct lateral and stratigraphic differences in mineralogy that relate to the interplay between different submarine fan systems sourced from both east and west. In T40-T45, sediment compositions become more homogeneous, causing difficulty in categorizing samples into the distinct sandstone types seen in T10-T38. This change coincides with a change in depositional environment, from deep water submarine fans to shallow water and fluvial facies, a result of a regional transient uplift phase related to the

Icelandic Plume (Rudge et al., 2008). This change in depositional setting allows greater mixing of sediment from different sources through coalescence of individual fluvial systems and homogenisation in shallow marine settings.

The change in mineralogy in the post-T50 sandstones coincides with a return to deep water conditions following the end of the transient uplift phase. The appearance of a new sandstone type (VI) at this time suggests that there was a reorganisation of drainage patterns compared with the pre-T50 succession.

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Faroes-Shetland Sand Transport ReadMe

The Project Files

An ***ArcGis*** project file is supplied (SINDRI Faroes-ShetlandSandTransport.mxd), for which *ArcGis/ArcView* version 9.2+ is required.

An ***ArcScene*** project file is supplied (SINDRI Faroes-ShetlandSandTransport.sxd), for which *ArcScene* version 9.2+ is required.

Double clicking a project file on the CD, will load the project. Alternatively, the contents of the CD can be copied to a hard disk directory and the project files run from there**.**

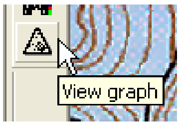
The Data Frames

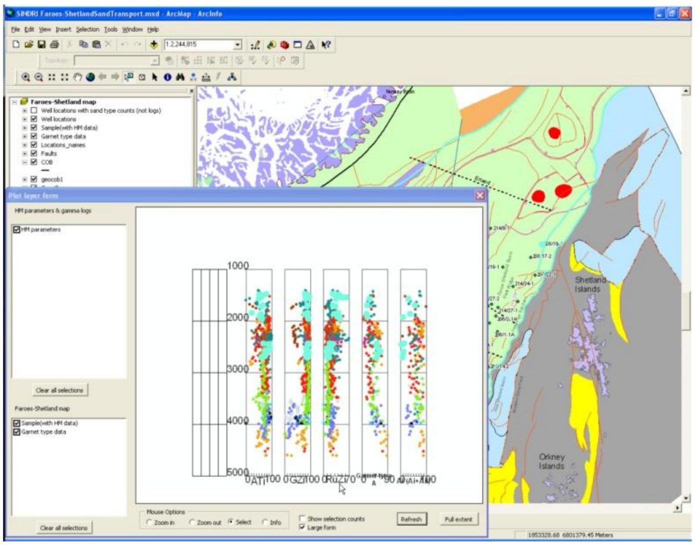
In the **Faroes-Shetland map** dataframe, a layer (**Well locations with sand type counts (not logs)**) is created for the wells showing them as stacked bar charts giving the counts of the sand types found in that well. **Note these charts are not logs**.

Graphs have been created of the gamma logs and various heavy mineral parameters plotted against depth. In the data frame **HM parameters & gamma logs**, these plots may be viewed together for each well. The plots are symbolised by Sand Type and Sample Type (i.e. core or cutting type). (In the ArcScene project (SINDRI Faroes-ShetlandSandTransport.sxd), these variables may be seen in 3D).

Viewing the graphs

You can view any of the dataframes in the usual way by selecting it and then activating it (right click it and select activate). However, a 'View graph' tool, developed in CASP, allows you to view two dataframes at the same time and you may find it useful for viewing the layer **HM parameters** in the **HM parameters & gamma logs** dataframe. Activate the map then select the **HM parameters & gamma logs** dataframe (having made **HM parameters** and **Sample grid** the only visible layers); clicking the 'View graph' button (shown on the right) will open a floating window containing the selected dataframe. It is best to have only one the sample layers visible – this will speed up the link to the graph.





If you select a point or group of samples, the corresponding samples will be automatically highlighted in the other dataframe using the sample number to link the points. Similarly samples can be selected on the activated dataframe using the standard selection tool and the corresponding samples will be highlighted on the graph. The window containing the graph can be moved.

If it occupies too much of the screen area the window can be reduced in size by unchecking 'Large form' on the lower part of the window, which is on by default. The messages giving the number of samples selected may be turned off using the "Show selection counts" check box.

There are also buttons on the lower part of this window to allow zooming in and out of the graph and an information tool to allow access to attribute information from the graph. Rather than pointing and clicking, it is easier to drag a rectangle around a point or points to get the information. The panels in the left of the window show which layers within the data frames with provenance data are visible, both on the map and on the graph, and therefore involved when the selection tool is being used.

Technical detail.

When the control is clicked then a VBA error may occur because the controls for the MS Tree Control & the ESRI Map Control are not in the reference list. If this happens stop the macro, then

1. Select Tools/Macros/Visual Basic Editor.

2. Select Tools/References.

3. Click the Browse button; select Files of Type *.ocx; select C:\Windows\System32\MSCOMCTL.OCX.

4. Click the Browse button; select Files of Type *.ocx; select C:\Program Files\ ArcGIS\Bin\ MapControl.ocx.