Provenance of sub-Paleocene reservoir sandstones west of Shetland: an integrated heavy mineral, mineral chemical and zircon age dating project

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INTRODUCTION

Although Paleocene targets remain the primary focus for hydrocarbon exploration in the Faroes sector of the Faroe-Shetland Basin, pre-Paleocene clastic successions are also of interest. In the UK sector, pre-Paleocene clastic reservoirs have been found in the Devonian-Carboniferous, as in the Clair Field (Coney et al., 1993; Johnstone et al., 1995; Witt, in press), the Triassic, as in the Strathmore Field (Herries et al., 1999), the Jurassic, as in the Solan Field (Herries et al., 1999) and the Early Cretaceous, as in the Victory Field (Goodchild et al., 1999). Hydrocarbons have also been found in the Jurassic in the Rosebank area. Understanding the provenance of these sandstones is crucial in establishing paleogeographies and likely distribution of potential reservoir rocks in the subsurface.

Previous studies funded by SINDRI have shown the value of integrated heavy mineral and mineral chemical analysis in identifying sand sources, sediment input points, and mapping intrabasinal sand distribution patterns in the Paleocene of the Faroe-Shetland Basin (Frei et al., 2005; Jolley and Morton, 2007; HM Research Associates, 2008). The same integrated approach has therefore been applied to the pre-Paleocene intervals, involving four key elements:

(i) conventional heavy mineral analysis and provenance-sensitive ratio determination, which provides the basic framework for identification of sand types and discrimination of sources;

(ii) major element garnet geochemistry by electron microprobe, which enables further subdivision of sand types and provides detailed information on sand source lithology;

(iii) trace element rutile and apatite geochemistry by laser ablation ICP-MS, which complements and extends the information gained from garnet geochemistry;

(iv) zircon age determination by laser ablation inductively-coupled plasma-mass spectrometry (LA-SF-ICP-MS), which provides geochronological constraints on the source rocks.

The provenance study is based on data from 16 wells from the area west of Shetland. Data from 12 of these (202/3-1a, 202/3a-3, 204/23-1, 204/27-1, 204/28-1, 205/20-1, 205/23a-2, 206/4-1, 208/26-1, 209/12-1, 213/23-1 and 214/9-1) were collected during the course of this project. Data from 205/26a-3 and 205/26a-4 (Triassic, Strathmore Field) were published by Morton et al. (2007), and data from 206/8-2 and 206/8-8 (Devonian-Carboniferous, Clair Field) were presented by Morton et al. (2009a). The report also discusses data from the Cretaceous succession in Kangerlussuaq published by Whitham et al. (2004). Locations of the studied sites are shown in Fig. 1 and the stratigraphic coverage of the data is given in Fig. 2. Analytical methods, sample listings and the complete data set are supplied in the Appendix (provided as a CD accompanying this report). The accompanying CD also provides the data in GIS format.

HEAVY MINERAL PROVENANCE CHARACTERISTICS

The heavy mineral provenance characteristics of the sandstones discussed in this report are shown by means of the following:

- Binary plots of the provenance-sensitive heavy mineral ratios apatite:tourmaline (ATi), garnet:zircon (GZi) and apatite:tourmaline (ATi), as shown in Figs 3-6. Note that GZi values are likely to have been modified in the deeper parts of the basin because of garnet dissolution.

- Ternary plots of garnet compositions (Figs 7-10). These are generated by plotting the relative proportions of garnets falling into fields Ai, Aii and B+C as described by Morton et al. (2004), Jolley and Morton (2007) and Morton et al. (in press), as shown in Fig. 11. Given the evidence for advanced garnet dissolution in the deeper parts of the basin, a second ternary diagram has also been generated. This diagram compares the relative abundance of garnets that fall in different areas of the <10% X_{Ca} field (Ai, Aii and Bi), as shown in Fig. 11. Garnets with low Ca contents are more stable than those with high Ca (Morton, 1987; Morton and Hallsworth, 2007), and hence the Ai-Aii-Bi diagram is more suitable when comparing garnet provenances in sandstones with variable degrees of garnet dissolution.

- Variations in rutile composition, expressed in terms of source lithotype (relative abundance of metapelitic and metamafic rutile) and metamorphic grade (abundance of granulite-facies rutile), as shown in Fig. 12. Relative abundances of metamafic and metapelitic rutile were calculated following the method outlined by Meinhold et al (2008), and crystallisation temperatures were determined using the Zr-in-rutile thermometer described by Watson et al. (2006).

- Relative abundance of apatites derived from acidic, mafic/intermediate and alkaline sources (Fig. 13). Discrimination of apatite provenance was achieved using the La/Nd – (La+Ce+Pr)/REE_{tot} plot of Fleischer and Altschuler (1986), as recommended by Morton and Yaxley (2007).

- Zircon age spectra, as illustrated in Figs 14-16.

Well 202/3-1a

Well 202/3-1a (Fig. 1) is located in the Solan Basin, between the Rona Ridge to the NW and the West Shetland Spine Fault to the SE. Five sandstone samples, all from the Rona Fm., were analysed from this well, three from core and two from sidewall core. The Rona Fm. in this well is ascribed to the Middle Jurassic on the log supplied by Statoil (Fig. 2), although Verstralen et al. (1995) ascribe it to the Late Jurassic (Kimmeridgian-Volgian), correlative with the Rona Fm. in 204/27-1 and 204/28-1. The cored part of the succession in this well comprises deposits of high concentration turbidity currents (Verstralen et al., 1995).

The three core samples (from near the top of the succession) have very high ATi and GZi values (94-97 and 87-95 respectively), and have moderate RuZi of 21-25 (Fig. 4). The two sidewall cores from lower in the succession have lower ATi (76-84), with other parameters remaining comparable.

Garnets, rutiles, apatites and zircons have all been analysed from the sample at 1642.5 m at the top of the succession. The garnet assemblage (Appendix Fig. A1) has very high abundances of the Type Ai component, which forms 76% of the population (Fig. 8). The rutile population is distinctive in containing high abundances of metamafic rutile, many of which appear to have granulite facies crystallisation temperatures (Fig. 12, Appendix Fig. A20). The apatite population is dominated by grains of acidic origin, which form 74% of the assemblage (Fig. 13). The zircon population consists almost exclusively of Archaean grains in the 2650-2850 Ma bracket (Fig. 15). A high proportion of grains are >10% discordant (42 of the 103 grains analysed). The Wetherill concordia diagram (Appendix Fig. A31) shows that the discordance is the result of present-day Pb loss.

Well 202/3a-3

Well 202/3a-3 (Fig. 1) is located in the Solan Basin, between the Rona Ridge to the NW and the West Shetland Spine Fault to the SE. The interval analysed in this well belongs to the Stack Skerry Fm., which is of Early Jurassic (Sinemurian-Pliensbachian) age (Fig. 2). Most of the succession was uncored, and is therefore characterised using cuttings samples, but two samples from the short core at the top of the Stack Skerry Fm. were included in the study. The Stack Skerry succession comprises marginal to open marine sandstones and mudstones (Verstralen et al., 1995), and despite this being an isolated occurrence in the Solan Basin, it is considered likely that it represents an erosional remant of a more widespread Early Jurassic succession. This is supported by the presence of another isolated Early Jurassic occurrence on the Judd Platform (well 204/22-1), the presence of reworked Early-Middle Jurassic microfossils elsewhere in the area (Hitchen and Ritchie, 1987), and the recognition of an intra-Callovian deformational event (Booth et al., 1993) associated with regional uplift and erosion (Verstralen et al., 1995).

The Stack Skerry samples show comparatively little variation in terms of their provenance characteristics, and therefore form a relatively well-defined cluster on the ratio crossplots (Fig. 4). They have relatively high GZi and ATi (81-94 and 59-93 respectively), with moderate RuZi (16-36). ATi values tend to be lower towards the base of the succession, possibly indicating more extensive weathering.

Garnets have been analysed from 6 samples covering the entire succession (Appendix Fig. A2). The populations contain relatively high proportions of Type Ai garnets, with subsidiary types B and C. The deepest sample has the highest abundance of Type Ai garnet (66%), compared with 36-50% in the rest of the unit. With the exception of the deepest sample, the data form a distinct cluster on the garnet summary diagrams (Fig. 8), confirming the evidence for comparatively little variation in provenance throughout deposition.

A single rutile population was analysed (2100 m, Appendix Fig. A20). The population has more metapelitic rutiles (64%) than metamafic types (Fig. 12), and granulite-facies grains are also relatively common (36%). The apatite population at 2100 m is relatively diverse, with 62% of acidic origin, 30% of mafic origin and 8% of alkaline origin (Fig. 13). The zircon population at 2130 m contains a high proportion of Archaean grains in the 2650-2850 Ma bracket (Fig. 15), but 20 of the 70 concordant grains are Proterozoic in age. The Proterozoic grains are distributed across a wide age range without any well-defined groups, although 6 fall in a relatively narrow range between ~1880-1925 Ma. There is a high proportion of grains that are >10% discordant (38 of the 108 grains analysed). The Wetherill concordia diagram (Appendix Fig. A32) shows that the discordance is the result of present-day Pb loss.

Well 204/23-1

Well 204/23-1 (Fig. 1) is located north of the Judd Platform in the Faroe-Shetland Basin. Two samples were analysed from this well, both from a core in the conglomeratic Sola Fm. of Early Cretaceous (Aptian-Albian) age.

The two samples have extremely high ATi values (>99) and very low RuZi (<1). Their GZi values of 37-52 are considered to have been modified by garnet dissolution during burial diagenesis, since there is evidence for corrosion on garnet surfaces. Original GZi values are therefore likely to have been significantly higher.

Garnet analysis was not conducted on 204/23-1 because of the evidence for advanced garnet dissolution, which is likely to have caused severe modification of the compositional range. Rutile cannot be analysed due to its scarcity. Apatite analysis (Appendix Fig. A23) shows that the population consists almost exclusively of acidic types, which form 95% of the assemblage (Fig. 13). Zircons were not analysed from this well.

Well 204/27-1

Well 204/27-1 (Fig. 1) is located in the Solan Basin, between the Rona Ridge to the NW and the West Shetland Spine Fault to the SE. Six core samples from the Rona Fm. (Late Jurassic, Kimmeridgian-Volgian) were analysed from this well. The Rona Fm. in this well shows a marked evolution in sedimentary facies, from cohesionless debris flows and high density turbidites at the base, to well bioturbated fine sandstones and laminated argillaceous sandstones at the top, representing the deposits of a fan-delta system during a period of overall transgression (Verstralen et al., 1995).

The heavy mineral assemblages in the Rona Fm. contain a relatively high proportion of unstable phases, notably calcic amphibole (up to 10%) and epidote (up to 20%), suggesting first-cycle input. Another distinctive feature of the assemblage is the presence of pumpellyite in very small amounts. The entire Rona succession has extremely high ATi values (>99). GZi values are generally very high (>98), except for the basal sample (28). RuZi is also relatively high (23-54) but, as with GZi, is lower at the base.

Garnets have been analysed from two samples, one at the base and one near the top. The assemblages (Appendix Fig. A3) have high abundances of the Type Ai component, with subordinate Aii and C components (Fig. 8), especially in the lower of the two samples. The rutile population (Appendix Fig. A20) is distinctive in containing high abundances of metamafic rutile, many of which appear to have granulite facies crystallisation temperatures (Fig. 12). The apatite population is dominated by grains of acidic origin, which form 89% of the assemblage (Fig. 13). The zircon population consists almost exclusively of Archaean grains in the 2700-2800 Ma bracket (Fig. 15). A relatively small proportion of grains are >10% discordant (17 of the 106 grains analysed). The Wetherill concordia diagram (Appendix Fig. A33) shows that the discordance is the result of present-day Pb loss.

Well 204/28-1

Well 204/28-1 (Fig. 1) is located in the Solan Basin, between the Rona Ridge to the NW and the West Shetland Spine Fault to the SE. Only the basal part of the Rona Fm. (Late Jurassic, Kimmeridgian-Volgian) was cored in this well, and three samples were analysed. The coreed part of the Rona Fm. in this well comprises normally graded pebbly sandstone with occasional intercalations of massive pebbly sandstone, representing the products of high density turbidity currents (Verstralen et al., 1995).

The heavy mineral assemblages in the Rona Fm. are similar to those in 204/27-1, with a relatively high proportion of unstable phases (calcic amphibole up to 12%, epidote up to 26%, and pumpellyite present in minor amounts), and the same comments regarding provenance apply here. All three samples have extremely high ATi values (>99), with GZi and RuZi showing similar, but more muted, upward-increasing trends to those seen in 204/27-1. The garnet populations (Appendix Fig. A4) are also similar to those of 204/27-1, again showing a trend from Aii and C-rich assemblages at the base to Ai-dominated at the top. In view of the similarity with 204/27-1, no additional analyses (rutile, apatite, zircon) were conducted.

Well 205/20-1

Well 205/20-1 is located in the West Shetand Basin, adjacent to the Rona Ridge (Fig. 1). The Early Cretaceous Victory Fm. is the interval of interest in this well, with analysis conducted on three core samples of Barremian age and one cuttings sample from the Ryazanian-Hauterivian.

Recovery of heavy minerals was not especially good from the core, mainly as a result of the very fine grained nature of the sandstones. Recovery from the cuttings sample was better, but limited by the sample size (small-volume washed and dried material from the DTI core store). The assemblages are dominated by garnet (60-88%) in all cases, with GZi very high in the core (86-93) and somewhat lower in the cuttings (68). Likewise RuZi is high in the cored interval and lower in the cuttings. Both of these differences essentially result from differences in the abundance of zircon, which is higher in the Ryazanian-Hauterivian sample, and probably indicates a change in the nature of the sediment source. ATi is low throughout (11-15).

Because of the relatively poor recovery, additional analysis was confined to a single sample for garnet geochemistry (Appendix Fig. A5). The population is dominated by Aii and B garnets, forming 34% and 46% respectively.

Well 205/23a-2

Well 205/23a-2 is located on the Rona Ridge (Fig. 1). The analysed succession comprises a thin Rona Fm. (Late Jurassic, Kimmeridgian-Volgian) sandstone overlying a red-bed succession ascribed to the Triassic Foula Fm., inferred to be of Carnian-Rhaetian age. All samples analysed are washed and dried cuttings, but despite this, heavy mineral recovery was comparatively good.

The Foula Formation interval is characterised by relatively high ATi throughout (73-98). GZi varies considerably, from 22 to 89, with an overall upward-decreasing trend, and RuZi is low throughout (2-19). The single Rona Fm. sample has lower ATi (52) but otherwise has similar parameters.

In view of the variable GZi in the Foula Fm., garnet compositions were analysed from several samples (Appendix Fig. A6). The populations are diverse, with Ai, Aii, B and C fields all represented, but are mainly dominated by the B- and C-components, with variable Ai and minor Aii (Fig. 9). There does not appear to be any relationship between variations in GZi and garnet composition. The Rona Fm. sample has a more restricted garnet population, having a much higher proportion of Type B garnet (Fig. 8, Appendix Fig. A6).

Rutiles were analysed from one Foula Fm. sample (786 m, Appendix Fig. A20). The assemblage is rich in metapelitic types with moderate abundances of granulitic grains (Fig. 12). The zircon spectrum from an adjacent sample (768 m) shows a dominance of Archaean grains (50 of the 78 concordant grains), most of which fall in the 2700-2800 Ma bracket. The rest of the population is Proterozoic, ranging from ~1000-2300 Ma, with a distinct grouping in the 1850-1900 Ma range (Fig. 16). A small proportion of the zircons are > 10% discordant: the Wetherill concordia diagram (Appendix Fig. A34) indicates this is caused by present-day Pb loss.

Wells 205/26a-3 and 205/26a-4

Wells 205/26a-3 and 205/26a-4 are located in the Strathmore Field, East Solan Basin (Fig. 1). Data from Triassic sandstones in the two wells have already been published by Herries et al. (1999) and Morton et al. (2007), but new rutile and apatite data are reported herein. In addition, data from two Rona Fm. (Late Jurassic, Volgian) sandstones samples are also discussed.

The Triassic succession in the Strathmore Field is nearly 1000 m thick, and comprises two sand-rich formations, the Otter Bank Fm. and the overlying Foula Fm. The Otter Bank Fm. is underlain by the Otter Bank Shale Fm., dated as Griensbachian (basal Scythian) on the basis of a distinctive palynological assemblage (Swiecicki et al., 1995; Herries et al., 1999). The Otter Bank Fm. contains a very sparse palynological assemblage, most likely indicating a Scythian (Early Triassic) age (Swiecicki et al., 1995). Palaeomagnetic data (Swiecicki et al., 1995) indicate that the Otter Bank Fm. has predominantly reversed polarity, suggesting that it was deposited in the Diererian-Smithian (mid-Scythian). The lower part of the Otter Bank Fm. comprises braided sandy fluvial deposits, with the upper part containing interbedded fluvial and aeolian sabkha deposits. Palynological constraints on the age of the Foula Fm. are also poor, but suggest that deposition began in the Ladinian and extended into the Carnian (Swiecicki et al., 1995). The Foula Fm. has also predominantly reversed polarity, consistent with a Ladinian age (Swiecicki et al., 1995). The lower part of the Foula Fm. comprises interbedded fluvial and aeolian sabkha deposits, replaced by wholly fluvial deposits higher in the succession.

The heavy mineral assemblages are dominated by garnet throughout, but there are marked variations in ATi, GZi and RuZi in the succession. The most dramatic change is the sudden increase in RuZi from a baseline value of ~20-30 in the Otter Bank Fm. to a baseline value of ~60 in Foula Fm. (Fig. 5). ATi and GZi also show changes across the Otter Bank-Foula boundary. GZi is consistently extremely high in the Foula Fm., but is slightly lower and more variable in the Otter Bank Fm. ATi is also consistently high in the Foula Fm. and generally lower in the Otter Bank Fm. (Fig. 5).

The heavy mineral ratio evidence for a major difference in provenance between the Otter Bank and Foula Fms is substantiated by mineral chemistry and zircon age data. Garnet populations (Appendix Figs A7 and A8) in the Foula Fm. are dominated by Type Ai. This component is scarce in the Otter Bank, which is dominated by Type B with subordinate Types Aii and C (Fig. 9). Foula Fm. rutiles mostly comprise metapelitic types formed during granulite facies conditions (Fig. 12, Appendix Fig. A20). Otter Bank rutiles are also predominantly metapelitic, but granulite facies grains are less abundant (Fig. 12, Appendix Fig. A20). Apatite populations, however, show virtually no difference, both Foula and Otter Bank apatites being predominantly of acidic origin (Fig. 13).

The zircon populations in the two formations are also distinctly different (Fig. 16). The Foula Fm. sample, which is from the base of the succession in 205/26a-3, has three clearly defined components (Archaean, Early Proterozoic and Permian). The Archaean group forms 32% of the zircon population, most of which lie between 2700 and 2800 Ma. The Early Proterozoic group, which comprises 30% of the zircon population, has a relatively narrow age range (~1800-1900 Ma), peaking at 1880 Ma. The Permian zircons are dated between ~250 Ma and 300 Ma, and form 26% of the population. The zircons in the Otter Bank sample (also from 205/26a-3) are dominated by the Archaean (64% of the assemblage between ~2500-3000 Ma), with a subordinate Proterozoic group, most of which lie between ~1050 Ma and 1850 Ma, and a single Early Palaeozoic grain. There is no evidence for either the major Early Proterozoic (1880 Ma) or Permian zircon groups found in the Foula Fm., and although both formations contain Archaean zircons, there is a distinct difference in the distribution of the Archaean grains (Fig. 16). The Otter Bank has a much broader spread, ranging from 2650-3000 Ma, compared with the Foula Fm., which is mainly concentrated in the 2700-2800 Ma range.

The Rona Fm. sandstones have distinctly different characteristics to the Foula and Otter Bank, with lower GZi (62-68) and RuZi (9-13) than either Triassic unit (Fig. 4). No further constraints are available on the provenance of this unit at present.

Well 206/4-1

Well 206/4-1 is located on the eastern margin of the Faroe-Shetland Basin (Fig. 1). The analysed interval ranges from the Albian Royal Sovereign Fm., through the Cenomanian Commodore Fm., to the Turonian Macbeth Fm. (Fig. 2). Most of the succession was not cored, so the majority of the data are from cuttings, but there is a short core in the Macbeth Fm. from which two samples were included in the study.

There is a distinct shift in heavy mineral characteristics between the Royal Sovereign and the Commodore-Macbeth Fms. The Royal Sovereign Fm. which is described as conglomeratic on the well completion log, has very high ATi (>99) and very low RuZi (<2). It also has very low GZi (<7) but this could be due to garnet dissolution, given the comparatively deep burial and the evidence for surface corrosion textures on garnets higher in the well. The Commodore and Macbeth sandstones show comparatively little internal variations, with ATi between 66 and 95, GZi between 54 and 82 and RuZi between 11 and 22, and as a result form a well-defined cluster on ratio crossplots (Fig. 3). The two core samples have the highest ATi, possibly due to mechanically-induced apatite depletion in cuttings, but it may also be an effect of apatite growth, since the two core samples contain apatites that have well-defined secondary overgrowths. Garnet grains show evidence for surface corrosion, but since there is no obvious downhole decrease in GZi, the effect is not considered to have caused significant garnet depletion.

Garnet populations in the Macbeth and Commodore Fm.s show little compositional variation, all being dominated by the Type Aii and B components (Fig. 5, Appndix Fig. A9). Rutile assemblages contain subequal proportions of metamafic and metapelitic types, and very low abundances of granulite-facies grains (Fig. 12, Appendix Fig. A21). The apatite population from a Macbeth Fm. sample (core) is unusla in the context of the study, having much higher contents of mafic/intermediate types than all the other samples. However, it is possible that this difference is due to the presence of apatite overgrowths, and hence the significance of the difference in composition is at present uncertain. Further analyses are required to determine if the apatites in the Macbeth and Commodore Fm. have different provenances to the other apatite populations from the sub-Paleocene.

Zircons have been analysed from two samples, one from the Macbeth Fm. (core) and one from the Royal Sovereign Fm. (cuttings). The Macbeth Fm. sample has a diverse spectrum with Archaean, Proterozoic and Early Paleozoic elements (Fig. 14). The Early Paleozoic group, which comprises 20% of the assemblage (15 of 74 concordant analyses), lies between 406 Ma and 461 Ma. The Archaean comprises 19% of the population (14 of 74 concordant analyses), mostly in the 2650-2800 Ma bracket. The Proterozoic group (61% of the population, 45 of 74 concordant analyses) is complex: it covers the 1000-2000 Ma range and shows several distinct groups, notably ~1000-1100 Ma, ~1150-1200 Ma, ~1400-1500 Ma, ~1600-1650 Ma and ~1750-1900 Ma. The spectrum from the Royal Sovereign Fm., by contrast, has a single well-defined peak between ~2650-2800 Ma that contains virtually the entire zircon population (Fig. 14). Both samples display a degree of discordance that appears to be the result of present-day Pb loss (Appendix Figs A35 and A36).

Wells 206/8-2 and 206/8-8

Wells 206/8-2 and 206/8-8 are from the Clair Field, located immediately east of the Rona Ridge (Fig. 1). The Devonian-Carboniferous Clair Group reservoir succession in the Clair Field comprises over 1000 m of clastic sediment deposited in a range of fluvial, lacustrine and aeolian environments. Owing to the unfavourable depositional conditions, palynomorphs and microfossils are almost entirely absent. Hence, a substantial amount of heavy mineral analysis has been undertaken, since the technique has been instrumental in developing a high-resolution non-biostratigraphic reservoir correlation framework (Allen and Mange-Rajetzky, 1992; Morton et al., 2009a). In this report, data from two key wells, 206/8-8 (located in the Core area) and 206/8-2 (located in the Ridge), are used to illustrate the heavy mineral assemblages found in the Clair succession. The available dataset comprises a large number of conventional heavy mineral and garnet geochemical analyses (Figs 6 and 10), with a limited amount of rutile and apatite data (Figs 12 and 13). Zircon age data are not yet available but will be collected as part of an ongoing PhD study at Royal Holloway University of London.

The reservoir succession in the Clair Field has been subdivided into two major lithostratigraphic units, the Lower Clair Group and the Upper Clair Group. These have been further subdivided into ten informal units (Units I-VI in the Lower Clair Group and VII-X in the Upper Clair Group), on the basis of sedimentological and heavy mineral data (Allen and Mange-Rajetzky, 1992).

The Lower Clair Group, which was deposited in an areally restricted intermontane basin with limited external drainage (Allen and Mange-Rajetzky, 1992; Nichols, 2005), represents a single first-order cycle of fluvial advance followed by fluvial retreat (McKie and Garden, 1996) driven by changes in climatic conditions (Nichols, 2005). Within the Lower Clair Group, three second-order cycles have been recognised

(McKie and Garden, 1996). The first of these cycles comprises Units I-III, the second comprises Units IV-V, and the third comprises Unit VI. According to McKie and Garden (1996) and Nichols (2005), Unit I consists of conglomerates and pebbly sandstones deposited on a coarse-grained fan delta, together with laminated sandstones and siltstones interpreted as open lake facies. Unit II comprises sandstones and conglomerates representing the depositional products of a braided fluvial system. Unit III consists of ephemeral fluvial sandstones and sandflats, with Unit IV marking a return to braided river channel deposits with minor aeolian reworking. There is some disagreement over the depositional environment of the high-quality reservoir Unit V interval. McKie and Garden (1996) considered Unit V to comprise aeolian sandsheets with minor fluvial deposits, Nichols (2005) interpreted it as being of fluvial origin, and Allen and Mange-Rajetzky (1992) considered that it consists of medium-grained cross-stratified sheetflood sands interbedded with fine-grained horizontally laminated sands representing reworking by aeolian processes on an inland sabkha. Unit VI is the most heterolithic unit of the Lower Clair Group comprising thinly interbedded sediments on a scale of < 1m. The facies comprise cross-bedded fluvial sandstones, ripple laminated sandstones, calcite-cemented conglomerates (interpreted as channel base facies), soils and lacustrine siltstones. The lacustrine siltstones are interpreted as interdistributary lake deposits. Approximately mid-way through Unit VI is a particularly conspicuous and widely correlated mudstone horizon, which was termed the Lacustrine Key Bed (LKB) by Allen and Mange-Rajetzky (1992).

The Upper Clair Group is believed to comprise a single major cycle (Coney et al., 1993). Units VII, VIII and IX comprise mainly fluvial sandstones, with marginal marine and distributary bay deposits becoming prevalent in Unit X. Allen and Mange-Rajetzky (1992) considered that the Upper Clair Group was deposited by a larger fluvial system draining a wider hinterland compared with the Lower Clair Group.

Biostratigraphic controls on stratigraphy within the Clair Group are extremely sparse. Unit X is known to be Carboniferous (Dinantian) in age on the basis of miospores (Blackbourn, 1988), and the top of the Lower Clair Group is believed to be Late Devonian on the basis of holoptychian fish scales (Ridd, 1981; Trewin and Thirlwall, 2002). The rest of the succession is devoid of biostratigraphic markers, although the Devonian-Carboniferous boundary is commonly placed at the boundary between the Lower and Upper Clair Group (e.g. Coney et al., 1993).

Downhole plots of key heavy mineral parameters (Fig. 17) show two major provenance shifts within the Clair Group succession. One of these is at the Lower Clair-Upper Clair boundary, and is marked by upward-increasing GZi, RuZi and SZi (staurolite:zircon), together with decreasing ATi. The other is near the top of the Upper Clair Group (base Unit X), which is marked by decreasing RuZi, SZi and GZi, together with continued decreasing ATi. There are a large number of subordinate variations in heavy mineral assemblages and garnet composition, which prove useful for detailed reservoir subdivision and correlation, including real-time well-site applications for geosteering purposes (Morton et al., 2003), but these are beyond the scope of the present report. For further information, see Morton et al. (2009a).

Garnet assemblages throughout the Clair Group are dominated by Type B, but Type Aii garnets are common at some levels, most notably in part of Lower Clair Group Unit IV. Type Ai garnets are scarce, rarely forming > 10% of the garnet populations (Fig. 10). There are significant variations in the abundance of high-Mn garnets (typically derived from granitoid, see Mange and Morton, 2007) within the Clair succession, the most notable zone being the abundance of such garnets at the top of Unit VI (Fig. 17).

The limited amount of rutile data (Fig. 12) show that granulite-facies grains are scarce and that metapelitic sources are more important than metamafic rocks. Apatite assemblages (Fig. 13) are all dominated by grains of acidic parentage.

Well 208/26-1

Well 208/26-1 is located on the eastern margin of the Faroe-Shetland Basin (Fig. 1). The analysed succession comprises the Aptian (Early Cretaceous) Royal Sovereign Fm. The succession is uncored, but the composite log shows the interval to be highly conglomeratic, and sits directly on basement.

The heavy mineral assemblages show markedly fluctuating compositions, some being dominated by calcic amphibole, some by epidote, some by clinopyroxene, some by orthopyroxene and some by garnet. These marked fluctuations are typical of cuttings samples from conglomeratic successions that contain a wide variety of clasts. The data suggest that the clasts are predominantly of gneissic origin, with the lack of minerals such as kyanite and staurolite indicating an absence of metasedimentary lithologies. In terms of provenance-sensitive ratios, the succession is characterised by very high ATi (>97), with highly variable GZi (5-100) and RuZi (0-79).

Well 209/12-1

Well 209/12-1 is located in the northern part of the Faroe-Shetland Basin, close to the northeastern margin of the Orkney-Shetland Platform (Fig. 1). The analysed interval consists of the Rona Fm. (Volgian, Late Jurassic). Two core samples and one cuttings sample were analysed.

The lower of the two core samples has an unusual heavy mineral assemblage consisting exclusively of clinopyroxene. A basaltic source is considered most likely. At this stage, no further work has been done, but microprobe analysis of the pyroxene is recommended in order to determine its magmatic affinity. The overlying core sample and the cuttings sample at the top of the analysed interval have stable heavy mineral assemblages, dominated by rutile and zircon. The general stability of the assemblage is probably a function of dissolution of unstable phases during burial. As a result, GZi values are low (Fig. 4). RuZi is relatively high, and ATi is moderate.

Garnet geochemical analysis could not be conducted on the succession owing to the scarcity of garnet. The rutile population (Appendix Fig. A21) contains a moderate number of granulite-facies grains, although the population is dominated by grains of upper amphibolite origin. Metapelitic rutiles form the large majority of the population (Fig. 12).

The zircon population (Fig. 15) is noteworthy for the large number of Early Paleozoic grains, with 37 of the 75 concordant grains dated between ~360 and ~460 Ma. The population also contains a range of mid-Proterozoic grains (14 in the range ~890-1780 Ma) and 23 Archaean to very early Proterozoic grains. The relatively small amount of discordance associated with the sample (Appendix Fig. A37) is attributable to present-day Pb loss.

Well 213/23-1

Well 213/23-1 is of particular interest for understanding the provenance for the pre-Paleocene succession in the Faroe-Shetland Basin, because it is located in a more basinward location than most of the wells in the study (Fig. 1) and contains clastics ranging in age from Cretaceous to Devonian (Fig. 2). The succession comprises Cretaceous clastics ranging in age from Aptian to Santonian, overlying a red-bed unit ascribed to the ?Triassic on the Mobil composite log. This in turn sits on top of a

Devonian-Carboniferous succession overlying basement. The upper part of the Devonian-Carboniferous succession appears to have good biostratigraphic constraints, with the Namurian and Visean (including the Holkerian-Asbian stages) identified on the composite log. Biostratigraphic constraints on the underlying red-bed succession, however, appear to be absent.

The main stratigraphic units are clearly differentiated by heavy mineral data (Fig. 18), with marked changes in mineralogy occurring at the stratigraphic unit boundaries. The Cretaceous-?Triassic boundary coincides with a major downhole increase in ATi, and associated falls in GZi and RuZi. The top of the Carboniferous is marked by the start of a downhole-decreasing ATi trend, continued variable GZi and relatively low RuZi.

The Cretaceous clastic succession is predominantly mud-rich, and hence heavy mineral recovery (entirely from cuttings) was relatively poor. The problem is compounded by the abundance of clinopyroxene, which is a contaminating phase from the overlying Palaeogene basalts. As a consequence, heavy mineral ratio determnations have been made on sub-optimal counts, and rutile, apatite and zircon analyses were not undertaken. The Cretaceous is characterised by high GZi, relatively high RuZi and an upward-increasing ATi trend. Since garnet is the most abundant heavy mineral in the Cretaceous, it was possible to undertake mineral chemical analysis on this phase. This showed that the Cretaceous sandstones have relatively diverse garnet assemblages (Appendix Fig. A19). Although Type B garnets are most abundant, Type A garnets (both Ai and Aii) are also common (Fig. 7), with Ai garnets being especially common in the Royal Sovereign Fm. (Aptian-Albian).

The underlying ?Triassic has extremely high ATi, low RuZi (increasing towards base) and variable GZi. There are two cores in the ?Triassic section, one at the top and one at the base. Most of the core samples have low GZi, but one (from the lower core) has a higher garnet content, the garnets in this sample showing evidence for advanced garnet dissolution. The cuttings samples have uniformly moderate GZi, similar to that found in the high-garnet core sample. The cuttings probably provide an average value for GZi across the ?Triassic interval. Evidence from core shows that the original GZi value is likely to have been much higher throughout. Garnets were analysed from the core sample with abundant garnet. The population comprises low-Ca varieties consistent with advanced garnet dissolution, with the Aii component being the dominant type (Fig. 9; Appendix Fig. A19). Rutiles were analysed from another sample from the lower of the two cores (Appendix Fig. A22). The assemblage has high abundances of metapelitic grains, with granulite-facies grains forming a significant but subordinate component (Fig. 12). Apatites were analysed from two core samples, one from the upper and one from the lower. The assemblages (Appendix Fig. A25) indicate derivation from acidic source lithologies (Fig. 13). Zircons have been analysed from a sample in the upper of the two cores. The population consists almost exclusively of Archaean grains, but the age distribution is somewhat different to the other Archaean-dominated zircon spectra analysed in this study. Unlike the other spectra, which are unimodal with peaks in the ~2650-2800 Ma range, the 213/23-1 sample has a polymodal distribution, with a dominant peak at ~2800-2850 Ma, a secondary peak at ~2650-2750 Ma and a minor group of zircons at ~2950 Ma.

Within the Devonian-Carboniferous section, there are distinct variations that enable further subdivision. The upper section (informally termed 'upper' Clair Group) has a downhole-decreasing ATi trend, variable but generally low GZi, and relatively low RuZi. The middle section ('middle' Clair Group) has a downhole-increasing ATi pattern, much higher GZi, and higher GZi, and the lower section ('lower' Clair Group) has uniformly high ATi, low RuZi, and displays a downhole-decreasing GZi trend. The boundary between the 'middle' and 'upper' Clair Group is within the Holkerian-Asbian (intra-Visean), and the boundary between the 'middle' and 'lower' Clair Group is within the biostratigraphically poorly-constrained Devonian section.

The stratigraphic pattern shown by the Devonian-Carboniferous section in 213/23-1 bears strong similarities with that in the Clair Field. The heavy mineral events at the boundary between the 'lower'and 'middle Clair in 213/23-1 are directly analogous to those at the Lower/Upper Clair boundary in the Clair Field (increase in GZi, increase in RuZi, start of an upward decrease in ATi). Likewise, the change from the 'middle' to 'upper' Clair Group in 213/23-1 compares closely with that seen at the boundary between Unit IX and Unit X in the Clair Field (upward decrease in RuZi and GZi, continued decline in ATi). The differences between the successions in 213/23-1 and the Clair Field, such as the absence of staurolite and the overall lower GZi, can all be ascribed to more advanced burial-related mineral dissolution in 213/23-1. The change from 'middle' to 'upper' Clair Group in 213/23-1 occurs within the Visean, consistent with the limited biostratigraphic information from Clair, which places Unit X (equivalent to 'upper' Clair) in the Visean. The close similarity between the 213/23-1 Devonian-Carboniferous succession and that present in the Clair Field suggests that the two successions have similar provenances and were subject to the same influences that caused changes in source. The most likely explanation is that the two successions represent the products of the same transport and depositional system.

The similarity between the two successions is further demonstrated by the ratio crossplots, especially ATi-RuZi, since neither parameter is affected by burial diagenesis. This plot (Fig. 6) clearly demonstrates that the Lower Clair Group in the Clair Field has overlapping provenance characteristics to ‘lower’ Clair in 213/23-1, and that Upper Clair Group units VII-IX in the Clair Field has overlapping characteristics to ‘middle’ Clair in 213/23-1. Finally, Unit X in the Clair Field and ‘upper’ Clair in 213/23-1 both show strong deviations towards low ATi, although the effect is stronger in 206/8-2 than in 213/23-1. This may be a function of a difference in sample type (core vs cuttings) and the wider sampling interval in 213/23-1. Garnet geochemistry also demonstrates close similarities in provenance between the two successions (Fig. 10). Rutile compositions are also comparable, the sample from the ‘middle’ Clair Group in 213/23-1 (Appendix Fig. A22) having low abundances of granulitic grains and having metapelitic types dominant over metamafic grains, very similar to rutile populations from both Upper and Lower Clair in the Clair Field (Fig. 12). The rutile population in the Namurian (‘upper’ Clair) of 213/23-1 is different to that from the underlying section and from those in the Clair Field, having a much higher metamafic rutile component (Fig. 12, Appendix Fig. A22).

Zircons have been analysed from a Namurian core sample (Fig. 16). The population is dominated by mid-Proterozoic zircons between ~900-2000 Ma, with a subordinate group of Archaean grains ~2500-2900 Ma, and a small Early Paleozoic group (401-419 Ma). There is a wide spread of ages within the mid-Proterozoic group, but there is one major peak at ~1650 Ma (Fig. 16). There is a relatively high degree of discordance with 43 of the 102 grains being > 10% discordant (Appendix Fig. A29). The discordance can be attributed to present-day Pb loss (Appendix Fig. A39).

Well 214/9-1

As with 213/23-1, Well 214/9-1 is located in a more basinward location than most of the wells in the study (Fig. 1). It contains sandstones in the Macbeth Fm. (Turonian, Late Cretaceous) and the Kimmeridge Clay Fm. (Volgian and Ryazanian-Hauterivian) (Fig. 2). The entire succession is uncored, and most of the analyses are therefore from cuttings. However, one sidewall core sample was made available from the Macbeth Fm., and this was therefore used for zircon and rutile geochemistry in order to avoid possible contamination problems.

The assemblages in the Macbeth Fm. contain high abundances of clinopyroxene, present as a contaminating phase from the overlying Paleogene basalts. The main indigenous phases are rutile, tourmaline and zircon. Garnet is very scarce, interpreted as due to dissolution during burial. The Macbeth Fm. has uniform provenance characteristics, with low ATi (0-5) and high RuZi (44-58). The low GZi values are not considered to be representative of provenance, but an effect of burial diagenesis.

The rutile assemblage in the sidewall core from the Macbeth Fm. (Appendix Fig. A23) has relatively high abundances of granulite-facies grains, and is dominated by metapelitic types (Fig. 12). The zircon assemblage in the same sample (Fig. 14) consists of a wide-ranging group of mid-Proterozoic grains, together with subordinate Archaean and Early Paleozoic grains. The large mid-Proterozoic ranges from ~900-2100 Ma, most of which fall in the 1600-1900 Ma bracket, the main peak being at ~1650 Ma. The Early Paleozoic zircons (12 of the 74 concordant grains) range from ~370-450 Ma.

Heavy mineral recovery from the Kimmeridge Clay Formation samples is relatively poor. This, together with high abundances of clinopyroxene resulting from downhole contamination, means that heavy mineral parameters have been deternmined on sub-optimal counts. The sandstones have moderate ATi values (43-47) and relatively low RuZi (11-17), and therefore differ significantly to the overlying Cretaceous. The relatively poor recovery precluded further analysis of phases such as rutile, apatite and zircon.

STRATIGRAPHIC AND GEOGRAPHIC VARIATIONS IN PROVENANCE

In this section, the evolution and geographic variations in provenance characteristics are discussed, together with the constraints on source nature and lithology. It is important to stress that, with the exception of published data on the Clair and Strathmore fields (Morton et al., 2007; Morton et al., in press), the data set is relatively small, given the geographic and stratigraphic coverage of the study. Furthermore, the amount of mineral chemical and especially zircon age data is even more limited. Hence, it is not yet possible to define specific sand types, as has been done with the Paleocene (Jolley and Morton, 2007; HM Research Associates, 2008; Morton et al., in press). Nevertheless, the new data acquired during the pilot study, intergrated with existing information, provides important insights into the provenance history of the Faroe-Shetland Basin fill through time.

Devonian-Carboniferous

Devonian-Carboniferous successions have been analysed from two well locations, 213/23-1 and the Clair Field (206/8-2 and 206/8-8), together with data from Old Red Sandstone outcrops from Orkney (Morton et al., 2005a). As discussed above, there are strong similarities between the successions in 213/23-1 and Clair, with three major heavy mineral units defined. These comprise:

(i) the Lower Clair Group as defined in the Clair Field area, which correlates with 'lower' Clair Group informally recognised in 213/23-1 (Figs 17 and 18)
(ii) Upper Clair Group units VII-IX as defined in in the Clair Field area, which correlates with 'middle' Clair Group informally recognised in 213/23-1 (Figs 17 and 18)
(iii) Upper Clair Group Unit X, which correlates with the lower part of 'upper' Clair Group informally recognised in 213/23-1 (Figs 17 and 18). 'Upper' Clair Group extends to stratigraphically higher levels (Namurian) in 213/23-1 than in the Clair Field area.

'Lower' Clair Group

The similarity in provenance-sensitive heavy mineral ratios and geochemical data from garnet and rutile indicates that the sandstones in 'lower' Clair Group in 213/23-1 have a similar provenance to Lower Clair Group sandstones in the Clair Field. They have high ATi, relatively low RuZi, garnet assemblages dominated by Type B, and amphibolite-facies metapelitic rutile populations (Figs 6, 10 and 12). These are features found in the majority of Lower Clair Group sandstones in the Clair Field. It is therefore considered likely that the succession in 213/23-1 represents the products of the same transport system that fed the Clair area. The overall nature of the assemblages in the Lower Clair Group suggests derivation from relatively low grade metasedimentary rocks, the lack of high-grade metasedimentary indicator minerals such as staurolite and kyanite being key to this interpretation (Allen and Mange-Rajetzky, 1992). This is supported by garnet geochemistry, the low abundances of Type Ai garnet indicating a scarcity of granulite-facies metamorphics, and the rutile geochemistry, which shows that the source terrain largely comprised lower amphibolite facies metapelites.

The greater heterogeneity in provenance characteristics in the Clair area (Figs 6 and 10) could be partially due to the nature of the samples analysed from 213/23-1 (cuttings taken at wide sample spacings, compared with core with narrow sample spacings), but there is also evidence for local gneissic basement sourcing in the Clair Field, especially in the lower part of the succession (Morton et al., 2009a). For example, Unit I in 206/8-8 is interpreted as having been derived from Archaean basement gneisses on the basis of clast composition (Nichols, 2005), and heavy mineral data have enabled the identification of a locally-derived unit in 206/8-2 with characteristics typical of first-cycle derivation from intermediate-acidic gneisses (Morton et al., 2009a). The presence of relatively low GZi sandstones with high abundances of Mn-rich Type B garnets at the top of Unit VI (Fig. 17) also suggests input from acidic gneisses or granites. It therefore seems likely that the Clair area was periodically fed from local exposed Archaean basement rocks as well as by a larger fluvial transport system tapping a relatively low-grade metasedimentary terrain analogous to the Scottish Moine and Dalradian, or the Caledonian fold belt of East Greenland. Such a model is consistent with that proposed by Allen and Mange-Rajetzky (1992) and Nichols (2005).

The available data from the Old Red Sandstone of Orkney suggests that this region could represent the products of the same depositional system. Owing to more advanced burial diagenesis, garnet is scarce or absent in these sandstones, but they have closely comparable ATi and RuZi values (Morton et al., 2005a, their fig. 5). Their rutile compositions are also closely comparable, being dominated by amphibolite facies metapelitic grains (Fig. 12).

Further work is needed to provide better constraints on the provenance of this part of the succession. Additional rutile geochemistry is needed on all three locations (213/23-1, Clair Field, onshore Old Red Sandstone), and detrital zircon data are entirely lacking at present. These issues will be at least partially addressed as part of an ongoing PhD study into Devonian-Carboniferous provenance in the Faroe-Shetland area.

'Middle' Clair Group

The dramatic change in mineralogy at the Lower Clair Group – Upper Clair Group boundary in the Clair Field (Fig. 18) indicates a significant change in provenance. The increase in garnet, staurolite and rutile all suggest involvement of higher-grade metasedimentary rocks (Allen and Mange-Rajetzky, 1992; Morton et al., 2009a). The same change is seen in 213/23-1, but appears less dramatic owing to the more advanced burial-related mineral dissolution, which has entirely removed staurolite and caused a decrease in garnet content and GZi. The other significant change between the 'lower' Clair Group and 'middle' Clair Group units is the trend towards lower ATi. This is interpreted as due to changing climatic conditions, rather than provenance, since apatite dissolution is promoted by warm humid surficial weathering environments. Allen and Mange-Rajetzky (1992) interpret the changing sedimentary environments within the Clair Group as reflecting an upward increase in humidity and run-off, consistent with changes seen elsewhere in Scotland during the transition from the Devonian to the Carboniferous.

Despite the heavy mineral evidence, however, rutile geochemistry (Fig. 12) does not show any dramatic change in metamorphic source conditions, neither sample analysed showing any increase in content of granulite-facies grains (Fig. 12). Likewise, Type Ai garnets remain scarce. There is a slight increase in the abundance of upper amphibolite facies rutiles compared with low amphibolite facies types (31-35%, compared with 16-25%), but this canot be regarded as conclusive given the limited size of the data set.

Given the nature of the heavy mineral assemblage, the source terrain was clearly dominated by amphibolite facies metasedimentary rocks. As with the 'lower' Clair Group unit, suitable sources can be found within the Caledonian fold belt, including the Moine and Dalradian successions of Scotland and equivalent rocks in East Greenland. Further work is needed to provide better constraints on the provenance of this part of the succession. Additional rutile geochemistry is needed, and detrital zircon data are entirely lacking at present. These issues will be at least partially addressed as part of an ongoing PhD study into Devonian-Carboniferous provenance in the Faroe-Shetland area.

'Upper' Clair Group

The change to lower RuZi, lower GZi and lower SZi at the base of Unit X in 206/8-2 and at the equivalent point in 213/23-1 is attributable to another change in source. The further decrease in ATi, by contrast, is interpreted as the result of the continuing trend toward warm humid climatic conditions. Heavy mineral, mineral chemical and zircon age constraints on the provenance of the basal part of the 'upper' Clair Group section are poor, but this problem will be addressed during the ongoing PhD study described above.

The ‘upper’ Clair Group section in 213/23-1 extends to stratigraphically younger sediments compared with the Clair Field area, the Namurian having been identified at this location. RuZi values in the Namurian remain at similar levels to those in the Visean. GZi values are variable, attributed to differences in the extent of burial-related dissolution. ATi values show an overall upward increase, but it is possible this trend is partly due to downhole contamination from the overlying ?Triassic, which has uniformly high ATi.

Mineral chemical constraints on provenance of the Namurian are scarce, but the single rutile population that has been analysed suggests a change from the metapelitic-dominated terrains that sourced the ‘lower’ and ‘middle’ Clair Group to a source that includes a higher proportion of metamafic types. There is no evidence for any increase in metamorphic grade, however, with granulite-facies rutile remaining scarce. The zircon population in the Namurian is dominated by mid-Proterozoic zircons between ~900-2000 Ma (with one major peak at ~1650 Ma), a subordinate group of Archaean grains, and a small Early Paleozoic group. This zircon age spectrum is typical of sourcing from within the Caledonian fold belt, with the Proterozoic and Archaean zircons recycled from Neoproterozoic-Early Paleozoic metasediments (such as the Moine and Dalradian of Scotland and equivalents units in East Greenland) and the Early Paleozoic zircons derived from Caledonian granites.

Triassic

Triassic sandstones have been analysed from three locations, covering a number of stratigraphic levels. Otter Bank Fm. (Scythian, Early Triassic) and Foula Fm. (Ladinian-Anisian, Middle Triassic) sandstones have been analysed from the Strathmore Field. Foula Fm. sandstones interpreted as Carnian-Rhaetian (Late Triassic) have been analysed from 205/23-2, and ?Triassic sandstones of uncertain stratigraphic affinity have been analysed from 213/23-1.

There is a distinct change in provenance between the Otter Bank and Foula Fms in the Strathmore Field, manifested by changes in provenance-sensitive heavy mineral ratios, garnet geochemistry and zircon age dating (Morton et al., 2007), supplemented by rutile geochemistry discussed herein. The Otter Bank Formation was interpreted as having a source on the eastern margin of the Faroe-Shetland rift by Morton et al. (2007), with two main provenance components (recycled Devonian-Carboniferous Upper Clair Group in conjunction with Lewisian orthogneiss). Provenance-sensitive ratios and garnet geochemical data are consistent with this suggestion. As shown in Figs 5 and 6, there is good overlap between the Upper Clair Group and the Otter Bank Fm. in terms of heavy mineral ratios. Likewise, garnet compositions in the two units are similar (Figs 9 and 10), although the Otter Bank has slightly higher contents of Type Aii garnet. This can be reconciled by reworking of some Lower Clair Group as well as the Upper Clair. However, rutile geochemistry indicates that the Otter Bank source included higher proportions of granulite-facies metamorphic compared with the Clair Group (Fig. 12), and it seems more plausible that the Otter Bank was derived from similar Neoproterozoic to Early Paleozoic metasedimentary sources to those involved in the Clair Group, but at somewhat higher metamorphic grade. Involvement of Archaean gneisses similar to those found in the onshore Lewisian is a possibility, especially given the relatively wide spread of Archaean ages in the Otter Bank sample (~2650-3000 Ma). The onshore Lewisian comprises a number of terranes, each with a different geological history (Kinny et al., 2005), and hence sediment derived from this region is likely to have a range of Archaean ages. For example, a modern river sand sample sourced from the Tarbert Terrane on the Isle of Lewis has zircons ranging from ~2550-3100 Ma (Morton et al., in press). However, the Otter Bank sample does not show any evidence for the ~1675 Ma event associated with parts of the onshore Lewisian (Kinny et al., 2005), and also recognised in the Isle of Lewis river sand (Morton et al., in press). It therefore remains possible that the Archaean zircons were recycled from the Neoproterozoic to Early Paleozoic metasediments: for example, Archaean zircons ranging from ~2500-3000 Ma are common in parts of the Dalradian of the Scottish Highlands (Cawood et al., 2003).

The overlying Foula Formation in the Strathmore Field has a distinctive heavy mineral assemblage. Characteristic features include high RuZi, GZi and ATi; garnet assemblages rich in the Ai component, typical of a high-grade metasedimentary provenance; rutile populations with high abundances of granulite-facies metapelitic grains; and a zircon population with three distinct peaks, one in the Archaean (~2700-2800 Ma), one in the Paleoproterozoic (~1880 Ma) and one in the Permian (~250-300 Ma). Suitable source lithologies are not available on the UK margin of the Faroe-Shetland Basin, but are available in the eastern Nagssugtoqidian belt of East Greenland. This, together with evidence for deposition by easterly-flowing currents (Swiecicki et al., 1995), led Morton et al. (2007) to suggest derivation from the conjugate margin of the Faroe-Shetland rift. However, it is possible that similar source lithologies were available within the Faroe-Shetland rift system, for example in the northern part of the Rockall Plateau, and derivation from such intrabasinal highs cannot be ruled out (Morton et al., 2007). The origin of the enigmatic Permian zircons remains unclear, but zircons with similar ages have been found in sandstones along the NE Greenland margin (Morton et al., 2005b), adding further weight to the concept of a source on the Greenland margin of the basin.

The Foula Fm. in 205/23-2 is believed to be younger than that in the Strathmore Field (Carnian-Rhaetian, compared with Ladinian-Anisian), and has markedly different characteristics. It has lower GZi than either the Foula or the Otter Bank Fms in Strathmore (Fig. 5), and given the shallow burial of the succession in 205/23-2, this cannot be attributed to garnet dissolution. RuZi values are also lower than either the Foula or the Otter Bank Fms in Strathmore (Fig. 5). ATi, by contrast, is high, as in all the Triassic sandstones analysed in the study. Type Ai garnets are less abundant than in the Foula Fm. of Strathmore, but are more common than the Otter Bank Fm. (Fig. 9). Granulite facies rutiles are less abundant than in the Foula Fm. of Strathmore, but are similar in abundance to the Otter Bank (Fig. 12). The zircon population in 205/23-2 bears some similarities to that of the Foula Fm. in Strathmore, in that the two main peaks in 205/23-2 (~2700-2800 and ~1880 Ma) are also present in the Strathmore area. However, the relative proportions of the the two peaks are different, the Archaean being much more important in 205/23-2 than in Strathmore, and the ~1880 Ma correspondingly less well represented. Furthermore, the Permian group is absent in 205/23-2, and there is greater heterogeneity within the Proterozoic range.

The provenance of the Foula Fm. sandstones in 205/23-2 therefore shows significant differences to the older part of the formation in the Strathmore area to the south. There is evidence for continued supply from the same high-grade granulite facies metasedimentary source, as shown by the continued presence of Type Ai garnet and granulite facies rutile, and possibly also by the same two main peaks in the zircon spectrum. However, this component is markedly reduced in 205/23-2, the main source being characterised by low GZi and RuZi, and by zircons in the 2700-2800 Ma age range. Archaean intermediate-acidic gneisses are the most likely source for detritus with these characteristics. Such sources are prevalent at some levels in the overlying Jurassic and Cretaceous (see below) and are considered to be of local origin. Zircon geochronology of basement rocks along the Faroe-Shetland Basin margin is to form the focus of the next SINDRI provenance study in the region, and will help confirm the location and nature of the sources of such detritus.

The heavy mineral ratio characteristics of the ?Triassic section in 213/23-1 are most closely comparable to those seen in 205/23-2, with low RuZi and ATi (Fig. 5). The low GZi is not considered reliable owing to the evidence for extensive garnet dissolution. The unit has consistently high ATi, similar to all the analysed sandstones of known Triassic age in the area. The high ATi therefore provides support for the proposed Triassic stratigraphic assignation. Rutile compositions in the single 213/23-1 sample are similar to those found in the Foula Fm. of 205/23-2 and to the Otter Bank in the Strathmore area. The garnet population is dominated by Type Aii garnets, and therefore plots in a markedly different part of the Ai-Aii-B+C ternary diagram to the other Triassic garnet populations (Fig. 9). However, given the evidence for garnet dissolution in the succession, it is likely that the original garnet composition (prior to modification during burial) would have been somewhat different to that presently observed. It is therefore more appropriate to use the Ai-Aii-Bi ternary diagram for comparative purposes. This diagram shows that the garnet population can still be distinguished from the other Triassic populations: although one Otter Bank Fm. sample also has a high Type Aii component on this plot, the 213/23-1 sample remains much richer in this component (Fig. 9).

Zircon data further demonstrate the difference in provenance between the Triassic in 213/23-1 and the other two locations, in that the assemblage consists almost exclusively of Archaean zircons. Furthermore, this Archaean-dominated spectrum is polymodal, with peaks at ~2800-2850 Ma, ~2650-2750 Ma and ~2950 Ma. This pattern contrasts with the other Archaean-dominated spectra in the study (Rona Fm. in 202/3-1a and 204/27-1; Royal Sovereign Fm. in 206/4-1), which all have a single peak in the 2650-2800 Ma range (Figs 14 and 15). In this respect, the population is more closely akin to zircon age spectra derived from the Kangerlussuaq area in East Greenland (Fig. 14), although the distinctive ~3150 Ma peak present in Kangerlussuaq-derived sediment is not apparent in 213/23-1.

In summary, the provenance of the ?Triassic interval in 213/23-1 appears, on the basis of the available evidence, to be different to that seen in the Strathmore and 205/23-2 areas, and may have greater affinities with the Archaean basement in the Kangerlussuaq region. It is not possible, on the basis of the available data, to correlate the 213/23-1 ?Triassic section with that in the other wells, but the consistent high ATi does support the view that the section is indeed Triassic in age.

Jurassic

Jurassic sandstones have been analysed from eight locations in the area. Early Jurassic Stack Skerry Fm. (Pliensbachian-Sinemurian) sandstones have been analysed from 202/3a-3, and Rona Fm. (mostly Kimmeridgian-Volgian) sandstones have been analysed from 202/3-1a, 204/27-1, 204/28-1, 205/23-2, 205/26a-3 and 209/12-1. Finally, sandstones assigned to the Kimmeridge Clay Fm (Volgian and Ryazanian-Hauterivian) have been analysed from 214/9-1.

202/3a-3, Stack Skerry Fm.

The Stack Skerry Fm. has uniform provenance characteristics through the ~400 m analysed interval, with relatively high GZi and ATi, moderate RuZi, and garnet populations with moderate abundances of Type Ai garnet (Figs 4 and 8). In terms of provenance-sensitive ratios, the formation is closely comparable with the Otter Bank Fm. (Fig. 5). The rutile populations in the Stack Skerry and Otter Bank Fms are also closely similar (Fig. 12). However, Type Ai garnets are more common in the Stack Skerry Fm. than in the Otter Bank Fm. (Figs 8 and 9). Zircon geochronology suggests that Archaean grains are more abundant in the Stack Skerry Fm. than in the Otter Bank. On balance, it therefore appears more likely that the Stack Skerry Fm. comprises detritus similar to that in the Otter Bank Fm, supplemented by local Archaean material similar to that supplying the Rona Fm. in the Solan Basin. It is uncertain if the Stack Skerry Fm. and the Otter Bank Fm. have a common provenance, or whether the Otter Bank Fm. was reworked to generate the Stack Skerry Fm.

202/3-1a, 204/27-1, 204/28-1, Rona Fm

Rona Fm. sandstones in 202/3-1a, 204/27-1 and 204/28-1 all share common features. They have very high ATi, and 204/27-1 and 204/28-1 both display upward-increasing trends in GZi and RuZi. Their garnet assemblages are dominated by the Type Ai component, although assemblages near the base of the succession are more heterogeneous, containing either Aii- or C-type garnets. Rutile assemblages are very distinctive, being rich in metamafic types and relatively high amounts of granulite-facies grains (Fig. 12). The assemblages in 204/27-1 and 204/28-1 contain unstable phases such as calcic amphibole and epidote, and a particularly unusual feature is the presence of pumpellyite. Zircon spectra in the two analysed samples, one from 202/3-1a and one from 204/27-1, virtually entirely consist of Archaean grains in the 2700-2800 Ma range.

The presence of calcic amphibole and epidote indicates a significant proportion of the detritus is of first-cycle origin. The upward increase in GZi and RuZi suggests an evolution in provenance, and is associated with a change from very proximal coarse-grained debris flows to more distal sandstones at the top. The change in mineralogy suggests that the source was initially dominantly by acidic gneisses (zircon-rich), with mafic gneisses and/or metasediments (garnet- and rutile-rich) becoming more important with time. The abundance of metamafic rutile suggests that mafic gneisses form a large part of the source terrain. However, the presence of Type Ai garnets may indicate the presence of high-grade metasediments in the source area, although such garnets are also found in charnockites (Mange and Morton, 2007). The zircon data indicate that the source virtually exclusively comprises Archaean rocks.

Pumpellyite is normally found as a key mineral in altered volcanic rocks of the prehnite-pumpellyite facies, and in blueschist facies metamorphic rocks (Deer et al., 1997). However, neither provenance seems likely in view of the associated heavy minerals (notably the abundance of garnet and the absence of glaucophane), which are more typical of high-grade metamorphic gneissic rocks. Pumpellyite has been found as a fracture-fill phase in Lewisian gneisses from NW Scotland (Hay et al., 1988): an alternative origin is as a retrogressive mineral phase.

The Rona Fm. in the Solan Basin was interpreted by Verstralen et al. (1995) as representing a syn-rift succession, with footwall uplift on the Rona and Judd Faults causing sediment to be shed from the Rona Ridge and associated basement highs to form isolated fan deltas. The provenance data are consistent with this interpretation, and indicate that the segment of the Rona Ridge that sourced the sediment comprised Archaean basement, with widespread metamafic gneisses, with subordinate acidic gneisses and high-grade metasediments or charnockites. Although reworking of Foula Fm. sandstones could be invoked in order to explain the high abundances of Type Ai garnet, all the other provenance features (notably rutile geochemistry and zircon age data) rule out recycling as a possible origin for the Rona in the Solan Basin.

205/26 a -4, 205/23-2, Rona Fm

The Rona Fm in 205/26a-4 and 205/23-2 has different characteristics to the successions in the main part of the Solan Basin. Both have lower GZi and lower RuZi (Fig. 4), suggestive of a greater input from zircon-rich (acidic) rocks, and 205/23-2 also has lower ATi, possibly indicating greater source area weathering. Mineral chemical constraints on provenance of these occurrences are scarce, with garnet data available only from 205/23-2, and rutile and zircon data entirely lacking. The garnet assemblage in 205/23-2 consists virtually exclusively of the Type B component, again markedly different to the assemblages in 202/3-1a, 204/27-1 and 204/28-1 (Fig. 8), and is consistent with derivation from acidic gneisses.

209/12-1, Rona Fm

The Rona Fm. in 209/12-1 contains two distinct heavy mineral assemblages. The assemblage in the lowest sample consists entirely of clinopyroxene. The lack of other phases makes it difficult to constrain the age of the magmatism, but the monomineralic nature of the assemblage suggests the source was probably penecontemporaneous and relatively local. Although there is no record to date of Jurassic volcanism along the Faroe-Shetland margin, Middle Jurassic rifting in the North Sea led to emplacement of the Forties volcanic centre (Fall et al., 1982), and there are several other isolated Jurassic volcanic occurrences in the North Sea. Possibly the most relevant in the present context is an alkali basalt dyke in 210/4-1, located in the northern North Sea east of the study area, which has been dated as 152 ± 3 Ma (Dixon et al., 1981). The data from 209/12-1 are interpreted as providing further evidence for Jurassic rift-related volcanism, either in the Faroe-Shetland Basin or in the northern North Sea.

The overlying sandstones have more normal terrigenous heavy mineral assemblages, and show significant modification due to burial-related dissolution. The assemblages have relatively high RuZi, and rutile compositions indicate the source terrain contained upper amphibolite and granulite facies metapelites. The zircon population contains a large number of Early Paleozoic grains, together with a range of mid-Proterozoic grains and Archaean to very early Proterozoic grains. The data indicate a source area with extensive Caledonian granites, supplying the abundant Early Paleozoic zircons, intruding amphibolite facies and granulite facies metasediments that supplied the Proterozoic and Archaean grains. This provenance is consistent with regional evidence, which indicates that the basement on the adjacent part of the Orkney-Shetland Platform consisting of Dalradian metasediments (Stoker et al., 1993) with Caledonian granites present in the offshore area north of Shetland (Hitchen and Ritchie, 1987).

214/9-1, Kimmeridge Clay Fm

The relatively poor heavy mineral assemblages from the Kimmeridge Clay Fm in 214/9-1 are characterised by low RuZi and moderate ATi, together with low GZi (the latter being due to post-depositional modification). The data indicate the Kimmeridge

Clay Fm. sandstones at this location have a different source to the Rona sandstones in 209/12-1, the only other well in the northern part of the study area. The low RuZi indicates a high proportion of the sediment was derived from acidic rocks, but there are no other data available to constrain the nature of the source. It is recommended that zircon age dating is attempted on this sample in order to help determine sand provenance at this key location.

Cretaceous

Provenance data are available from Cretaceous sandstones in 7 locations in the area (204/23-1, 205/20-1, 206/4-1, 208/26-1, 213/23-1, 214/9-1 and the Kangerlussuaq area of East Greenland). Of these, 205/20-1 contains Early Cretaceous (Ryazanian-Barremian) sandstones, 204/23-1, 206/4-1, 208/26-1 and 213/23-1 contain mid-Cretaceous (Aptian-Albian) sandstones, and 206/4-1, 213/23-1 and 214/9-1 contain Late Cretaceous (Cenomanian-Santonian) sandstones. There are distinct differences in provenance between these three stratigraphic intervals, as well as lateral variations, and each time-slice is therefore considered in turn.

Ryazanian-Barremian

Relatively few data are available from the Ryazanian-Barremian, with only one well (205/20-1) included in the sample set. The sandstones have low ATi throughout, probably a function of weathering prior to deposition in the marine environment. The single Ryazanian-Hauterivian sample (cuttings) has moderate GZi and RuZi, whereas the Barremian core samples have high GZi and RuZi (Fig. 3). The Ryanzanian-Hauterivian sample has characteristics that compare well with the Late Cretaceous in 206/4-1, but the Barremian samples do not have a direct counterpart in the rest of the Cretaceous data set. However, they compare reasonably well to parts of the Triassic (Otter Bank Fm.) and to the Clair Group in terms of GZi and RuZi (Figs 5 and 6). Garnet geochemistry does not entirely fit with this possibility, since Aii garnets are more abundant in 205/20-1 than in either the Otter Bank or the Clair Group (Figs 9 and 10). Nevertheless, it is possible that recycling of either unit provided some of the detritus present in these sandstones. Further mineral chemical and zircon age data are required to fully evaluate their origin.

Aptian-Albian

Three of the four analysed penetrations of the Aptian-Albian have extreme heavy mineral characteristics (Fig. 3). The samples from 204/23-1 have extremely high ATi and extremely low RuZi, with moderate GZi (the latter having been modified by garnet dissolution during deep burial). These characteristics compare closely with those in 206/4-1, although here, GZi is zero (possibly through complete garnet dissolution). Most of the samples in 208/26-1 have similarly extreme ATi and RuZi values, with fluctuating GZi, although one sample has exceptionally high GZi and RuZi. These heavy mineral characteristics suggest derivation predominantly from acidic gneisses, although mafic or metasedimentary lithologies were locally available (for example, supplying the sample with very high GZi and RuZi in 208/26-1). All three of these penetrations are described as conglomeratic, with abundant gneissic clasts.

Mineral chemical constraints on the provenance of these unusual assemblages are scarce, given the evidence for diagenetic modification of garnet abundances and the almost complete absence of rutile. Apatite data from 204/23-1 show the predominance of acidic source lithologies, but this applies to virtually all the apatite populations analysed in the study. However, the zircon age data from one sample in 206/4-1 are diagnostic of derivation from Archaean basement dated between 2700-2800 Ma (Fig. 14).

The conglomeratic nature of these three Aptian-Albian successions, their unusual and extreme heavy mineral assemblages, and the zircon age data, together indicate local derivation from Archaean basement highs, probably in response to mid-Cretaceous rifting (Dean et al., 1999).

The Aptian-Albian sandstones in 213/23-1 do not have unusual heavy mineral characteristics, and are essentially similar to the overlying Late Cretaceous interval (Figs 3, 7 and 18). In this instance, therefore, local sourcing from uplifted Archaean basement highs can be ruled out. Their provenance is discussed in the subsequent section together with that of the overlying Late Cretaceous.

Coeval Aptian-Albian sandstones have been analysed from the Kangerlussuaq area of East Greenland (Whitham et al., 2004). These sandstones also represent syn-rift deposits, and again display evidence of direct derivation from Archaean basement, being characterised by low RuZi (Fig. 3) and having a zircon population that consist exclusively of Archaean grains. However, the age spectrum in the Kangerlussuaq area is markedly different to that in the Aptian-Albian of the subsurface, displaying three main peaks at ~2720 Ma, ~ 2960-3020 Ma and ~ 3180 Ma, and evidently representing derivation from the local Archaean basement.

Late Cretaceous

Late Cretaceous sandstones have been analysed from three wells (206/4-1, 213/23-1 and 214/9-1). Within each well, heavy mineral characteristics remain essentially uniform, but each has different characteristics that indicate lateral differences in provenance.

The sandstones in 214/9-1 are particularly distinctive, in that they have low ATi and high RuZi, whereas 206/4-1 and 213/23-1 both have higher ATi and lower RuZi (Fig. 3). The 214/9-1 sandstones also have low GZi, but this is regarded as a diagenetic feature and not relevant in provenance terms. Their rutile compositions are also different, having higher contents of granulite facies grains and metapelitic grains than either sample from 206/4-1 (Fig. 12). Note that rutile compositions from 213/23-1 have not been determined at this stage. Sandstones with similar ratio characteristics (Fig. 3) have been found in Unit 2 (Late Campanian-Maastrichtian) in the Kangerlussuaq area of East Greenland (Whitham et al., 2004), and a similar provenance is therefore a possibility. This suggestion is supported by the rutile geochemical data (Fig. 12) from Kangerlussuaq Unit 2, which also have high abundances of metapelitic types and moderate abundances of granulite facies grains (Fig. 12). Finally, they have closely comparable zircon age spectra, both being dominated by wide-ranging groups of mid-Proterozoic zircons with a main peak at ~1650 Ma, together with subsidiary Early Paleozoic and Archaean grains. Although sandstones with these characteristics appear later in the Kangerlussuaq area (Late Campanian) than in the Faroe-Shetland Basin (Turonian), similar sandstones have been found as far back as the Jurassic in East Greenland and mid-Norway (Morton et al., 2009b).

The sandstones in 206/4-1 and 213/23-1 can be distinguished by their RuZi and GZi values (Fig. 3), 213/23-1 having high values of both parameters. They also have different garnet assemblages, with Aii garnets being more abundant in 206/4-1 and Ai and B garnets more common in 213/23-1. The garnet population in 206/4-1 is closely comparable to that seen in the Early Cretaceous of 205/20-1, and a common provenance is therefore a possibility. The rutile assemblages in 206/4-1 are distinctive in containing high abundances of metamafic varieties and having only a small granulite-facies component (Fig. 12). The zircon age spectrum is complex, with

Archaean, Proterozoic and Early Paleozoic elements. In all these aspects, the Late Cretaceous sandstones in 206/4-1 are closely comparable with Paleocene sand type FSP4 as described by Morton et al. (in press). This sand type is found in the northern part of the Faroe-Shetland Basin (wells 214/27-1, 214/27-2, 214/29-1 and 208/19-1) and is interpreted as the products of a submarine fan system draining the northern part of the Orkney-Shetland Platform. Similarities with assemblages in parts of the Clair Group, together with the presence of Namurian-Westphalian palynomorphs led Jolley and Morton (2007) and Morton et al. (in press) to propose that they were derived through recycling of Carboniferous sandstones formerly present on the Orkney-Shetland Platform. This suggestion is reinforced by the closely comparable rutile compositions in the Namurian of 213/23-1, the Late Cretaceous sandstones in 206/4-1 (Fig. 12), and Paleocene sand type FSP4. Furthermore, the zircon age spectrum in the Namurian of 213/23-1 has the same three main elements (mid-Proterozoic, Early Paleozoic, and Archaean). It therefore seems likely that Carboniferous sandstones, including those of Namurian age, were deposited on the northern part of the Orkney-Shetland Platform, and were available for erosion during the Late Cretaceous and Paleocene.

The provenance of the sandstones in 213/23-1 is more speculative. They do not have the same characteristics as the sandstones in 206/4-1, either in terms of heavy mineral ratios or garnet geochemistry, and neither do they compare with the sandstones in 214/9-1. They therefore appear to represent the products of a different transport system, but without rutile and zircon age data, it is difficult to provide further constraints. The location of the well towards the centre of the basin suggests a possible entry point on the Greenland margin. Garnet geochemistry (Fig. 7) is compatible with this suggestion, since the three analysed samples have similar assemblages to the Unit 2 sample from Kangerlussuaq, especially on the diagram comparing the stable components of the assemblages. However, RuZi values are lower than in typical Unit 2 sandstones from Kangerlussuaq (Fig. 3), and hence a direct analogue for the Late Cretaceous sandstones in 213/23-1 cannot be found at this stage. Further constraints on Cretaceous sand provenance can be gained by increasing the geographical coverage of the heavy mineral data set, and by acquiring further mineral chemical and zircon age data.

CONCLUSIONS

The combination of conventional heavy mineral analysis, determination of provenance-sensitive ratios, mineral chemical analysis on garnet and rutile, and detrital zircon age dating has provided important constraints on the provenance of Devonian-Cretaceous sandstones in the west of Shetland area.

The Devonian-Carboniferous succession in 213/23-1 is directly comparable with that in the Clair Field, although it extends to a higher stratigraphic level in 213/23-1. The 213/23-1 succession can be subdivided into three heavy mineral units, each representing different provenances. The lowest unit correlates with the Lower Clair Group in the Clair Field, the middle unit with Upper Clair Group units VII-IX, and the upper unit with Upper Clair Group Unit X. Biostratigraphic data indicate the boundary between the middle and upper units is coeval in the two areas, but age constraints on the earlier parts of the succession are absent due to paleoenvironmental conditions.

The mineralogical characteristics of the three Devonian-Carboniferous units are directly comparable between the two areas, apart from parameters affected by post-depositional burial diagenetic processes. The provenance data suggest that the sandstones at both sites were supplied by the same transport and depositional systems and lay within the same basinal area. Additional local input from Archaean basement rocks on the Rona Ridge is recognised in the Clair area, but not in 213/23-1: however, this could be an effect of differences in sample type and sampling strategy.

The source of the Devonian-Carboniferous sandstones is interpreted as mainly comprising amphibolite-facies metasediments with subordinate and variable supply from Archaean gneiesses (especially in the Clair Field). Heavy mineral data suggest the source of the Upper Clair Group (Units VII-IX) was at a higher metamorphic grade than that supplying the Lower Clair, but this is not reflected by rutile compositions. Zircon age data are presently lacking for the Clair Field, and in 213/23-1 are available only from the Namurian. The zircon data are consistent with a source within the Caledonian fold belt, with metasediments supplying recycled Proterozoic and Archaean zircons together with Caledonian granites supplying early Paleozoic grains.

The Triassic shows variations in provenance both stratigraphically and regionally. The earliest Triassic (Otter Bank Fm.) is comparable in some respects to parts of the Devonian-Carboniferous, but rutile geochemistry shows that the Triassic sources were at higher metamorphic grades than those supplying the older units. One possible explanation is that continued denudation exposed higher grade rocks with time.

The source of the Middle Triassic Foula Fm (found in the Strathmore Field), however, cannot be matched with source lithologies on the UK margin. The source comprised high-grade granulite facies metasediments, with zircon age data showing two main Precambrian crust-forming events (Archaean, ~2700-2800 Ma and Paleoproterozoic, ~1880 Ma). The data are consistent with a source in the eastern Nagssuqtoqidian belt of East Greenland, although intrabasinal highs (such as the northern Rockall Plateau) cannot be ruled out.

The Late Triassic Foula Fm. in 205/23-2 has some similarities with the Middle Triassic, notably regarding the presence of the same two main zircon peaks, but the assemblages have higher zircon contents, more abundant Archaean zircon, and more abundant of B- and C-type garnet. Continued supply from the source that was operative in the Middle Triassic is indicated, but the majority of the detritus was derived from Archaean acidic gneisses, most likely local.

The ?Triassic in 213/23-1 can be confidently assigned to the Triassic on the basis of high ATi values, but the sandstones have different characteristics to the Triassic successions further south, and their relationship with these other occurrences is presently uncertain. Zircon age data indicate derivation from Archaean rocks, but the spectrum has three peaks (~2800-2850 Ma, ~2650-2750 Ma and ~2950 Ma), different age structure to other Archaean-dominated spectra in the study, which all have a single peak in the 2650-2800 Ma range. This polymodal Archaean pattern is more closely akin to zircon age spectra derived from the Kangerlussuaq area in East Greenland, although the distinctive ~3150 Ma peak present in Kangerlussuaq-derived sediment is not apparent in 213/23-1.

Jurassic sandstones have been analysed from the Early Jurassic Stack Skerry Fm. in 202/3a-3, Solan Basin, and from several Rona Fm. or equivalent successions. The Stack Skerry Fm. has uniform heavy mineral parameters throughout the ~400 m section, with characteristics that resemble those found in the Otter Bank Fm. A similar provenance is envisaged.

The Rona Fm. in the Solan Basin has markedly different characteristics to the Stack Skerry Fm. The heavy mineral data indicate first-cycle input from metamafic gneisses, with subordinate acidic gneisses and high-grade metasediments or charnockites. Zircon age data indicate these gneisses are Archaean, ~2700-2800 Ma. The marked change in provenance between the Stack Skerry Fm. and the Rona Fm. is interpreted as an effect of a mid-Jurassic rift event that caused uplift and exposure of Archaean rocks on the Rona Ridge.

Rona Fm. sandstones further north on or adjacent to the Rona Ridge (205/23-2, 205/26a-4) have different characteristics, principally due to higher zircon contents, suggesting greater input from acidic rocks.

The Rona Fm. in 209/12-1 is unusual in containing two distinct heavy mineral assemblages. One of these consists solely of clinopyroxene, interpreted as indicating local derivation from basaltic rocks, almost certainly penecontemporaneous with deposition. This unusual assemblage is therefore considered to provide a record of Jurassic rift-related volcanism, either in the Faroe-Shetland Basin or in the northern North Sea. The other assemblage was derived from the northernmost part of the Orkney-Shetland Platform, with a source consisting of Dalradian metasediments and Caledonian granites.

The Late Jurassic-Early Cretaceous sandstones in 214/9-1 have characteristics suggesting derivation from acidic gneisses, but additional data (notably zircon age dating) are required to provide better constraints.

There are marked variations in provenance in the Cretaceous data set. An important phase of mid-Cretaceous rifting led to uplift of basement areas and caused the influx of coarse-grained, first-cycle sediment. These sediments were derived from acidic gneisses locally with subordinate mafic gneisses and high-grade metasediments or charnockites, formed between 2700-2800 Ma in the Archaean. This rift phase is also recognised in the Kangerlussuaq area of East Greenland, where it also led to influx of sediment derived from the local Archaean basement.

In the Late Cretaceous, at least three distinct transport systems have been identified. One of these supplied the 206/4-1 area, with detritus being recycled from Carboniferous sandstones (similar to those seen in the Namurian of 213/23-1) on the northern part of the Orkney-Shetland Platform. The sandstones in 206/4-1 have virtually identical characteristics to the younger Paleocene FSP4 sandstones described by Morton et al. (in press), and were evidently derived from the same source. The sandstones in 214/9-1 have closely comparable heavy mineral and zircon age characteristics to Late Campanian-Maastrichtian sandstones in the Kangerlussuaq region, indicating that these sands were fed from the west. The Late Cretaceous succession in 213/23-1 has different characteristics to both 214/9-1 and 206/4-1, but its provenance is less well constrained owing to lack of rutile and zircon data. Given the location of this well, it seems more likely that the sandstones were fed fom the west, but no direct analogues have been found as yet.

Although this study has provided important constraints on provenance and the evolution of the basin fill in the west of Shetland area, the picture is far from complete. It is important that further constraints are acquired from the present sample set, with substantial increases required in the amount of mineral chemical and zircon age data. Furthermore, regional variations in provenance need to be sunstantiated and delineated by increasing the number of wells in the study, with particular emphasis on the Triassic, Jurassic and Cretaceous levels.

The pilot study on apatite geochemistry has proved this technique to be less useful than the other methods, since all assemblages proved to be rich in apatites derived from acidic sources. Nevertheless, this technique offers important additional information and is considered to be especially important in provenance studies of the Paleocene-Eocene. The observation that pre-Paleocene apatite sources are all dominated by acidic lithologies means that the technique is likely to be informative in identifying input from the Early Teriary basaltic rocks widespread across the Faroe-Shetland Basin.

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