High resolution geochemical and petrographical correlation of deep marine Palaeocene sandstones from the Foinaven Field, West of Shetland

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ABSTRACT: Cores from three wells in the Upper Palaeocene deep-marine reservoir interval of the Foinaven Field, West of Shetland have been analysed using trace element geochemistry and petrography. The 60 m thick turbidite-dominated succession is restricted to the T34 biozone and comprises a series of seismically defined channel and overbank deposits. Petrographic and trace element geochemical data indicate that wells 204/24a-3 and 204/25b-5 have strong similarities and that strata in the remaining well (204/24a-7) have distinctly different signatures. Of the two related wells, 204/25b-5 is dominated by a thick amalgamated sandstone succession, 204/24a-3 by more thinly bedded and finer grained sandstones considered to represent channel and associated overbank deposits respectively. Similarities in geochemical and petrographic data allow division of the biozone in the two related wells into four principal correlation zones with two additional sub-zones. The study has established a high resolution correlation scheme and constrained correlation lengths for reservoir and non-reservoir facies in a deep marine depositional system.

KEYWORDS: trace analysis (chemical), geochemical data, Tertiary period, reservoir, turbidite, correlation

INTRODUCTION

Deep-water clastic reservoirs are difficult to correlate in the subsurface. They are commonly laterally variable in thickness and lithology, rarely contain lithologically distinctive marker beds and frequently have non-diagnostic petrophysical characteristics. In addition, interbedded mudstones may contain limited faunal assemblages and, when distinctive fauna are present, biostratigraphic techniques may be insufficiently accurate to determine the lateral extent of individual reservoir units. In order to address the problem of correlation in these successions, a number of sub-seismic scale techniques are commonly applied. These include wireline log correlation (although due to lateral facies changes, the precision of this technique is difficult to assess without independent supporting data), magnetic anisotropy (Løvlie & van Veen 1995), magnetostratigraphy (Turner & Turner 1995), strontium isotope residual salt analysis (Mearns & McBride 1999) and heavy mineral stratigraphy (Morton 1992). The above techniques may be used individually or in combination, however, they may or may not prove reliable and can be time consuming and costly. In recent years chemostratigraphy has become an important additional tool in enhancing correlation within deep-water clastic successions (Pearce & Jarvis 1995). Here, we present a case study using trace element geochemistry in combination with petrographic analysis to correlate between three cored wells taken from the Upper Palaeocene deep marine reservoir interval of the Foinaven Field, West of Shetland (Fig. 1).

STUDY OUTLINE

Three wells (204/24a-3, 204/24a-7 and 204/25b-5, these are referred to as wells 3, 7 and 5 respectively) were selected for study from a single biozone (T34, see Ebdon et al. (1995) for a detailed stratigraphic analysis) of the Upper Palaeocene deep marine reservoir interval of the Foinaven Field (Fig. 1). For a detailed description of the Foinaven Field see Cooper et al. (1999). Seismic and well data within the study interval reveal two apparently intersecting confined channel systems (Fig. 1). Wells 7 and 5 are located in narrow, elongate anomalies which are considered to represent confined, possibly channelized, depositional features, while well 3 is situated within a broad anomaly interpreted as more unconfined, possibly overbank deposits. The key issue was whether the confined system penetrated by Well 5 fed the unconfined system in the Well 3 area, or whether the Well 5 system was continuous with that sampled by Well 7. Available data included: core for each well over the T34 biozone (approximately 60 m in thickness for each well), wireline log suites and graphic sedimentological logs. In addition, a heavy mineral study which had been carried out on the succession (A. Morton pers. comm. 1999) provided...
information on the heavy mineral species present, but did not identify any significant differences in provenance.

**SEDIMENTOLOGY**

Four sedimentary facies were identified (Fig. 2).

(1) High density turbidites comprising predominantly massive, coarse to medium grained sandstone beds (10 to 200 cm thick), which occasionally fine upwards in the upper few centimetres to horizontally laminated fine sandstone with some carbonaceous material. In some wells coarser-grained intervals are present, comprising 50 to 200 cm thick beds of intraformational mudstone and siltstone clasts within a medium- to coarse-grained sandstone matrix, which show no apparent grading. Soft sediment deformation including centimetre-scale slumps, dish and injection structures were occasionally observed.

(2) Low density turbidites comprising upward-fining beds of medium/fine-grained sandstone to siltstone. Beds range from 2 to 20 cm in thickness and display parallel and cross-lamination.

(3) Muddy debris flow deposits, 20 cm to 7 m thick, comprise contorted beds with tight folds developed in siltstones and sandstones set within a mudstone matrix. Well rounded extraformational clasts are present occasionally.

(4) Basinal deposits comprise laminated mudstones and thin siltstones. These represent the background fallout of hemipelagic mud from the water column and thin dilute low density turbidity currents, respectively.

Summary logs of the studied wells are shown in Figure 2. Well 3 largely comprises stacked high density turbidites, 1 to 8 m thick, separated by up to 8 m thick sections of mudstones and low density turbidites. Well 5 is dominated by debris flow deposits at the base, which are overlain by a 25 m thick fining-upwards package of intraformational conglomerate, high density sandy turbidites to thin muddy debris flows. In the top 15 m a further fining-upward package is developed. Well 7 contains muddy debris flow deposits at the base overlain by a succession of stacked high density turbidites with occasional intraformational conglomerates. Fining-upwards packages are not developed in Well 7, in contrast to Well 5, and debris flow deposits are absent in Well 3, but present in the other two wells.

The sedimentological descriptions, when combined with the seismic data, support the interpretation that Well 3 is located in a more distal location than Wells 5 and 7, which penetrated relatively thick stacked sandstone bodies. The wells cannot be
correlated with confidence on a sedimentological basis, and biostratigraphic resolution is below the scale of heterogeneity present in the wells. In order to establish a higher resolution correlation than the biozone level, a trace element geochemical study was undertaken and integrated with heavy mineral and petrographic studies.

### TRACE ELEMENT GEOCHEMISTRY

The trace element geochemical technique used here has been outlined previously (Preston et al. 1998) and is briefly summarized below. Whole rock samples are taken from core or over a specific cuttings interval. Samples are then prepared and analysed for specific trace elements using an X-ray fluorescence spectrometer. Selected trace element concentrations are measured which are (1) considered immobile under normal diagenetic conditions (e.g. Zr, Cr and Nb) and (2) characteristic of certain heavy mineral species. The chemical formulae and the common trace element substitution schemes for each of the heavy mineral species present in individual samples, together with any compositional variation within heavy mineral species are documented in Table 1.

The geochemical data will reflect the absolute whole-rock abundance of the various detrital and authigenic minerals present in individual samples, together with any compositional variation within heavy mineral species. From the heavy mineral assemblage (Table 1), it can be deduced that the distribution of trace elements in this study, Zr, Cr and Nb will be dominated by the heavy mineral phases zircon, spinel and Ti-bearing minerals (e.g. rutile) respectively. Although it is known that Cr may also occur in very limited amounts in amphiboles and micas (Deer et al. 1992), the likely contribution of trace elements from these minerals to the overall trace element budget is negligible.

### Table 1. Trace element substitution schemes for heavy minerals and feldspars present in the three studied wells

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Formula</th>
<th>Common trace element substitutions</th>
</tr>
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<tbody>
<tr>
<td>Garnet</td>
<td>(Mg,Fe2+),Ca,Mn)Al,SiO4</td>
<td>Mn2++Si4+⇔Y3++Al3+</td>
</tr>
<tr>
<td>Rutile</td>
<td>TiO2</td>
<td>3Ti4+⇔2Fe2++2Nb4+</td>
</tr>
<tr>
<td>Ilmenite</td>
<td>FeTiO3</td>
<td>3Ti4+⇔2(Fe2++Mn2++Mg2+)</td>
</tr>
<tr>
<td>Zircon</td>
<td>ZrSiO4</td>
<td>Zr4+⇔Hf4+</td>
</tr>
<tr>
<td>Apatite</td>
<td>Ca5(PO4)</td>
<td>Ca3++P5+⇔REE3++Sr2++2Ca2++Na+</td>
</tr>
<tr>
<td>Tourmaline</td>
<td>(Na,Ca)Fe,Mg(Mn)3(Al,Fe3+)</td>
<td>(Fe,Mg)2++Zn2+</td>
</tr>
<tr>
<td>Staurolite</td>
<td>(Mg,Fe)2Al,SiO4(Fe)2(OH)2</td>
<td>2Ca2++Ti4+ ⇔2REE3++Fe2+</td>
</tr>
<tr>
<td>Titanite</td>
<td>CaTiO4</td>
<td>Ca3++Fe3+ ⇔RE3++Fe2+</td>
</tr>
<tr>
<td>Monazite</td>
<td>(REE,Tb)PO4</td>
<td>(Mg,Fe)2++Mn2+</td>
</tr>
<tr>
<td>Kyanite</td>
<td>Al2SiO5</td>
<td>Fe3++Al3+ ⇔RE3++Cr3+</td>
</tr>
<tr>
<td>Epidote</td>
<td>Ca2(Al2+,Fe3+)2(OH)2</td>
<td>Fe2++2Al3+ ⇔Ba++</td>
</tr>
<tr>
<td>Chloritoid</td>
<td>Mg,Fe)Al,SiO4(Fe)2(OH)2</td>
<td></td>
</tr>
<tr>
<td>Amphibole</td>
<td>Ca2(Mg,Fe3+)2SiO4(Fe)2</td>
<td></td>
</tr>
<tr>
<td>Spinel</td>
<td>Fe++,Mg2+,Al3+</td>
<td></td>
</tr>
<tr>
<td>K-feldspar</td>
<td>KAlSi3O8</td>
<td></td>
</tr>
<tr>
<td>Plagioclase</td>
<td>NaAlSi3O8</td>
<td></td>
</tr>
</tbody>
</table>

Elements in bold represent the common trace element substitutions.

Detection limits for the trace elements Zr, Cr and Nb are approximately 2 ppm, and machine precision is in the order of 3–5%. This technique was used in preference to inductively coupled plasma techniques (ICP-AES and ICP-MS) because XRF does not require sample dissolution.

### Results

Concentrations of the trace elements Nb, Cr and Zr are plotted against facies types and depth for each well (Fig. 3). A number of observations can be made from these data. Wells 3 and 5 show distinctive variations in concentration throughout the studied interval (Fig. 3). In both wells the trace element data display the same trends with gradational increases and decreases in concentrations. The gradational nature of these transitions is important as it indicates a continuous variability to the data rather than isolated spurious high or low data points. In contrast, the data for Well 7 show little variation with no obvious trends in the data despite containing similar facies to Well 5. Trace element concentrations from Well 7 also differ to the other wells with lower overall values.

Trace element concentrations appear to vary between different facies (Fig. 4). Concentrations from mudstones in Well 3 are generally higher or have similar values to the highest concentrations from sandstone units in the same well (Fig. 3). The debris flow facies (Wells 5 and 7), in general, has high concentrations similar to those recorded from the mudstones in Well 3. In addition, the debris flow facies also shows large variations in trace element concentrations between individual sample points particularly in Well 5, these variations are restricted to individual sample points and do not form a trend. The highest concentrations in the sandstones tend to occur in the low density turbidite facies. In contrast, high density turbidites, including intraformational units, have a tendency towards lower trace element concentrations. It is interesting to note that the debris flow and low density turbidite deposits have similar Cr and Zr contents, which are significantly higher than those of the high density turbidites and intraformational conglomerates (Fig. 4). There are also variations in concentrations within individual facies, e.g. at 23 m in Well 3, which suggests that there are changes in the concentration and/or composition of the trace element-bearing mineralogy.

### Analytical techniques

A total of 142 samples were taken for trace element geochemical analysis from the cored intervals. Samples were taken at a metre spacing in all lithologies or where a lithology change occurred. All whole-rock samples were analysed using an ARL8410 fully automatic, sequential, wavelength dispersive X-ray fluorescence spectrometer. All trace elements were determined on pressed powder pellets (Rice et al. 1995).
Petrographic data were collected by point count analysis (200 mineral counts from standard thin sections). A total of 65 samples were analysed from the high density turbidite facies ($n=26$, Well 3; $n=22$, Well 5; $n=17$, Well 7). The sandstones typically classify as lithic arenites with some lithic greywackes. In order to constrain possible provenance variations within the sampled units, the lithic fragment assemblage was studied in detail. Lithic fragments comprise between 2 and 15% of the total bulk mineralogy of the samples, averaging 7% (Fig. 5a). Wells 3 and 5 show consistent variation in composition, whereas little variation is present in Well 7. Another significant variation is the greater proportion of igneous and metamorphic clast types in Well 7 compared to Wells 3 and 5 (Fig. 5a). In the upper part of Wells 3 and 5 strong similarities are present between lithic fragment type and abundance, notably with the altered, metamorphic, igneous/metamorphic and volcanic lithic fragments which show virtually identical trends (Fig. 5b). In addition, between 35 and 48 m in Well 3, and 52 and 66 m in Well 5, similar increases and decreases can be seen in the amount of metamorphic and igneous/metamorphic lithic fragments.

**INTERPRETATION OF GEOCHEMICAL AND PETROGRAPHIC DATA**

The initial aim of the study was to establish the relationship between the three studied wells. From Figures 3 and 5 it can be seen that Wells 3 and 5 display similar geochemical and petrographic profiles across different facies, whilst Well 7 has markedly different profiles to the other wells. This suggests that there are strong similarities between Wells 3 and 5 and that they have little or no relationship to Well 7. Integration of trace element geochemical and petrographic data allow construction of a high resolution correlation scheme for Wells 3 and 5 (Fig. 6).

Trace element data illustrated in Figure 6 are normalized to the average mudstone composition, taken from Well 3 (Fig. 3). The mudstones are taken as representative of background sedimentation, consequently the values reflect variations relative to background compositions and accentuate the contrast in relative trace element concentrations. Four correlatable zones have been identified.
Zone 1
The top of zone 1 is taken at the biostratigraphic pick which defines the top of the biozone. The base of the zone is defined by a characteristic high in the Zr, Cr and Nb data and is supported by petrographical data highlighted in Figure 5b. The boundary occurs in different facies between the two wells (low density turbidites in Well 3 and debris flow deposits in Well 5). The zone is divided into two subzones by a subsidiary pick that separates an upper zone of relatively high trace element concentrations in the low density turbidites, and muddy debris flow deposits from a lower zone of relatively low trace element concentrations in high density turbidite beds. This zonation scheme implies that the sandstone package in zone 1 can be correlated laterally between Wells 3 and 5. In addition, the debris flow deposits at the top of the Well 5 interval may be equivalent to the low density turbidites and, possibly, the mudstones at the top of the studied interval in Well 3.

Zone 2
The top of zone 2 has been picked using trace element geochemical data, supported by petrographical data (Fig. 5b). The base is defined using trace element geochemical data, and taken where high concentrations of Zr, Nb and Cr are present in both wells. A subzone pick has been taken at a characteristic high Zr peak. In the lower subzone the trace element profiles show similar trends in the two wells. There is a gradual decrease in concentrations downward from the subzone pick and then a gradual increase in concentrations to the high values, which define the base of zone 2. The correlation scheme suggests that low density turbidites and mudstones in the upper subzone of Well 3 are laterally equivalent to predominantly low density turbidites in Well 5. Sandstones in the lower subzone of Well 3 are likely to be equivalent to the sandstone package developed between 41 and 45 m in Well 5, as they show similarly high trace element concentrations. The sandstones in Well 5 that are present between 46 and 50 m have similar trace element values to mudstones and low density turbidites in the lower part of the subzone in Well 3 and are, therefore, likely to be equivalent.

Zone 3
The top and base of zone 3 are taken at peaks in trace element concentrations and occur in different facies in the two wells. In
Well 3 the top zone 3 peak is located in high density turbidites and in Well 5 in low density turbidites. In Well 3 the base zone 3 peak occurs in high density turbidites, but in Well 5 it is located in debris flow deposits. Similar trace element concentration profiles are present in both wells in zone 3 with the exception of Zr in Well 5, which has high concentrations. Both wells show a downward decrease in concentrations from the top of the zone and a gradual increase in concentrations towards the base of the zone. The similarity in these profiles suggests that the thick sandstone package in Well 5 does not extend as far as Well 3, where fine grained sediment dominates in zone 3.

**Zone 4**

Zone 4 is defined by a biostratigraphic pick at the base and a geochemical pick at the top. In Well 3 relatively low trace element concentrations are present in this zone in comparison to the relatively high values in Well 5. In addition, in Well 3 there is a gradual decrease in concentrations from the top of the zone downward and an increase at the base of the zone. In contrast, the equivalent interval in Well 3 shows much more variable values with no discernible trends. The variation in values in Well 3 is likely to be due to the chaotic nature of this debris flow-dominated package. The source material from which the debris flow deposit was derived may have contained a number of depositional units with different geochemical signatures, which may account for the large variation.

**DISCUSSION**

A sedimentary model can be proposed to explain the relationship between the studied wells determined from the geochemical and petrographic datasets. Interpretation of the datasets suggests that Wells 3 and 5 form part of the same depositional system. It is envisaged that the more confined, possibly channelized system penetrated by Well 5 fed the more distal, fine grained unconfinned system of Well 3. The values of Cr and Zr are generally lower in Well 3 than Well 5 (Fig. 3). This is considered to be a hydrodynamic effect reflecting the more distal location of Well 3 relative to Well 5, where the transport capacity of flows decreased between Wells 5 and 3.

The sediment in Well 7 has a different geochemical and petrographic signature to that from Wells 3 and 5 but was deposited within the same stratigraphic interval – biozone T34. As previously noted, available heavy mineral data suggest that there is no significant difference in provenance between the studied wells. This apparent contradiction between the geochemical and heavy mineral data can be explained if the sediment in Well 7 is considered equivalent to a small part of the stratigraphy present in Wells 3 and 5. Unfortunately neither the geochemical or petrographic data allow definition of which part of the stratigraphy the section in Well 7 could equate to. However, as it is possible to correlate the majority of the stratigraphy between Wells 3 and 5, it is possible that the channelized interval in Well 7 is relatively younger than, and cuts down through, the interval penetrated in Wells 3 and 5.

Debris flow deposits are only present within the confined systems penetrated in Wells 5 and 7. Where these deposits do occur in Well 5, they are laterally equivalent to low density turbidites and basinal mudstones in Well 3 (Fig. 6). Trace element concentrations in the debris flow, low density turbidite and mudstone facies have a similar range and are higher than those recorded from the high density turbidite deposits (Fig. 3). The above features suggest that there is a causal relationship between these facies. A model is proposed where the low density flows in Well 3 would have been deposited from low density plumes produced by the debris flows seen in Well 5. The low density plumes overtopped the banks of the channel in which Well 5 is located and spread over a large area, including the Well 3 locality. A modern analogue is provided by the slide induced turbidity flow offshore Nice 1979, in which a low density sediment plume was observed in association with a debris flow (Mulder et al. 1997). In the Nice flow, Mulder et al. (1997) differentiated between an erosive, dense flow and a low density depositional flow associated with the same event. This is consistent with the location of the stacked debris flow deposits in the confined system sampled by Well 5 and the low density turbidites in the unconfined system penetrated by Well 3. The low density turbidites in the Nice event deposited over a wide area from around 50 km from the source to 200 km from the source. This suggests that an overbank setting 2 km from the channel would easily be achieved, and that the overall well spacing of 6 km is also no obstacle to correlation when dealing with these deposits.
CONCLUSIONS

An integrated trace element geochemical and petrographic study of three wells from a deep marine clastic reservoir succession was undertaken to assess (1) whether the wells could be correlated and (2) if so, what resolution could be achieved. Trace element geochemical data indicate that of the three wells two (Wells 3 and 5) show strong geochemical affinities with similar variations in trace element concentrations throughout the studied interval. In contrast, geochemical data for Well 7 show no consistent variations across the studied interval. Petrographic data indicate that similar lithic clast types are present in all wells, but that variations in composition and clast type abundances are similar between Wells 3 and 5, but differ in Well 7. Integration of geochemical and petrographic data suggests that Wells 3 and 5 form part of the same depositional system. Well 3 is therefore considered to represent an equivalent overbank depositional package to the channel system sampled by Well 5. The channel system penetrated in Well 7 is considered to be partly equivalent to the strata penetrated in Wells 3 and 5, as, despite having a different geochemical signature, petrographic and unpublished heavy mineral data (A. Morton pers. comm.) indicate similar source area for all 3 wells, and biostratigraphic data constrain all the sections as having been deposited within the same biozone.

The trace element geochemical data and petrographic results allowed detailed correlation between Wells 3 and 5 with the definition of 4 zones and 2 subzones. Following this zonation scheme, a detailed sedimentary model was constructed which allows the lateral extent of reservoir and non-reservoir units to be defined. The integration of high-resolution trace element geochemistry with sedimentological and petrographical data has resulted in the provision of a much higher resolution correlation than would be possible with any single technique.

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REFERENCES


