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Constraining sub-seismic deep-water stratal elements with electrofacies analysis; a case study from the Upper Cretaceous of the Måløy Slope, offshore Norway

Amandine Prélat[1*], David M. Hodgson[2], Mark Hall[3], Christopher A-L. Jackson[1], Carol Baunack[4] and Bjarne Tveiten[3]

[1]Basins Research Group (BRG), Department of Earth Sciences and Engineering, Imperial College, London, UK

[2]Stratigraphy Group, School of Earth and Environment, University of Leeds, Leeds, UK

[3]VNG Norge, Oslo, Norway

[4]Verbundnetz Gas, Leipzig, Germany

* Email address of the corresponding author: aprelat@imperial.ac.uk

ABSTRACT

Electrofacies represent rock facies based on wireline-log measurements and allow extrapolation of petrophysical characteristics away from levels that are calibrated to core. This approach has been employed to reduce uncertainty in the sub-seismic depositional elements of the late Cenomanian-Coniacian succession, northern Måløy Slope, offshore Norway. From core logging, eleven distinct sedimentary facies are grouped into four facies associations: FA A-turbidite sandstones, FA B-heterolithic siltstones and sandstones, FA C-debrites and FA D-slide and slump deposits. Each sedimentary facies association is characterised by a distinct combination of petrophysical characteristics, such as porosity, density, gamma-ray, sonic and resistivity. Using a neural network, calibration of electrofacies with sedimentary facies association allows their thickness and stacking pattern to be documented across the Upper Cretaceous stratigraphy. This approach is particularly useful where well log facies associations are poorly constrained due to the variable presence of glauconite, and sandstone units are challenging to distinguish from shale-rich units on a gamma-ray log. Results indicate that the succession of interest is dominated by debris flow, slide, and slump deposits, which are commonly poorly imaged on seismic reflection datasets in the northern North Sea. The methodology presented here represents a step forward in correlation at production and exploration scales of stratigraphic successions with similar burial histories, and in the identification of widespread mass flow deposits present in Upper Cretaceous deep-water systems of the North Sea.

KEYWORDS: electrofacies, well data, Måløy Slope, deep-water deposit, glauconite, artificial neural network

INTRODUCTION

In the northern North Sea, deep-water systems have been widely studied because they represent potentially large oil and gas reservoirs and are therefore economically important (e.g. Johnson and Stewart, 1985; Løseth et al., 2009; Stow and Mayall, 2000; Ziegler, 1977). Deep-water sandstone reservoirs contain a variety of architectural elements, but are dominated by channel-fill, sheet and thin-bedded levee deposits (e.g. Lawrence and Bosman-Smits, 2000). In contrast, mass transport deposits (including debrites, slides and slumps) are commonly regarded as low potential reservoirs, because of the lack of vertical and horizontal connectivity between sandbodies that are typically contained as isolated clasts (Bull et al., 2009; Weimer and Shipp, 2004). Shanmugam et al. (1994, 1996) used ~3700 m of core to illustrate that most Cenozoic-Tertiary basin-floor fans of the North Sea are dominated by relatively muddy slump and debris flow deposits, rather than sandstone-rich turbidites. However, this interpretation was challenged by Hiscott et al. (1996), who argued that the criteria used by Shanmugam et al. (1994, 1996) to differentiate between classic turbidites and mass flow deposits (e.g. grading, sorting, sedimentary structures) were flawed. This dispute highlights the need to develop new workflows to better constrain the sub-seismic elements that comprise deep-water successions in subsurface datasets, especially where core data are lacking.

Comment [DM1]: Alphabetical rather than chronological?

The depositional architecture of deep-water systems results from the interplay of autogenic (such as depositional relief and system avulsion) and allogenic controls (such as the tectonic setting, sediment provenance and eustasy) (Calvache et al., 1997; Martinsen et al., 2005). To help us better understand the stratigraphic architecture of deep-water reservoirs, seismic reflection and well data need to be integrated. Seismic data can provide information on the basinal context and large-scale morphology of a deep-water depositional system, whereas well data allows us to determine the vertical distribution of sandstone from logging tools such as gamma-ray, density and neutron porosity. The presence of some cements and minerals, for example glauconite, can influence the response of the logging tools within the formation and make the distinction between sand-rich (reservoir) intervals and claystone-rich (non-reservoir) intervals equivocal (McRae, 1972; Rider and Kennedy, 2011). The current study proposes a methodology based on neural network analysis using Petrel 2013 software. Neural networks use the petrophysical signature of pre-defined rock unit (here sedimentary facies associations) to generate electrofacies and extrapolate their distribution away from the cored sections of the well.

The aims of this study are: 1) to describe and interpret the core-based sedimentology of 125 m of core from a 600 m thick deep-water succession preserved on the northern Måløy Slope, offshore Norway (wells 6204/10-1, 6204/10-2A, 6204/10-2R, 6204/11-1, Fig. 1); 2) to calibrate electrofacies logs with core data and extrapolate facies associations defined at core level along the well; 3) to test how far, geographically and stratigraphically, core-calibrated electrofacies logs can be applied away from the study interval; and 4) to establish the proportion and distribution of mass flow deposits within the Upper Cretaceous succession of the northern Måløy Slope, with the aim of determining their significance in terms of basin margin evolution. The methodology developed is then tested on the same deep-water succession on an offset well (35/9-3T2), which is located ~50 km south of the study area. In this well, a core and a similar set of well data are available, thus allowing a far-field test of the reliability of electrofacies analysis at predicting facies associations. The application of electrofacies analysis is especially valuable in the studied succession because the seismic data quality is variable, and the presence of authigenic and detrital glauconite means it is difficult to use individual tools, especially gamma-ray, to discriminate between reservoir sandstone and non-reservoir mudstone.

STUDY AREA

Tectono-stratigraphic evolution of the northern Måløy Slope

The Måløy Slope is bounded to the west by large (>5 km displacement), west-dipping normal fault complexes that form the eastern margin of the Sogn Graben, and to the east by the Øygarden Fault Complex. The study area includes the Selje High, a ~30 km long Cretaceous structure oriented SW-NE (Fig. 1). Rifting and formation of normal fault blocks in the Middle to Late Jurassic was superseded by thermally-driven, post-rift subsidence in the Cretaceous and Tertiary, and the formation of a deep-water basin (Surlyk et al., 2003). Syn-rift relief was infilled and draped by Upper Cretaceous to lower Palaeogene post-rift deposits (Surlyk et al., 2003).

Comment [DM2]: This is where a seismic line added to figure 1 would help the reader, and address a key reviewer concern. The large-scale structural template does not undermine the second paper.

Upper Cretaceous stratigraphic framework

The study interval is located in the Upper Cretaceous Shetland Group (Fig. 2), which is well-developed in the graben areas (e.g. Sogn Graben), where it is up to 2 km thick, and thins towards the eastern basin-margin (Surlyk et al., 2003). It can be subdivided into five siliciclastic-dominated formations, which are, in stratigraphic order, the Svarte, Blodøks, Tryggvason, Kyrre, and Jorsalfare formations (Deegan and Scull, 1977) (Fig. 2).

In the southern part of the northern North Sea, the Cenomanian succession (Svarte Formation) consists of calcareous mudstone interbedded with chalky limestones. The proportion of limestone gradually decreases northwards towards the Måløy Slope and away from syn-depositional structural highs over which the formation is thin or absent (Surlyk et al., 2003). The Turonian succession (Tryggvason Formation) is lithologically similar to the Cenomanian succession; the limestone content also decreases northwards towards the Måløy Slope, giving way to greater quantities of sandstone, especially within the Agat discovery area (Surlyk et al., 2003) (Fig. 1). The Turonian succession is up to 300 m thick. The latest Turonian to early Campanian succession (Kyrre Formation) comprises a thick (up to 1100 m), monotonous succession of silty mudstone that contains sporadic argillaceous limestone stringers. Sandstone-rich packages, such as the Røedspette Member, are found locally in the lower section of the formation (Jackson et al., 2008; Shanmugam et al., 1996). Sandstones in the Svarte, Tryggvason and lower Kyrre Formations have a high glauconite content, which is interpreted to indicate reworking of shallow marine deposits that had been stored for relatively long periods on the shelf (Jackson et al., 2008). In the southern part of the Måløy Slope, around well 35/9-3, these sandstone-rich packages have been interpreted as submarine channels-fills and fans (Bugge et al., 2001; Jackson et al., 2008; Martinsen et al., 2005). On seismic data, they are characterised by bright amplitudes (Jackson, 2011; Jackson et al., 2008; Sømme et al., 2013). The current study represents the first detailed study on the sedimentology and stratigraphy of the late Cenomanian-Coniacian, deep-water succession in the northern part of the Måløy Slope (Figs.1, 2).

Database

The database includes three sub-vertical exploration wells (6204/10-1, 6204/10-2A, and 6204/11-1) and one sidetrack well (6204/10-2R) (Fig. 1). All four wells include gamma-ray (GR), density (RHOB), neutron (NEU), and resistivity (RMED) log data. The four cored wells provide a total of ~125 m of coverage through the interval of interest and allow the detailed sedimentology and stratigraphy of this deep-water succession to be constrained. The cores and linked facies depth were shifted as appropriate.

Comment [DM3]: To what? Not clear on method

Primary petrophysical properties include the density, gamma-ray, sonic, and resistivity and derived petrophysical properties include porosity. Core plug-derived porosity and permeability measurements are available for all four wells and a total of 37 thin sections permitted detailed analysis of the mineralogy of the different sedimentary facies. Over 800 data points from cored intervals in wells 6204/10-1, 6204/10-2A, 6204/10-2R and 6204/11-1 are compiled to constrain the petrophysical characteristics of the four sedimentary facies associations; this data density corresponds to a sample point every ~15 cm. The neutron and density wireline logs were used to calculate the porosity, which were matched to core porosity. In order to compensate for the high density iron-bearing glauconite, a density matrix higher than sandstone was used.

Comment [DM4]: Reordered to deal with core then logs

Comment [DM5]: Can you be quantitative? Back to the repeatability issue

SEDIMENTARY FACIES AND FACIES ASSOCIATIONS

The late Cenomanian-Coniacian succession was deposited in a deep-water environment (Bugge et al., 2001; Jackson et al., 2008; Lien et al., 2003; Sømme and Jackson, 2013; Sømme et al., 2013; Surlyk et al., 2003). Below is a description of the core-based sedimentary facies analysis from wells 6204/10-1, 6204/10-2A, 6204/10-2R, and 6204/11-1. Sedimentary facies are defined by grain-size, sedimentary structures, and petrography. The sedimentary facies are grouped into four sedimentary facies associations (named A to D); each sedimentary facies within these associations display similar grain-sizes and sedimentary structures and can be shown to occur in discrete, genetically related stratigraphic packages. The cores were targeted to sample dominantly sandstone-rich packages; consequently, no core data are available from claystone-rich packages. We therefore use understanding of regional geology and previous work on the lithology of the Upper Cretaceous succession (Bugge et al., 2001; Jackson et al., 2008; Martinsen et al., 2005; Surlyk et al., 2003) to constrain the occurrence of dominantly claystone-rich units, which are based on seismic reflection data and well-to-well log correlation.

Sedimentary facies association A: sandstones (Fig. 3)

Sedimentary facies A1 - structureless thick-bedded coarse-grained sandstone

Description: Facies A1 consists of thick beds and bedsets (1-9 m) of poorly to moderately sorted, medium- to coarse-grained sandstone (see 6204/10-1, 1974-1994.15m and 1890-1899m) (Fig. 3a). Commonly, A1 beds have sharp and erosional bases and sharp tops, and typically overlie facies A2 (Fig. 3a). Average bed thickness is challenging to assess because criteria to define bed boundaries, for example grain-size breaks, are not observed. No sedimentary structures or bioturbation is observed within A1.

A total of 12 thin sections from facies A1 have been analysed and these indicate that A1 is composed of a mixture of quartz, feldspar, mica, and glauconite (Fig. 3a). The large proportion of glauconite grains (~20-30%), which are up to 2 mm in diameter, gives a greenish color to the sediments. Rare pollen grains and calcareous bioclasts are also observed. Facies A1 has the best reservoir quality of all the sandstone-dominated facies in facies association A and all other sedimentary facies described in this paper (see Fugelli and Olsen, 2007), with an average horizontal permeability of 2606 mD and an average porosity of 29.1% (Fig. 4).

Comment [DM6]: Do we need to be US spelling for MPG???

Interpretation: Structureless coarse-grained sandstone beds that lack internal sedimentary structures are reminiscent of subfacies A1 of Lien et al. (2003), which were interpreted to have been deposited by high-density turbidity currents or en masse freezing of hyperconcentrated-to-concentrated flows (Bouma, 1962; Kneller and Branney, 1995; Kuenen et al., 2006; Pickering et al., 1989; Pickering et al., 1986; Talling et al., 2012). The degree of bed amalgamation is a function of the degree of erosion and time between emplacement of deposits from successive flows (Lien et al., 2003). The thick structureless beds are interpreted to document deposition by large, sandy turbidity currents in the axes of submarine channels and/or near the mouth of channels where flows expanded and deposited rapidly (Lien et al., 2003). The source for the sandstone in A1 is interpreted to be a mix of hinterland-derived material that underwent only limited transport (i.e. sandstones rich in detrital feldspar) and sediment locally reworked from the shelf (i.e. sandstones rich in glauconite) (Odin and Matter, 1981).

Sedimentary facies A2 – structureless sandstone with siltstone and claystone clasts

Description: Facies A2 consists of medium to thick beds (0.2-1 m) of very poorly sorted sandstone, rich in claystone and siltstone clasts (Fig. 3b). Bed bases are sharp and erosional, and bed tops are sharp. Clasts are typically 0.5 to 1.5 cm in diameter and angular to sub-angular, although some clast diameters are greater than the core width (>11 cm) (Fig. 3b). Clasts are commonly evenly distributed throughout the beds and are supported by a very poorly sorted (i.e. fine-to-coarse-grained) sandstone matrix that is rich in quartz and glauconite. No sedimentary structures, dewatering structures, or bioturbation is observed within A2.

One thin section from facies A2 has been analysed and indicates that A2 is composed of a mixture of quartz, feldspar, mica, kaolinite and glauconite (Fig. 3b). Facies A2 has an average horizontal permeability of 0.1 mD and an average porosity of 7.8%, which is interpreted as non-reservoir (see Fugelli and Olsen, 2007).

Interpretation: We interpret that facies A2 represents the deposits of medium- to high-density turbidity currents that had sufficient energy to erode a muddy substrate. The angular nature of the clasts suggests they were transported a short distance. Furthermore, the poorly sorted matrix suggests they were deposited during periods of increased sand bypass into the deeper basin (Sinclair and Tomasso, 2002). When overlain by facies A1, this sedimentary facies is interpreted to document deposition at the base of a channel or channel complex (Eschard et al., 2003).

Sedimentary facies A3 – structureless to parallel laminated fine-grained sandstone

Description: Facies A3 consists of 0.05 to 0.4 m thick, fine- to medium-grained sandstone beds. Bed boundaries are flat and sharp (Fig. 3c). Normal grading is common in A3 and beds are typically capped by a thin (<5 cm) siltstone. Parallel to sub-parallel planar lamination is common in the upper part of a normally graded bed or throughout the entire bed (Fig. 3c). Locally, the laminae can be cm-thick, where they alternate in colour between light and dark grey.

Thin section analysis indicates that A3 consists of a mixture of quartz, glauconite, mica, and organic matter (Fig. 3c). Light grey laminae are quartz- and glauconite-rich and matrix-poor, whereas dark grey laminae are rich in mica and organic material. Sedimentary facies A3 has an average horizontal permeability of 24.3 mD and an average porosity of 18.7%, indicating a low to moderate reservoir quality when compared to reservoir quality defined by Fugelli and Olsen (2007).

Interpretation: Facies A3 is interpreted to have been deposited by low- to high-density turbidity currents. The finer-grained, siltier beds represent the deposits of low-density flows, whereas the normally graded sandstone beds represent deposition from medium to high-density turbidity currents (Johnson et al., 2001). The beds with alternating matrix-rich and matrix-poor sand laminae are similar to the banded facies reported from the Britannia Formation (Lowe and Guy, 2000) and facies H2 of Haughton et al. (2009). Banding has been attributed to flows that are intermediate between fully turbulent and laminar flow behaviour (Haughton et al., 2009; Lowe and Guy, 2000). Deposition of facies A3 requires time and space to create and preserve laminae, but also changing flow properties to deposit a range of sediment grainsizes (Lowe and Guy, 2000). We infer that A3 was deposited down-dip from the channelized parts of the system (Haughton et al., 2009), in a setting dominated by submarine lobes (Prélat et al., 2009).

Sedimentary facies A4 – fine-grained and coarse-grained clastic injectites

Description: Facies A4 is rare in core but can reach 1m in thickness (i.e. in 6204/11-1). Facies A4 is characterised either by: (i) sharp-based, sharp-topped, structureless sandstone that has a discordant relationship with encasing stratified siltstones and mudstones; and (ii) sharp-based and sharp-topped mudstone that is discordant with encasing sandstone (Fig. 3d). Sedimentary facies A4 is commonly overlain by facies association A (Fig. 3c). Facies A4 has no thin section available to characterise its mineralogy, and no porosity or permeability data are available.

Interpretation: A4 is interpreted as clastic intrusions, emplaced in host rocks of varying grain-sizes. Clastic dykes and sills imply that nearby sandstone was buried whilst unlithified and containing significant amounts of pore water (Hiscott, 1979). The intrusion of sand into fine-grained material implies that bodies of poorly consolidated and overpressured sands encased in a fine-grained succession were subjected to liquefaction and remobilization (Hiscott, 1979; Lien, 2005).

Petrophysical characteristics of FA A:

Sedimentary facies association A (FA A) is characterised by a narrow range of petrophysical properties (Fig. 4) with a distinct cluster of dominant values for each parameter (Fig. 5). FA A is characterized by the highest average porosity (28%), highest average sonic (99 us/ft) and lowest average density (2.37 g.cm^{-3}) of all four facies associations (Fig. 4). FA A is also characterised by low resistivity values (2.2 ohm/m) and average gamma-ray values (87 gAPI). The low density values and high porosity values of FA A are unique and mean FA A is petrophysically distinct from the three other facies associations (Fig. 4).

Sedimentary facies association B: heterolithic siltstones and sandstones (Fig. 6)

Sedimentary facies B1 – finely laminated siltstone

Description: Facies B1 has a sharp base and top, is characterised by mm-scale laminated, dark, fine-grained siltstone (Fig. 6a). A single package of facies B1 (40 cm thick) is observed in well 6204/10-2R and is laminated from base to top. This package is sharply overlain by a unit of A3. No bioturbation is observed within B1.

No thin sections are available to characterize the mineralogy of facies B1. The petrophysical data available for B1 demonstrate very low reservoirs qualities (after Fugelli and Olsen, 2007), with a low horizontal permeability of 0.14 mD and an average porosity of 18.6%.

Interpretation: Facies B1 is interpreted to be deposited via suspension settling of low-density dilute turbidity currents. We infer that this sedimentary facies documents deposition in either a low-energy setting, such as the fringe of a lobe or levee, and/or deposition during a period when no sand was being supplied to the deep basin (Mutti, 1977).

Sedimentary facies B2 – bioturbated interbedded thin siltstone and sandstone

Description: Facies B2 consists of thinly bedded (centimetre scale) coarse siltstones and very fine-grained sandstones (Fig. 6b). Facies B2 is observed in packages of up to 4 m in thickness (6204/11-1). The difference in grain size is highlighted by a change in colour, from light- (sandstone) to dark-grey (siltstone). This facies is characterised by intensive bioturbation (Zoophycos and Helminthopsis) (bioturbation index ranges from 4 to 6; Droser and Bottjer, 1986). The original sedimentary structures, and locally the original stratification, are therefore difficult to identify. Facies B2 is commonly overlain by units of facies C2 or C3 (see description and interpretation below).

No thin sections are available to characterize the mineralogy of facies B2. Petrophysical data suggest that facies B2 has low reservoir quality (after Fugelli and Olsen, 2007), with a horizontal permeability averaging 5.1 mD and an average porosity of 11%.

Interpretation: We interpret that the interbedded thin beds (1 to 3 cm) of siltstone and very fine-grained sandstone that characterise B2 were deposited from low-density turbidity currents. The alternation of sandstone and siltstone beds indicates that sediment supply was low. The presence of Zoophycos supports a low-energy and deep-water setting. Facies B2 is therefore interpreted to characterise deposition in a distal setting, most likely at the basinward or lateral end of the depositional system.

Petrophysical characteristics of FA B:

Petrophysical characteristics of sedimentary facies association B (FA B) are more challenging to constrain because of the low number of available data points (60) compared to the three other facies associations (Fig. 4). The low number of data point available for this facies association is due to the On average, FA B is characterised by an average density (2.36 g.cm^{-3}), low porosity (14%), average gamma-ray (73 gAPI), average sonic (85 us/ft) values, and high resistivity (8.3 ohm.m) values (Fig. 4). Nevertheless, based on the detailed distribution of some petrophysical characteristics, two populations can be highlighted that correspond to the two facies B1 and B2 (Fig. 4 and 5). Gamma-ray values are similar between the two facies, but porosity, density, sonic and resistivity values are different, which defines a bi-modal distribution in Figure 4 and two non-overlapping clusters in Figure 5. Both facies are fine-grained and interpreted to represent deposition in distal or lateral areas of deep-water systems, but they could be interpreted in having different petrophysical properties, due to a different sediment source for the two facies. The existence of two distinct populations can also be attributed to the small amount of data point available for FA B compared to other facies associations (Fig. 4).

Comment [DM7]: Incomplete sentence

Sedimentary facies association C: debrites (Fig. 7)

Sedimentary facies C1 – clast-rich muddy sandstone

Description: Facies C1 consists of 0.2-0.5 m thick beds of muddy, very fine-grained sandstone with randomly oriented, cm-scale, tabular mudstone clasts (Fig. 7a). No plant fragments or bioturbation is observed within this facies, although fragmented and articulated thin-walled bivalves shells are present. This facies can be present in relatively thick packages (up to 10 m in 6204/10-2R) that display little variation in matrix grain size or sedimentary structures. Rare beds are normally graded, which may be accompanied by a reduction in clast

Comment [DM8]: Laminated or massive?

size (Fig. 7a). Facies C1 is only observed in 6204/10-2R, where the overlying and underlying strata were not penetrated.

Two thin sections from facies C1 have been analysed and show that elongate minerals, such as mica fragments, are randomly oriented within the matrix (Fig. 7a). The petrophysical data available suggest that C1 is non-reservoir, with an average horizontal permeability of 0.06 mD and an average porosity of 17.1% (Fugelli and Olsen, 2007).

Although sedimentologically similar to A2 (i.e. sandstone-rich matrix with fine-grained clasts), there are some noticeable differences between A2 and C2. These include the geometry of the clasts (i.e. A2 is characterised by angular clasts whereas C1 is characterised by tablet-shaped, rounded clasts), and the abruptness of the contact between the clasts and the matrix (i.e. A2 is characterised by sharp contacts whereas C1 is characterised by gradational contacts).

Interpretation: The lack of grading and large mudstone clasts indicates inefficient sorting and en masse deposition from a cohesive flow (Mulder and Alexander, 2001; Talling et al., 2012) . The poor sorting of the matrix and the presence of thin-walled shells suggest an absence of effective grain size segregation and intra-flow abrasion, which are the result of collision and corrosion in a more turbulent flow (Haughton et al., 2003). C1 beds are thus interpreted as debrites (Haughton et al., 2003; Mulder and Alexander, 2001).

Sedimentary facies C2 – sandstone with limestone clasts

Description: Facies C2 consists of meter thick beds of poorly sorted, structureless, and coarse-grained sandstone matrix containing limestone clasts (Fig. 7b). The limestone clasts have sharp and locally angular edges and range from 0.2 to 4 cm in diameter. Facies C2 is clast supported. Facies C2 typically underlies or overlies C3 across a gradational contact, with the amount of clasts and the average grain-size of the matrix gradually changing (see description and interpretation of C3 below) (Fig. 7b).

One thin section is used to characterize facies C2. It shows that the contact between the matrix and the limestone clasts is sharp and that all pore space is occluded with an early, poikilotopic, calcite cement (Fig. 7b). The petrophysical data suggest that C2 is non-reservoir, with a low horizontal permeability (average 0.91 mD) and a low porosity (10.6%) (Fuggelli and Olsen, 2007)..

Interpretation: The disorganized and poorly sorted nature of the matrix, combined with a large proportion of clasts, indicates deposition from a debris flow (Haughton et al., 2009; Mulder and Alexander, 2001). The large number of limestone clasts is likely to be produced by erosion and reworking of a buried chalky limestone interval, such as the Svarte Formation (Cenomanian) (Surlyk et al., 2003). However, no in situ chalk has been intersected in this part of the basin-fill.

Comment [DM9]: Why use Haughton 2003 for one and 2009 for the other interpretation of debrite?

Sedimentary facies C3 – silty sandstone with limestone clasts

Description: Facies C3 consists of up to 7 m thick beds of a poorly sorted silty sandstone matrix that contains carbonate clasts (Fig. 7b). The limestone clasts are more rounded than those in C2 and are smaller in size (0.5-2 cm). The matrix characterising C3 is finer than in C2 and has a darker colour. Similarly to facies C2, facies C3 is characterised by gradational contacts (Fig. 7b).

No thin sections are available to characterize the mineralogy of facies C3. Petrophysical data suggest very low reservoir quality, with a horizontal permeability averaging 0.11 mD and a porosity averaging 7.9% (Fugelli and Olsen, 2007).

Interpretation: Facies C3 is sedimentologically similar to facies C2 (i.e. carbonate clast-rich, disorganised and poorly sorted matrix) and is also interpreted to have been deposited by debris-flows (Haughton et al., 2009; Mulder and Alexander, 2001). The more rounded clasts suggest either a longer transport distance compared to C2, or entrainment of a clast population that has already undergone a degree of reworking. Furthermore, the fewer number of chalk clasts and the finer-grained nature of the matrix in C3 also suggest a longer transport distance compared to C2.

Petrophysical characteristics of FA C:

Despite the wide range of petrophysical properties, facies association C (FA C) can be clearly differentiated from other facies associations, especially when comparing their average gamma ray values, which is higher than the three other facies associations (Fig. 4 and 5). FA C is characterised by an average density (2.48 g.cm^{-3}), high gamma-ray (113 gAPI), high sonic (90 us/ft), low porosity (9.7%), and high resistivity (7.8 ohm.m) (Fig. 4).

Sedimentary facies associations D: Slide and slump deposits (Fig. 8)

Sedimentary facies D1 – folded and deformed sand-rich strata

Description: Facies D1 is up to 15 m in thickness and contains 2-20 cm folded sandstone beds, with rare interbedded thin claystone and siltstone (1-10 cm). The average sand-to-shale ratio of facies D1 is around 80%. In 6204/10-2A, the bedding orientation is variable, but is typically orientated at a high angle to the vertical well direction. The underlying and overlying strata were not penetrated in this well. Sandstone beds are locally faulted (cm-scale) and contain rare laminae, although the folding has obliterated most of the original sedimentary structures (Fig. 8a).

The sandstone-rich clasts of facies D1 are characterised by an assemblage of quartz and glauconite, with secondary feldspar and opaque fragments (Fig. 8a). Some samples show a large proportion of bioclasts (foraminifera, bivalve fragment, large bryozoan) and woody fragments within the clay dominated part of the sample. Some samples also contain fragments of coccolithophore plates and well-preserved, complete coccoliths. Facies D1 has very low horizontal permeability (average of 0.1 mD) and an average porosity of 15.1%, indicating that it has non-reservoir quality (Fugelli and Olsen, 2007).

Interpretation: The folding of the sandstone beds demonstrates that packages of D1 have been remobilised down–slope as a coherent mass with limited disaggregation, which is supported by the preservation of fragile biogenic material. Facies D1 has similar characteristics, such as the folding style and the average sand-to-shale ratio, to slide deposits exposed at outcrop in the Vischkuil Formation (Karoo Basin, South Africa) (Van der Merwe et al., 2011) and the Ross Formation (western Ireland) (Strachan, 2002). The lithologies and facies preserved in D1 should record the environment from which the slide was derived. In this context, fine-grained deposits are preserved between thin sandstone beds, which can be laminated. The original environment of deposition could therefore include a submarine levee setting close to a turbidite channel (Lien et al., 2003a), an upper slope or an outer shelf prodelta. The presence of bivalve fragment and large bryozoan within facies D1 indicates a shallow marine environment, and the high sand-to-shale ratio a relatively proximal environment. The slide generating facies D1 is here interpreted to come from an upper slope environment.

Sedimentary facies D2 – folded and deformed silt-rich strata

Description: Facies D2 consists of up to 10 m units of deformed and folded interbedded sandstone and siltstone beds (see 6204/11-1). Sandstone bed thickness ranges between 1 and 20 cm and silt-rich interval thicknesses vary between 5 and 30 cm, although contacts between the two lithologies are gradational (Fig. 8b). Parallel laminations can sometimes be preserved in sandstone clasts, although the original sedimentary structures are rarely preserved due to the folding. The average sand ratio of facies D2 is ~60 %. The underlying and overlying strata have not been penetrated during coring.

A total of three thin sections are available for facies D2. Thin section analysis indicates that the sandstone-rich units of D2 consist of a mixture of quartz, glauconite, and feldspar (Fig. 8b). More specifically, thin-section analyses indicate the presence of an iron-rich dolomite cement and a micritic matrix. Facies association D2 has no reservoir quality, with low horizontal permeability (average of 0.03 mD) and an average porosity of 13%.

Interpretation: The folding of the sandstone beds demonstrates that packages of D2 have been remobilised down–slope as a coherent mass. Facies D2 is interpreted as a slide deposit with a higher degree of disaggregation compared to facies D1.

Petrophysical characteristics of FA D:

Sedimentary facies association D (FA D) is characterised by sonic values averaging 88 us/ft, density values averaging 2.42 g.cm^{-3}, low gamma values averaging 58 gAPI and porosity values around 15 % (Fig. 4 and 5). These points define a distinct cluster, distinct from FA A (sandstones) and FA C (debrites), especially because of its unique low gamma-ray values, but somewhat similar to FA B (heterolithic siltstones and sandstones) (Fig. 4 and 5). This means that discriminating FA B from FA D is more challenging using their petrophysical signature.

ELECTROFACIES CHARACTERISATION AND PREDICTION OF FACIES ASSOCIATIONS AWAY FROM THE CORES

The term ‘electrofacies’ was defined by Serra and Abbot (1982), and is used to describe the characterization and interpretation of sedimentary facies using electrical well logs. Electrofacies analysis calibrates wireline log data with core data, and uses either a supervised or unsupervised technique to cluster data into a number of groups (called electrofacies) (Adoghe et al., 2011; Inwood et al., 2013; Lertlamnaphakul, 2011; Mahdavi, 2009; Tudge et al., 2009; Ye, 2000). Electrofacies do not directly correlate to sedimentary facies, but rather to a group of rock types that share similar petrophysical properties. Electrofacies analysis is therefore more commonly used to delineate petrophysical units rather than sedimentary facies when building static and dynamic reservoir models (Rider and Kennedy, 2011). Although this is widely used during the development and production stage of a hydrocarbon field lifecycle, electrofacies analysis can be used by geologists to help constrain the vertical (stratigraphic) and lateral distribution of sedimentary facies and depositional environments within ancient subsurface systems. Because core is relatively expensive to collect compared to electrical log data, electrofacies analysis represents a cost-effective way to determine the sub-seismic composition and architecture of depositional systems. The four facies associations described in the previous section are used to define four key electrofacies. Before detailing the results, the methodology and limitations are explained below.

Methodology

Input data for the characterisation and the prediction of deep-water deposits across the interval of interest include the petrophysical properties of each facies associations as outlined in the previous section. The likelihood that a certain facies association will be present at a given depth in an uncored section of the well is estimated using the known petrophysical properties associated with that specific facies association and depth in a cored interval. We estimate that the vertical resolution of the predicted facies equals the vertical resolution of the tools measuring the petrophysical parameters, which here is approximately 0.30 m. For example, if at a given depth, the petrophysical parameters illustrate a high porosity, low density, average gamma-ray, high sonic and low resistivity, then the likelihood of having turbidite sandstone (FA A) present at this depth is high compared to other facies associations. The dominant facies association predicted is interpreted to be the most likely present at this depth (Fig. 9). If, on the contrary, the petrophysical parameters do not correspond to any particular facies associations, then each facies associations will be equally likely to be present at the given depth. The unit characterised by these petrophysical properties are interpreted to represent a facies that has either not been cored or that is here characterised by new petrophysical properties. An alternative interpretation is that this unit could represent a unit comprised of thin layers (< 0.5 m) belonging to several different facies, and hence does not have a clear petrophysical signature at the metre scale.

Neural network implemented in Schlumberger's Petrel 2013 software is used to predict facies associations in the uncored sections of the wells (Lertlamnaphakul, 2011; Madhawi, 2009). The neural network is a function that estimates the likelihood of finding a particular facies at a location based on given measured parameters (e.g. logged porosity, density, gamma ray, sonic and resistivity). Here, a facies association is attributed when more than

80% of the input points match with an assigned facies association. Using neural networks for prediction in this way is a two-step process. First, the network must be trained in an area where the facies is known, where the function is created. In the second step, the function is applied to data where the facies is not known but the measured parameters used to define the function are (in our case the logs used to predict facies). Training the neural network is done over the section of the wells where core has been logged and the facies is therefore known. For each assigned facies, the data is split randomly into two groups. Half the data is used to estimate a function for predicting facies whilst the other half is used as a control to measure how effective that function is at predicting the facies. The correlation between the estimated facies in the control group and the actual facies logged is used to estimate the efficiency of the function. A perfect match would give a correlation of one. The function is changed slightly and the efficiency measured again. If the new function proves more efficient at predicting facies correctly then it is kept. If not, the original function is kept and a new change is tested. Once trained, the neural network can be used in areas with no interpreted facies to predict the facies at that location. The likelihood of finding each facies at each point in the well is calculated, giving a series of log curves (one for each facies), which are normalised to one. At each point the most likely facies is then assigned to that location, which results in a discrete log of predicted facies (Fig. 9).

In general, if when cross plotting log properties data points from one facies plot in a distinctly different area to another facies (Fig. 5), then the two facies will be easily distinguished by a neural network (Fig. 9). If two facies overlap, then it may be difficult to distinguish between them. The advantage of using a neural network is that this separation is assessed in a multi-dimensional domain. It is easy to visually assess the separation of facies in 2D, e.g. based on a gamma ray vs. density plot (Fig. 5b). However, some of the areas that overlap on this plot may separate when sonic and resistivity values are considered. A neural network can recognise this and differentiate these facies.

Limitations

In theory, if two facies have exactly the same log response (i.e. the same petrophysical signature) then they cannot be differentiated using electrofacies. The current study uses four petrophysical signatures, each corresponding to a previously described facies association. For each depth, the neural network analysis always assigns one of the four facies associations. The best case scenario corresponds to a depth where the petrophysical set found matches perfectly with those characterising a pre-defined facies association. In this case, the match equals 1, and the likelihood to fit the petrophysical set with a pre-define facies association is 100%. On the contrary, the worst case scenario corresponds to a depth where the encountered petrophysical parameters set does not match with any of the pre-defined facies association. In this case, the match equals 0, and the likelihood to fit this depth with each facies association is ~25% (Fig. 9). Two hypotheses can be postulated to explain an unknown petrophysical signature: it corresponds to a new facies association that has not been cored and for which no petrophysical signature has been defined. Alternatively, it could correspond to a known facies association, but characterised at this depth by a different petrophysical signature, due for example to a change of mineralogy or diagenetic state. Therefore, the higher the proportion of a certain facies association, and the better the match is between the input data and the pre-defined petrophysical signatures.

Additional limitations are linked to variations of petrophysical properties with depth (Fig. 10), the variations of petrophysical properties within a facies association, the definition and recognition of facies association, and the proportion of each facies association found within the cores. Petrophysical properties vary with depth (Rider and Kennedy, 2011). For example, for a given lithology, although radioactivity and thus gamma-ray value is not affected by burial depth, sediment density is expected to increase with depth while porosity will generally decrease (Nafe and Drake, 1957) (Fig. 10). Consequently, the combination of petrophysical properties that define a specific facies association is only robust across a relatively narrow depth range. In this study, the depth range covers ~600 m (Fig. 11). It can be seen that petrophysical properties demonstrate abrupt changes above and below this window, which limits the prediction of the facies associations present. When present in thick packages (> 2-3 meters), each facies associations is characterised by a large number of data points compared to rare and or thin units (< 1 m). Thin packages of a given facies association mean that the associated petrophysical parameters are more difficult to characterise and limit the application of electrofacies analysis.

STRATIGRAPHIC AND GEOGRAPHIC DISTRIBUTION OF THE CENOMANIAN-CONIACIAN DEEP-WATER DEPOSITS

Cenomanian

We only consider the upper part of the Cenomanian succession; the lower part is either not drilled (i.e. 6204/10-2A and 2R) or is located outside the stratigraphic window of interest (i.e. 6204/10-1 and 6204/11-1) (Fig. 11). 6204/10-2R (1961.14–1951 m), located on the south-western part of the Selje High, contains a ~10 m thick interval of debrite (FA C and mainly facies C1). Electrofacies analysis suggests that debrites dominate the upper ~150 m of the Cenomanian succession in this well. Likewise, debrites are inferred to be present and relatively abundant in 6204/10-2A, although only the upper 20 m of the Cenomanian succession has been drilled in this location. For these two wells, the Cenomanian-Turonian contact represents an abrupt change from a debrite-dominated (FA C) to a slide-/slump-dominated (FA D) succession, which also appears to be defined by an abrupt decrease in gamma ray values at or near this boundary (Fig. 11).

On the north-eastern side of the Selje High (6204/10-1 and 6204/11-1), the upper part of the Cenomanian succession is debrite (FA C) and slide-/slump-dominated (FA D) (Fig. 11). However, for these two wells, the upper Cenomanian is located > 250 m from cored sections, at the edge of the window of study and the wireline logs do not reduce uncertainty in the interpretation of the lithology.

Turonian

The Turonian succession is characterised by an abrupt thickness change across the Selje High (Fig. 11). On the south-western side of the Selje High (left hand side of Fig. 11), this unit is thin and can be less than 50 m thick in places (see well 6204/10-2R). No cores are available from this unit on wells 6204/10-2R and 2A. On the north-eastern side of the Selje High (right hand side of Fig. 11), the unit reaches almost 350 m thick (see well 6204/10-1). The cores available from 6204/10-1 and 6204/11-1 sample the upper part of the Turonian succession.

Within 6204/10-1 (1994.14–1974 m) a ~20 m thick package of turbidite sandstone is present (FA A). Electrofacies analysis suggests that turbidite sandstones (FA A) dominate the upper ~100 m of the Turonian succession within this well (equivalent to the lower Kyrre Formation). The basal surface of this package highlights a change from slide and slump deposits (FA D) in the lower Turonian to turbidite sandstones (FA A) in the upper Turonian. Based on the interpretation of core data from 6204/10-1, showing a thick package of amalgamated sandstone beds with erosional bases (A1) and the presence of siltstone and claystone clasts (A2), we interpret that these sandstones were deposited in stacked submarine channel complexes. Each channel complex-fill is interpreted to be 20-35 m thick, and is bounded by thin packages (<5m) of slide/slump deposit (FA D) and debrite (FA C) (Fig. 11).

In 6204/11-1 (2158.25 - 2133 m) a ~17 m thick debrite-dominated package is developed (Fig. 11). Electrofacies analysis suggests that this package is ~100 m thick, and that the top and base of this unit are sharp. The base surface corresponds to the top of the Tryggvason Formation and represents an abrupt change from a slide and slump dominated succession (FA D) in the lower Turonian (Tryggvason Formation) to a debrite dominated succession (FA C) in the upper Turonian (lower Kyrre Formation). The top surface (near top Turonian) corresponds to an abrupt change to a slide- and slump-dominated succession (FA D).

On the south-western side of the Selje High, electrofacies analysis suggests that the Turonian succession is dominated by thin (1-5 m) packages of turbidite sandstones (FA A) and slide/slump deposits (FA D) (6204/10-2A and 6204/10-2R; Fig. 11). There are two interpretations for the origin of this succession: (i) it records the abrupt transition between deposits of cohesive and weakly cohesive flows; or (ii) that the sandstone-rich packages detected by the electrofacies analysis are very large clasts or rafts encased in slumps and slides.

Coniacian

The Coniacian succession is 100-150 m thick and broadly tabular (Fig. 11). Core data are available from all four wells and this allows us to more confidently use electrofacies analysis to constrain facies association types within this interval. On the south-western side of the Selje High, the lower part of the Coniacian succession is dominated by slide and slump deposits (FA D) (6204/10-2A; 2120.28-2105 m and 6204/10-2R; 1961.14-1951 m) (Fig. 11).

Electrofacies analysis suggests that from base to top of the Coniacian succession, the proportion of slide and slump deposits (FA D) decreases while the proportion of turbidite sandstone (FA A) increases.

On the north-eastern side of the Selje High, core data from 6204/11-1(2025.8-2016 m and 2016-2008 m) indicates a dominance of slide and slump deposits (FA D; dominantly facies D2) (Fig. 11). Electrofacies analysis predicts that the whole Coniacian succession is dominated by FA D. In contrast to the south western margin of the Selje High, almost no turbidite sandstone (FA A) is predicted to have been deposited on the north-eastern margin.

Within 6204/10-1 (1955-1948 m and 1899-1890 m), the cores are dominated by turbidite sandstones (FA A) (Fig. 11), which contrasts with the slide-/slump-dominated (FA D) Coniacian succession encountered 16.5 km away within 6204/11-1. The sandstone-bearing part of the Coniacian succession is interpreted to have been deposited in a series of stacked channels, similar to those encountered within the upper Turonian succession (in terms of thickness and dominant lithology). In the Coniacian, the two channel complex-fills are ~30 m thick and separated by a ~30 m thick unit dominated by FA D (slide and slump deposits). Both channel complexes have sharp base and top surfaces. Within the upper Turonian and the Coniacian succession, the channel complexes are poorly defined and are difficult to distinguish from the slides and slumps deposits using the gamma-ray log alone because of the high proportion of glauconite present in the succession. Only the combination of well logs and the use of electrofacies analysis allow the presence of stacked channels to be inferred. Electrofacies analyses allow the base and top of the different channel complexes to be more accurately constrained, and therefore to measure their thickness.

PREDICTING VERTICAL AND HORIZONTAL FACIES DISTRIBUTION AWAY FROM CORE DATA

To test the general applicability of the approach outlined here, the electrofacies defined from Quadrant 6204 are used on genetically related deposits penetrated by a borehole on the southern Måløy Slope (see well location on Fig. 1). Well 35/9-3 T2 penetrates Upper Cretaceous deep-water deposits at a similar burial depth (~2000 m) to those encountered on the northern Måløy Slope. Any variations in petrophysical characteristics between 35/9-3 T2 and wells further north are therefore not expected to be the result of variations in burial depth. 35/9-3 T2 contains a complete set of logs (i.e. density, resistivity, gamma ray, etc.) and an 18.6 m of core from the upper part of the Tryggvason Formation (1888.6–1870 m) (Fig. 12).

Core logging indicates that two facies associations are present, and are, from base to top: ~8 m of turbidite sandstone (FA A), ~5 m of debrite (FA C), and ~5 m of turbidite sandstone (FA A) (Fig. 12). The electrofacies analyses correctly predicted the lower and upper sandstone packages observed in core (Fig. 12). However, electrofacies analyses do not predict correctly the middle debrite (FA C) unit, which is instead interpreted as a unit of slide and slump deposits (FA D) (Fig. 12). FA C is recorded as the dominant facies association, although the three other facies associations (FA A, FA B and FA D) share a high proportion of the facies associations distribution for this interval (Fig. 12), indicating a lower level of confidence in the neural network prediction. The inability of electrofacies analysis to accurately predict the facies association in this interval can be attributed to a variation in the petrophysical characteristics due, for example, to a difference between facies from the lower Turonian (Tryggvason Formation), and from the upper Turonian and Coniacian succession (lower Kyrre Formation). The debrite unit observed in well 35/9-3 T2 is sedimentologically similar (in terms of average grain size, marice and clasts content) to the debrite units observed in the studied wells. We speculate that different sedimentary facies, with different source areas and hence different mineralogy, were deposited during the Turonian and during the Coniacian. Sømme et al. (2013) demonstrated that during Turonian time, several deep-water systems were more-or-less simultaneously active on the northern Måløy Slope, all sourced from different parts of the hinterland.

IMPACT OF GLAUCONITE ON ELECTROFACIES ANALYSIS AND FACIES PREDICTION

Detailed logging and thin sections analysis of the ~125 m of cores demonstrate a high proportion of glauconite (up to 30% in sandstone packages) throughout the upper Cretaceous succession, especially within some of the sandstone-rich intervals (see facies A1 in well 6204/10-1; 1890-1899 m). Glauconite is an iron potassium phyllosilicate mineral (mica group) that can influence the response of the logging tools within the formation (McRae, 1972; Rider and Kennedy, 2011), making the distinction between sand-rich intervals (reservoirs) and claystone-rich intervals (non-reservoirs) challenging. For example, the current study highlights that some sandstone-rich packages are locally characterised by a higher gamma-ray values than finer-grained intervals (for example between 1950 and 1930 m or 1900 and 1875 m in well 6204/10-1, Fig. 11). Also, because of its relatively high density, the presence of glauconite may cause an apparent decrease in porosity (Rider and Kennedy, 2011).

None of the logs available for this study can accurately determine the amount of glauconite present in a formation; only thin-section analysis or detailed logging of material recovered in core (or cuttings) would permit the proportion of glauconite to be established. However, spectral gamma ray logs can be used to demonstrate the presence of glauconite (Inwood et al.

2013). In the present study, the high proportion of glauconite throughout the Upper Cretaceous suggests significant uncertainty in the interpretation of lithology from the gamma-ray log (Fig. 11). Therefore, a combined log response is used to characterise each of the four facies associations (Fig. 5). Electrofacies analysis allows us to ignore the gamma-ray log signature of the radioactive glauconite and enhance the overall petrophysical characteristics of each facies association.

DISCUSSION

Our results indicate that the probabilistic curves generated by electrofacies analysis provide a relatively good prediction (X % success rate) of the facies and facies associations identified in core (Fig. 9, 11 and 12). Electrofacies analysis can therefore help predict facies and facies associations in uncored wells or uncored portions of wells.

Mass flow-dominated successions in the northern North Sea

The two dominant Upper Cretaceous facies associations predicted from electrofacies analysis are slide and slump deposits (FA D) with a proportion of ~60 % (pink colour in Fig. 11) and debrites (FA C) with a proportion of ~33% of the entire succession (green colour in Fig. 11). In 6204/10-1, only the upper Turonian and early Coniacian comprise appreciable quantities of turbidite sandstones (FA A), with ~175 m of stacked channels encased within a thick slide/slump (FA D) and debrite-rich (FA C) package. In 6204/11-1, the upper Turonian represents a ~100 m thick debrite unit that is sharply overlain and underlain by packages of slide and slump deposits (FA D). On the western side of the Selje High, no thick (< 50m) unit of turbidite sandstone (FA A) is directly observed or predicted by the electrofacies analyses (Fig. 11), and the entire succession is dominated by slide and slump deposits (FA D) and debrite (FA C).

Despite the apparent predominance of slide/slump and debrite deposits, the Upper Cretaceous succession does not have the classic seismic expression of an mass transport complex-rich stratigraphic succession, which is typified by packages of chaotic reflections (Bull et al., 2009; Moscardelli et al., 2006). Within the northern North Sea the apparent absence of chaotic seismic facies within the Upper Cretaceous interval might be because individual mass flow deposits, although volumetrically significant, may be individually too thin to be resolved in seismic data. In addition, stacked or amalgamated mass flow deposits may lack sufficient lithological variation at their contacts to generate strong seismic reflections.

The common occurrence of mass flow deposits on the Norwegian margin was first noted by Shanmugam et al. (1994, 1996), who examined ~3700 m of cores from the Cretaceous and Palaeogene succession to demonstrate the abundance of mass-transport deposits emplaced by sandy slumps, slides, and debris flows. Detailed work on the Agat discovery, which is located in the vicinity of the current study area (Fig. 1), suggested a debrite and slump-dominated, upper slope environment during the Lower Cretaceous. The Upper Cretaceous succession studied here is interpreted to have been deposited in relatively proximal deep-water environments, located down-dip of a narrow (~20 km) shelf (Martinsen et al., 2005; Sømme et al., 2013) in a similar location to the successions studied by Shanmugam et al. (1994, 1996). During the Cretaceous, the narrow shelf was ~200 km long, extending from the Måløy Slope in the south to the Slørebotn sub-basin in the north. North and south of this area, the shelf was much wider (100-160 km) (Martinsen et al., 2005). Canyons that incise into narrow shelves can remain active and feed coarse-grained sediment to deep-water systems at all sea level stands (Covault et al., 2007), favouring instabilities on the slope.

This study shows that there are more mass transport deposits in the Upper Cretaceous stratigraphy than is apparent from seismic data alone. Further work, which integrates seismic reflection, core and electrofacies data, is needed to constrain the lateral and vertical extent of slide, slump and debrite deposits in the Upper Cretaceous succession, and to investigate the reasons for the susceptibility of the Måløy Slope area to mass flow behaviour in more detail.

Reservoir occurrence within the Upper Cretaceous stratigraphy

Electrofacies analyses demonstrate that, on the northern Måløy Slope, much of the upper Cretaceous succession (>90% of the studied interval) is dominated by slump and slide deposits (FA D) and debrites (FA C) characterised by very low or non-reservoir quality (Fig. 11). However, the thick (~175 m) stacked channels unit penetrated by 6204/10-1 has good reservoir quality (dominance of FA A). In the future, 3D seismic reflection data analysis could be integrated with borehole analysis to shed light on the 3D geometry of the channel complex observed in 6204/10-1, and to help constrain reservoir quality away from borehole. The recognition of the various depositional environments away from well data is a step toward a better understanding of the reservoir commonality during Upper Cretaceous time.

It is important to note the apparent lack of fine-grained and thin-bedded deposits in the ~600 m thick Upper Cretaceous deep-water succession (absence of FA B - blue color on Fig. 11). The electrofacies analysis is calibrated based on the cored intervals that targeted sandstone horizons. No interval of claystone was cored and therefore the petrophysical properties of this lithology in this location can only be estimated and cannot be used to train the neural network. Moreover, only a limited amount of other types of fine-grained deposits (FA B-heterolithic sandstones and siltstones) was cored resulting in a poorly defined petrophysical signature. Slide and slump deposits (FA D) have a relatively similar petrophysical signature to fine-grained deposits (FA B), and the differentiation between those two facies associations is challenging. It is possible that a proportion of the succession interpreted here as slump and slide deposits actually represent units of in place fine-grained deposits. To reduce this uncertainty, cores sampling fine-grained packages (from claystone and heterolithic sandstones and siltstones packages) need to be included in further studies. The cores need to come from a succession sharing a similar burial history (~2000 m) to have comparable petrophysical properties, and also share a similar sediment provenance source to have comparable mineralogy to the studied succession.

CONCLUSIONS

The aim of the current study was to use electrofacies logs to improve understanding of the distribution of facies associations through a late Cenomanian-Coniacian deep-water succession across the northern Måløy Slope. Locally, the interval of interest is glauconite-rich, which inhibits the simple application of traditional well logs to distinguish sand-rich packages and fine-grained packages from other deposits, such as mass flow deposits. Based on four cored wells and a suite of well logs, the study demonstrates that facies associations can be predicted accurately in a stratigraphic and geographic direction using electrofacies analysis. The methodology developed here can be used in more limited datasets, for example in sub-salt or sub-basalt sedimentary successions, to help determine the lithological distribution where seismic resolution is commonly poor and well data more widely available.

Electrofacies logs are calibrated with cores to extrapolate stratigraphic changes in environment of deposition throughout the succession of interest. Each facies association is characterised by a unique combination of petrophysical characteristics (Fig. 4).

Extrapolation of electrofacies to well 35/9-3 T2, demonstrates that turbidite sandstones (FA A) holds similar petrophysical characteristics over long distances and that sandstone packages can be predicted accurately away from data constraint. However, discrepancy exists for the prediction of other facies associations, such as debrites (FA C) and slide and slump deposits (FA D). This discrepancy is attributed to different petrophysical properties between the two localities which could reveal a different sediment source and hence mineralogy for both areas.

Results demonstrate that the late Cenomanian-Coniacian succession is characterised by a dominance of mass flow deposits, which are commonly poorly imaged in seismic datasets within the northern North Sea. A predominance of mass flow deposits across the succession can be explained by the existence of a narrow shelf and a proximal location within the basin.

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FIGURES:

Figure 1: Location map of the study area with inset map showing the location of the study area in relation to Norway. Wellbores 6204/10-2A and 2R are located on the western flank of the Selje High. The location of the Agat discovery is indicated (after Skibeli et al., 1995).

Figure 2: Simplified stratigraphic column through the study area indicating the interval of interest (thick black line) and the stratigraphic location of key biostratigraphic markers. Similar coloured horizons are used in figure 11.

Figure 3: Sedimentary facies association FA A ‘sandstones’, consisting of four sedimentary facies named A1 to A4. a) A1, structureless thickly bedded coarse-grained sand. b) A2, structureless sandstone with siltstone and claystone clasts. c) A3, structureless to parallel laminated fine-grained sandstone. d) A4, fine-grained and coarse-grained clastic injectites. Core photograph, sedimentary log and thin section are shown for sedimentary facies A1 to A3. Keys for sedimentary log are shown in c). Red line on core indicates the location of the thin section. Two examples of sedimentary facies A4 are shown with core photograph and line drawing.

Figure 4: Histograms of the distribution of porosity, density, gamma-ray, sonic and resistivity values for the four sedimentary facies associations: FA A (sandstones), FA B (heterolithic sandstones and siltstones), FA C (debrites) and FA D (slump and slide deposits). Note that the vertical axis varies between each histogram. The summary line shows the four sedimentary facies associations in the same histogram and illustrates that each sedimentary facies associations can be characterised by a unique set of petrophysical parameters.

Figure 5: a) Core gamma vs. core sonic and b) Core gamma vs. core density for the four sedimentary facies associations: FA A (sandstones), FA B (heterolithic sandstones and siltstones), FA C (debrites) and FA D (slump and slide deposits). Note that each sedimentary facies associations tend to plot in a distinct cluster (shaded area) with however some scattered points plotting away from this cluster.

Figure 6: Sedimentary facies association FA B: heterolithic siltstones and sandstones consisting of two facies named B1 and B2. a) B1, finely laminated siltstone. b) B2, bioturbated interbedded thin siltstone and sandstone. Both sedimentary facies are illustrated with a core photograph and a typical sedimentary log. Note that the sedimentary log does not represent the core photograph. For colour scheme, see figure 3.

Figure 7: Sedimentary facies association FA C: debrites. a) C1, muddy sandstone with clasts. b) C2, sandstone with limestone clasts and C3, silty sandstone with limestone clasts. Core photograph, sedimentary log and thin section are shown for each sedimentary facies. Note that the sedimentary log does not represent the core photograph in a).

Figure 8: Sedimentary facies association FA D: mass flow deposits with core photograph and line drawing for sedimentary facies D1 and D2. Core photograph and thin section are shown for each sedimentary facies. a) D1, folded and deformed sand-rich strata. The thin section shows the typical mineralogy assemblage of a sandstone clast. b) D2, folded and deformed silt-rich strata. The thin section shows in the upper part (dark colour) a large clay intra clast and in the lower part (white colour) a glauconitic sandstone clast. For colour scheme, see figure 3.

Figure 9: Composite log illustrating the methodology used in the current study. a) Log curves including the density, gamma ray, caliper, density and neutron log. Note the very similar log response to various sedimentary facies and facies association. b) Extrapolation of electrofacies distribution at the facies scale. From left to right, the first column indicates the various sedimentary facies observed within the core; the second column the proportion (out of 100%) of each sedimentary facies predicted to be present at a certain depth; the third column shows the dominant facies, which represents the sedimentary facies that has the highest chance to be present at each depth. c) Extrapolation of electrofacies at the facies association scale. The columns are similarly laid out than in b). d) Corresponding core log.

Figure 10: a) Porosity vs. depth and b) density vs. depth for the four facies associations. All data points are from core plugs. Note that the porosity decreases with depth while the density increases with depth.

Figure 11: Correlation panel between the four wells of interest: 6204/10-2A, 6204/10-2R, 6204/10/1 and 6204/11-1. Each well shows the gamma-ray log curve for reference, and the facies association prediction across the Cenomanian-Coniacian succession, including the core available and logged, the proportion (out of 100%) for each sedimentary facies association to be present and finally, the dominant facies association present at this depth. Note the dominance of debrite (FA C – green colour) and slump and slide deposits (FA D – pink colour on the logs) across the succession of interest. The background grey colour illustrates the quality of the reservoir with dark grey representing good reservoir and light grey representing average to low reservoir quality. The shaded sections of the logs (Santonian time) are discarded as located outside of the study interval (Cenomanian-Coniacian time).

Figure 12: Log curves and electrofacies interpretation for well 35/9-3 T2. The interval of interest is the Tryggvason and lower Kyrre Formation, where one core from the upper part of the Tryggvason Formation has been logged in detail. No biostratigraphy is available for this well. Note the correct prediction of the packages of turbidite sandstone (FA A) present in the core with the electrofacies. Note the discrepancy between the middle unit of debrite (FA C) observed in the core, predicted as a unit of slide/slump deposits (FA D) with electrofacies.