Role played by clay content in controlling reservoir quality of submarine fan system, Forties Sandstone Member, Central Graben, North Sea

Abdulwahab Muhammad Bello[a*], Stuart Jones[a], Jon Gluyas[a], Sanem Acikalin[b], Matthieu Cartigny[c]

[a] *Department of Earth Sciences, Durham University, South Road, Durham DH1 3LE, UK*

[b] *School of Natural and Environmental Sciences, University of Newcastle, Newcastle upon Tyne, NE1 7RU*

[c]*Department of Geography, Durham University, South Road, Durham DH1 3LE, UK*

*Corresponding author

email address: abdulwahab.m.bello@durham.ac.uk

Abstract

Proximal to distal fan change in grain size, clay matrix content, and grain-coating clays have been identified as key contributing factors for reservoir quality evolution of submarine fan turbidite sandstones. This study evaluated the role played by grain-coating and pore-filling clays, depositional facies, and diagenesis in reservoir quality evolution of the Paleocene Forties submarine fan sandstones (Central North Sea) from proximal to distal fan settings. To help provide a comprehensive understanding of the role played by pore-filling and grain-coating clays in destroying and preserving reservoir quality, respectively, in turbidite sandstones, we have used a multi-disciplinary approach including petrography, burial history, scanning electron microscopy, and stable isotopes analysis. Results of the study showed that reservoir quality is influenced by both depositional facies and diagenesis. The proximal-fan, amalgamated sandstones facies have the best reservoir quality due to coarser grain size, lower pore-filling clays, and lower amount of ductile grains. In contrast, the distal-fan, mud-prone heterolithic facies have the poorest reservoir quality due to finer grain size, higher pore-filling clays, and higher amount of ductile grains. Pore-filling clays between 10 and 30 % have a deleterious effect on reservoir quality, reducing porosities and permeabilities to generally < 10 % and < 1 mD, respectively. Based on the relatively shallow, present-day burial depths of the studied Forties Sandstone Member (2200-3100 m TVDSS), the percentage of clay-coating coverage to significantly inhibit quartz cementation ranges from 40 to 50 %. Detrital, grain-coating smectites, probably inherited from the shelf/continental environments and/or emplaced through sediment dewatering, have transformed into chlorite, illite, and illite-smectite. Calcite and siderite, where well-developed, have arrested mechanical compaction and also occluded

porosity, thereby rapidly degrading reservoir quality in the sandstones; however, their dissolution by acidic pore fluids could potentially create secondary intergranular porosity, enhancing reservoir quality of the sandstones. Evidence presented demonstrates that, high quality reservoir sandstones that deviate from normal porosity-depth trends for submarine fans sandstones can be attributed to facies changes (composition and grain size) with a complex interplay of mechanical compaction, detrital clays and authigenic clay coatings inhibiting quartz cement precipitation.

1. Introduction

Understanding of the distribution of diagenetic processes and products is of major importance for the characterisation of quality and overall heterogeneity of clastic reservoirs (Ma et al., 2017; Morad et al., 2010, 2000). In general, the influence of diagenesis in clastic turbidite reservoirs is relatively poorly understood and believed to be mostly mediated by marine pore waters (Bjorlykke and Aagaard, 1992; Dutton, 2008; Mansurbeg et al., 2008). In the past decades, offshore hydrocarbon exploration has been increasingly concentrated in marine turbidite sandstone reservoirs (e.g. Chudi et al., 2016; Marchand et al., 2015; Porten et al., 2019, 2016). More recently, the need to better understand reservoir quality has become paramount for carbon capture and storage (CCS) projects, where turbidite sandstones are potential storage sites that require a comprehensive understanding of their reservoir properties, facies distribution and migration pathways prior to any CO_2 injection (Xia and Wilkinson, 2017).

The Paleocene turbidite sandstones of the Central North Sea contain about half of the total recoverable oil reserves within the region (2.99 billion barrels), with estimated reserves of approximately 6.01 billion barrels (Brennand et al., 2009). Therefore, quantitative evaluation of the sandstones reservoir quality is crucial for understanding of reserve estimations and development of continued hydrocarbon production strategies (Chen et al., 2019; Marchand et al., 2015; Morad et al., 2010). Reservoir quality is strongly influenced by depositional parameters (e.g., primary sediment composition, grain size, sorting, and clay content, which constitute depositional facies) (Bell et al., 2018; Marchand et al., 2015; Porten et al., 2016; Stammer, 2014) and diagenetic alterations (Morad et al., 2010; Oluwadebi et al., 2018). Depositional parameters commonly have a significant impact on primary reservoir porosity and permeability and on early diagenetic processes (Porten et al., 2016). Diagenetic processes, which include mechanical compaction, cementation and mineral dissolution, can extensively affect the reservoir quality of sandstones. Numerous studies have focused on establishing the link between depositional sand quality [defined by Ehrenberg, (1997) as the combined impact of primary sediment composition, texture, and early diagenetic alterations, influenced by depositional environment controls on reservoir quality] and reservoir quality in deep-water turbidite sandstones (e.g. Bell et al., 2018; Lien et al., 2006; Marchand et al., 2015). Surprisingly, little has been published on the impact of diagenesis on reservoir quality evolution of the Paleocene deep-water turbidite sandstones of the Central North Sea (e.g., Mansurbeg et al., 2008; Stewart, 1995).

The Paleocene Forties turbidite sandstones are characterized by rapid variation in sedimentary facies, influenced by topography of older formations and salt-induced highs, causing significant variation in clay content (pore-filling) from proximal to distal fan (Collins et al., 2015; Hempton et al., 2005). The variation in clay content is common even within the same sedimentary facies, thereby affecting the reservoir quality of the sandstones. Clay minerals play a key role on diagenesis and reservoir quality of sandstones (Houseknecht and Ross, 1992; Stricker and Jones, 2018; Taylor et al., 2010). The amount, mode of occurrence and distribution patterns of clay minerals strongly influence sandstones reservoir porosity and permeability (Worden and Morad, 2003) . Quartz-rich sandstones which are clay-poor often lose significant intergranular porosity at deeper burial depths due to quartz cementation (Porten et al., 2016). Conversely, quartz-rich, clay-coated sandstones preserve porosity at deeper burial depths by inhibiting quartz cementation (Bloch et al., 2002; Heald and Larese, 1974; Pittman et al., 1992; Stricker, 2016; Stricker et al., 2016; Stricker and Jones, 2018). Grain-coating clay minerals such as chlorite and illite/illite-smectite can significantly enhance and preserve porosity in deeply buried sandstone reservoirs by reducing the nucleation sites available for the development of authigenic quartz cements on detrital quartz grains (Dos Anjos et al., 2000; Ehrenberg, 1993; Lander et al., 2008; Lander and Walderhaug, 1999; Stricker et al., 2016; Tang et al., 2018). Porosity can be at least 10% higher than anticipated where grain-coating clays are well-developed on detrital grains (Wooldridge et al., 2017). However, pore-filling detrital and authigenic clays can destroy reservoir quality by occluding intergranular pores and bridging pore-throats (Oluwadebi et al., 2018).

In this study, we investigate the effect of pore-filling and grain-coating clays on deep-water sandstones porosity and permeability evolution from Forties Sandstone Member, Central Graben, North Sea. Specific objectives are to determine the effects on reservoir quality of 1) grain size and clay content, 2) grain coating clays, and 3) diagenetic cements, and 4) compaction.

2. Geological background of the Forties fan

The Upper Paleocene Forties Sandstone Member of the Sele Formation has been recognised as a deep-water submarine fan system, hosting a significant number of producing fields in the North Sea Central Graben, including the Forties, Everest, Nelson, Pierce, Lomond and Mirren (see Hempton et al., 2005) (Figure 1). The Forties Fan system developed in response to the accumulation of clastic deltaic and shelf sediments, and it is situated to the north and west of the main depocenter (Bowman, 1998; Scott et al., 2010; Whyatt et al., 1992). Thermal doming associated with the Early Paleocene rifting of the Greenland and European plates initiated the uplift (up to 2 km) of Scottish Highlands and East Shetland platforms (Den Hartog Jager et al., 1993), causing more than 800 m drop in the relative sea level and a 90 km basinward regression (Davis et al., 2009). This led to intensified erosion of the uplifted igneous, metamorphic, and meta-sedimentary hinterland and the subsequent accumulation of extensive deltaic and shallow marine sediments on the basin margin. The resulting high sedimentation rates and steep basin margins created unstable delta fronts with frequent slope failures, delivering large volumes of sediments into the basin by a combination of turbidity currents and debris flow processes along the main NW-SE graben axes (Charles and Ryzhikov, 2015). A regional 3D seismic study by Kilhams et al. (2014) has shown that there are two principal sediment routes into the Central Graben: a NW to SE oriented axial system along the graben, and a west to east trending lateral system crosscutting the axial system (Figure 1). The primary NW-SE sediment route, which was sourced in the Outer Moray Firth, forms the axial Forties Fan and serves as the principal reservoirs in the Forties, Everest, Nelson, Montrose, Arbroath, Arran, Pierce, and Blane fields (Figure 1). The secondary lateral fans systems, sourced from the west, form the reservoirs in some fields, including Bittern, and Gannet, which also extend as far east as Merganser and Scoter fields in the Central Graben (Hempton et al., 2005) (Figure 1). The distribution of the Sele Formation gravity flows were primarily controlled by local reactivation of the Palaeozoic and Mesozoic faults due to uplift (Eldrett et al., 2015), local-scale bathymetric relief at diapir crests (Davis et al., 2009; Davison et al., 2000; Hempton et al., 2005), and relief associated with the deposition of the earlier, Danian–Selendian-aged Maureen and Lista Formations (Mudge, 2015). Figure 1B shows GR logs demonstrating reservoir lithologies, sand thicknesses in some selected wells, and change in grain size from proximal to distal fan of the axial Forties system.

2.1. Stratigraphy

The lithostratigraphic framework of the Palaeogene Central North Sea has been well established by Deegan and Scull (1977), and further refined using biostratigraphic techniques (Knox and Holloway, 1992; Neal, 1996; Vining et al., 1993) and seismic reflection data (Eldrett et al., 2015). Three major depositional cycles of deep-water sedimentation occurred in the Central North Sea during the Paleocene to Early Eocene (Kilhams et al., 2014), with each cycle representing a period of relative sea level lowstand, which enabled routing of sediments from the shelf to the basin floor (Jennette et al., 2000). The earliest stratigraphic units are the Maureen Sandstone Member of the Maureen Formation (c. 63 to c. 59.8 Ma) (Figure 2). The Maureen and the overlying Lista Formations constitute the first and second deep-water depositional cycles, respectively. The two formations constitute the Montrose Group (Mudge and Copestake, 1993). Stratigraphically lying above the Montrose Group is the Moray Group, which consists of the Sele Formation (c. 56.8–54 Ma) and the Balder Formation, and constitutes the third depositional cycle. Sedimentation during the Sele deposition was dominated by submarine fan systems and/or phases of submarine fan systems that covered a large part of the Central Graben.

The depositional architecture and facies distribution are interpreted to have been influenced by basin configuration, palaeo-topographic highs, and salt diapirs (Den Hartog Jager et al., 1993; Eldrett et al., 2015; Hempton et al., 2005; Scott et al., 2010). The Forties Fan system is a restricted, sand-rich fan within the Central Graben, forming an elongate depositional system that lacks classical 'fan' morphology (Scott et al., 2010). The palaeo-highs and highs developed by salt diapirs constrained and funnelled flows from proximal to distal fan, resulting in channelization and slumping (Eldrett et al., 2015; Hempton et al., 2005), with channels and channels facies often persisting to the fringes of the fan system (Collins et al., 2015; Kessler et al., 1980; Thompson and Butcher, 1990). Salt withdrawal in medial to distal fan settings (e.g., Pierce field) decreased the velocity of sediment gravity flows (Scott et al., 2010), confining and depositing sediments in a mini-basin fill and spill fashion.

Although the biostratigraphic analysis of the Sele Formation is characterised by limited faunal abundance and diversity due to high sedimentation rates and basin restriction, four distinct sandstone members have been identified within the formation based on palynology (Eldrett et al., 2015). These include the Forties, Bittern, Cromarty and Gannet Sandstone Members (Figure 2), which are discrete fan systems or phases of fan deposition. Restricted to the Central Graben, the Forties Sandstone Member of the Sele Formation is the most areally extensive (300 km by 100 km) and thickest discrete fan (over 200 m) (Eldrett et al., 2015; Hempton et al., 2005). The sandstone has been described as the product of relatively rapid deposition of a mixed sand and mud sequence by turbidity currents and hemipelagic mud (Collins et al., 2015; Jones et al., 2015). By the end of the Paleocene, a regional, basinal mudstone of the Sele Formation was deposited in response to a sea level rise. These fine-grained sediments act as a regional seal to the Forties Sandstones reservoirs (Whyatt et al., 1992). This study focuses on the proximal through to distal parts of the axial Forties Fan (Figure 1), dominated by channels and submarine fan lobes.

3. Samples and methodology

3.1. Sedimentary facies

In this study, we established sedimentary facies based on core descriptions. We examined a total of 266 m of cores from thirteen (13) wells in six (6) oil and gas fields from the proximal to distal parts of the axial Forties Fan system (Figure 1). The results of the sedimentary core descriptions are presented in section 4.1.

3.2. Petrography and stable isotope analysis

A total of one hundred and ninety-one (191) representative sandstone core samples of the Forties Sandstone Member were collected for analysis. Based on sedimentary characteristics, samples were collected from key facies, from proximal to distal settings. Each sample was impregnated with blue epoxy for identification of porosity and stained with alizarin red and potassium ferricyanide for carbonate cement identification. The samples were examined using a Leica DM2500P standard petrographic microscope. Modal point count analysis using 300 counts per thin section was conducted on all the samples to determine the percentage of detrital grains, clay matrix content, pore-filling and grain-coating cements, and porosity (both primary intergranular and secondary intragranular). Grain size and sorting were determined by measuring the long and short axes of 100 grains per thin section using the Petrog and ImageJ software packages, and then calculating the average value for each sample.

For detailed analysis of sandstone microstructure, clay mineral composition, morphology and distribution, selected diamond-polished, carbon-coated thin sections were studied using a Hitachi SU70 scanning electron microscope (SEM) equipped with a backscatter electron detector (BSE) and an energy dispersive X-ray spectra (EDS) under acceleration of 12-15 kV.

Stable isotope analysis for carbon and oxygen isotopes were conducted on 18 sandstones samples with variable amounts of carbonate cements, consisting of calcite (ferroan and non-ferroan), dolomite, and siderite. Based on carbonate content, bulk samples were powdered (< 200 mesh), and each sample was weighed out to give a CO_2 signal of 12mV, and was reacted with 99% ortho-phosphoric acid for 2 hours at 70^{o}C. The resultant gas mix of helium and CO_2 was then separated and analysed via a Thermo Fisher Scientific Gasbench II interfaced with a Thermo Fisher Scientific MAT 253 gas source mass spectrometer for isotopic analysis. Duplicate analysis of 3 samples yielded a precision of <± 0.1 ‰ for both δ^{13}C and δ^{18}O, with one sample having a slightly higher standard deviation of ± 0.2 for δ^{13}C. All standards yielded an analytical reproducibility of <± 0.1 ‰ standard deviation for both δ^{13}C and δ^{18}O. All values have been normalised to the accepted values of +2.49‰VPDB and -46.6‰VPDB for δ^{13}C, and -2.40‰VPDB and -26.70‰VPDB for δ^{18}O, for both IAEA-CO-1 and LSVEC respectively. Data are reported in standard delta notation as per mil (‰) relative to Vienna Pee Dee Belemnite (V-PDB).

Porosity and permeability (poroperm) datasets for a total of one hundred and sixty-seven (167) core sampled were supplied by UK common data access (CDA). Porosity measurements were made using helium in a Boyle's Law porosimeter to give grain volume. Air permeability measurements were conducted using oxygen-free nitrogen as the flowing fluid with the plug mounted in a Hassler cell under a routine confining pressure of 200 psi.

3.3. Clay-coating coverage measurements

Clay-coat coverage was measured on 50 selected thin sections using the JMicrovision (v. 1.3.3) software. The samples were selected based on high and low volume of grain-coating chlorite and illite/illite smectite determined from thin-section point counts. Volume of grain-coating clays in the samples ranges from 0.30 to 10.70 % of the whole rock volume, averaging 4.63 %. Clay-coat coverage was measured on 50 randomly selected quartz grains in each thin section using montaged SEM/BSE images and high-resolution photomicrographs as used by Wooldridge et al. (2019) and Dutton et al (2018), respectively. The measurements were carried out based on the procedure described by Dutton et al (2018).

3.4. One-dimensional burial history modelling

1-D basin modelling was carried out using Schlumberger's Petromod (V.2015) software to determine the burial and thermal history of the Forties Sandstone Member in the proximal and distal fan. Two wells (Nelson-22/11-6 and Blane-30/03a-1) were selected to represent proximal and distal fan respectively and to show the differences in their burial and thermal history (Figure 3). The one-dimensional burial history models were constructed using input data from well completion reports provided by the UK CDA. The data include the present-day well stratigraphy, lithologic descriptions, and wireline-logging-derived bottom hole temperature (BHT). BHT corrections were applied using the equation and method developed by Waples et al. (2004). The BHT correction is mainly based on time since end of mud circulation (TSC) and, to a smaller degree, on depth. Information on TSC, surface temperature, measured log temperature, and measurement depth are input into the equation to calculate the corrected temperature. Paleo-basement heat flow model and paleo-surface temperature history have been adopted from Swarbrick et al. (2000).

4. Results and interpretations

4.1. Sedimentary lithofacies

Seven core facies and three sub-facies were identified using a depositional, process-based facies scheme (Figure 4A-I). The subdivision is mainly due to minor differences in depositional processes within the main facies. The facies consist of thick, structureless sandstones (Figure 4A), dewatered sandstones (Figure 4B), interbedded sandstones (Figure 4C), parallel laminated sandstones (Figure 4D), wavy laminated sandstones (Figure 4E), slump sandstones (Figure 4F), sand injections (Figure 4G), laminated mudstones (Figure 4H), and hemipelagic mudstones (Figure 4I). Table 1 shows description of the facies grain size, bed thicknesses, main features, depositional processes, and environments of deposition. The facies classification was based on the Bouma turbidite facies model (Bouma, 1962) and the low- and high-density turbidite facies of Lowe (1982).

4.2. Lithofacies associations

Core lithofacies were grouped into three predominant depositional facies associations based upon the previous interpretations of the Forties Fan's architectural elements and depositional facies schemes of Collins et al. (2015) and Kunka et al. (2003) for proximal to distal fan settings.

4.2.1. Amalgamated sandstone facies association

This facies association consists of stacked, thick-bedded (beds with thicknesses from 2.5 to 100 cm), structureless, and dewatered fine- to medium-grained sandstones (Figure 5A). This facies association, which form 44 % of the studied cores, is characterized by amalgamated beds, commonly identified by shifts in grain size and minor scour surfaces that form relatively homogeneous sand packages. Minor amounts of dark, silty claystone rip-up clasts are commonly incorporated into the basal sections of the sandstone beds.

Although the individual beds are generally homogeneous in grain size, they occasionally exhibit a subtle upward-fining profile. Individual bed thickness typically ranges between 60 and 100 cm, while the composite amalgamated sandstone bodies in the Nelson Field are up to 600 cm thick. Amalgamated sandstone deposits exhibit high net to gross (total sand/total interval), with a total sandstone thickness exceeding 2500 cm in the Nelson field areas (Figure 5A). The GR log curve of single channel sandbody exhibits box-shaped appearance in the Nelson field (Figure 1B). These facies associations are capped by lower-energy, channel abandonment facies consisting of thinly bedded turbidites (Sp), slumps (Sl) and muddy debris flows deposits or abandonment claystone/shale.

The amalgamated sandstones facies associations are interpreted as products of high-density turbidity currents, probably confined to submarine channels, in which sediments are supported by buoyancy, grain collisions and fluid turbulence (Lowe, 1982; Talling et al., 2012). They are deposited from rapid fallout of sediments from confined high-density flows, and because of the high suspended load fallout rates, the sediments had insufficient time to be reworked by traction currents on the beds, resulting in the deposition of thick, structureless sand (Middleton and Hampton, 1973; Talling et al., 2012). The rapid deposition of sand from a turbulent flow leads to entrapment of abundant fluids between sand grains, and during the early stages of bed compaction (due to the deposition of the overlying parts of the same bed), the entrapped excess pore fluid escaped and formed water escape pipes (Figure 4A) (Lien et al., 2006). The amalgamated sandstones facies associations, therefore, are suggested to be deposited in submarine channel and proximal lobe (Huang et al., 2020; Porten et al., 2016).

4.2.2. Sand-prone heterolithic facies association

Forming 24 % of the studied cores, the sand-prone heterolithic facies association comprises structureless (and often dewatered), fine to medium-grained sandstones, interbedded with siltstones and mudstones (Figure 5B). The sandstones are similar to those of the amalgamated sandstone facies, but with decreased bed thicknesses and increased mud content (Figure 1B; Arran-23/16c-8). The sandstones are typically less well-sorted than the amalgamated sandstone facies and are fine-medium grained (Figure 5B). They are characterized by laminated argillaceous mudstones forming bed tops and discrete interbeds with the sandstones (Figure 5B). The argillaceous bed tops and interbeds mostly form gradational and sharp-based contacts with the underlying structureless and/or dewatered sandstones, respectively.

The sandstone beds range in thickness from 15 cm to *c*. 70 cm, with an average of 40 cm. The interbedded argillaceous sandstones, shale drapes, and silty mudstones range from 10 to 30 cm. The argillaceous sandstones contain injection and slump features and mud clasts.

The structureless sandstones in these facies are interpreted predominantly as deposits of high-density turbidity currents that are overlain by, or grade into, linked debrites (Haughton et al., 2003; Talling et al., 2004), whereas the finer-grained rippled or parallel-laminated bed tops were interpreted as products of low-density turbidity currents (Lowe, 1982; Talling et al., 2012), with localized turbiditic and/or hemipelagic shale drapes. The sandstone beds represent individual depositional units, separated by low-energy bed tops, which markedly indicate the interbedded nature of the non-amalgamated sandstones (Collins et al., 2015).

These facies are interpreted to have been deposited in the lobe off-axis depositional environment (Bell et al., 2018; Huang et al., 2020), and the transition from amalgamated sandstones to non-amalgamated sandstones could occur within a single depositional lobe, both laterally lobe off-axis and longitudinally down-flow (Collins et al., 2015). Their abundance decreases from proximal to distal fan.

4.2.3. Mud-prone heterolithic facies association

The mud-prone heterolithic facies association forms 25 % of the total studied cores, and predominantly consists of mudstones, silty mudstones, siltstones, and very fine- to medium-grained sandstones (Figure 5C). The sandstones are thinly-bedded, very fine- to fine-grained, parallel- and ripple-laminated, with slump deposits in some cases (Figure 5C). However, unlike in the amalgamated sandstones and sand-prone heterolithic facies associations, the structureless, relatively clean sandstones in the mud-prone heterolithic facies are thinner, the thickest units being less than 50 cm. Furthermore, discrete sand beds are characterized by sharp, non-erosional bases and gradational bed tops (Figure 5C).

The structureless sandstones in this facies association are interpreted as deposits of high-density turbidites which transform into, or are sharply overlain by, linked debrites. These are of relatively lower energy, however, than the sandstones of the preceding facies associations. The laminated, heterolithic sandstones, which may be locally slumped and deformed, were formed by low-density turbidity currents, and are equivalent to the type 7 event beds of Davis et al. (2009). Although the likely origin of the silt-mud lamination in this heterolithic packages is somewhat poorly understood, the planar lamination is thought to have formed by a process that sorts silt and very fine sand from mud (Talling et al., 2012). The parallel laminated siltstone/mudstone interval suggests a weak, lower flow regime traction process, which leads to the formation of the individual laminae (Lowe, 1982). The laminated siltstones, therefore, indicate deposition from a relatively weak and dilute turbidity current that might be comparable to the Td subdivision of Bouma (1962) or TE-1 subdivision of Talling et al. (2012). The laminated mudstones, on the other hand, are thought to indicate a transition to an overlying hemipelagic and pelagic sedimentation (Lowe, 1982), which form the mudstones of the equivalent to the Te subdivision of the Bouma (1962), and indicate sediment settlement from suspension.

Overall, the mud-prone heterolithic facies abundance increases from proximal to distal fan, and are thought to have been deposited in a lobe off-axis and lobe margin areas, on the margins of the coeval depositional fairway (Bell et al., 2018; Collins et al., 2015; Huang et al., 2020).

4.3. Petrology

4.3.1. Sandstone composition

The Forties Sandstone Member mainly consists of arkose to subarkose and rarely lithic arkose sandstones (Figure 6A). The average, present-day framework composition of the sandstones is $Q_{69}F_{27}R_4$. Sorting ranges from moderately to well sorted. Quartz grains are mainly monocrystalline, whereas polycrystalline quartz, which is counted as a rock fragment on the QFR plot (Figure 6A), occurs as trace to up to 6 %. Microcline and orthoclase are the two types of detrital potassium feldspars present. Overall, potassium feldspar predominates over plagioclase feldspar. The rock fragments consist of metamorphic, polycrystalline quartz, mudclasts, and volcanic fragments. The detrital mica occurs in variable amounts, with biotite dominating over muscovite. Accessory minerals consist of glauconite and heavy minerals (e.g., rutile). The detrital clay matrix is composed of smectitic, mixed-layer clays (mainly illite-smectite), with moderately high birefringence and greenish to brown in color (Figure 6B, C & D) (Shaw and Conybeare, 2003; Ulmer-Scholle et al., 2015). The smectitic clays also occur as moderately high birefringent and greenish to brown grain coatings (Figure 6E). (Ulmer-Scholle et al., 2015).

4.4. Grain size and clay content

Variations in grain size and clay content were observed among all the studied samples of the established reservoir facies associations from proximal to distal fan. Amalgamated sandstones facies, from submarine channels and proximal lobes, are fine- to medium-grained (mean grain size 0.25 mm) (e.g., Figure 7A), with less detrital clay matrix that ranges from 0.3 to 28 % (average 7 %). Figure 7A shows a representative sedimentary core log for the amalgamated sandstones facies in well 22/11-8 (Nelson field), with vertical mean grain size profile (Figure 7B), mud content (Figure 7C), and samples of thin-section photomicrographs (Figure 7D & E). Samples with finer grain size (Figure 7B) have higher pore-filling, detrital clay content (Figure 7C & D), whereas samples with coarser grain size have less pore-filling, detrital clay content (e.g., Figure 7E).

The minor channel margin facies association are coarse silt to fine sand (mean grain size 0.10 mm), with detrital clay matrix ranging from 3.3 to 21.5 % (average 12 %)

Sand-prone heterolithic facies are predominantly fine grained (average grain size 0.19 mm) (e.g., Figures 5B & 8A), with clay matrix content ranging from 5 to 27 % (average 11.5 %). A representative sedimentary core log for sand-prone heterolithic facies association in well 23/16c-8 (Arran field) (Figure 8A) shows that, a decrease in grain size (Figure 8B) leads to an increase in pore-filling detrital clay content (Figure 8C & D). A coarser grain size has lesser clay content (Figure 8E).

Mud-prone heterolithic facies associations are very fine- to medium-grained (average grain size 0.17 mm), and are interbedded with mudstones, silty mudstones, and siltstones (e.g., Figures, 5C & 9A). Vertical mean grain size and mud content profiles (Figure 9B & C) show that there is an increase in pore-filling clay matrix with lower grain size (Figure 9D) and vice versa (e.g., Figure 9E). This facies association is characterized by abundant, greenish-brown clay matrix (e.g., Figure 6B), ranging from 0.3 to 44 % (average 15 %).

A plot of detrital, pore-filling clay content against mean grain size (Figure 10A) shows that, there is an increase in clay content with decreasing grain size from proximal to distal Forties Fan system. Additionally, ductile grain contents, consisting of mica and mudclasts, have been found to increase with decreasing grain size from proximal to distal fan (Figure 10B).

4.5. Diagenetic processes

The diagenetic processes affecting the Forties Sandstones Member include mechanical compaction, cementation (clay minerals, quartz overgrowth, carbonate cements), dissolution and replacement of unstable detrital grains by clay minerals, pyrite, and carbonate cements.

4.5.1. Mechanical compaction

Calculation of porosity loss by compaction and by cementation was performed following the criteria described by Lundegard (1992). Intergranular volume (IGV) was calculated using the method of Paxton et al. (2002). However, sandstones with > 10 % matrix content and > 40 % combined volume percent of cement and intergranular porosity were excluded from the calculation of the porosity loss, as they are susceptible to intense compaction and displacive or replacive cementation, respectively (Lundegard, 1992). One major source of uncertainty in the calculation of porosity loss by compaction and by cementation is the initial depositional porosity of the sediments, with high estimated initial porosity resulting in high calculated compactional porosity loss (Lundegard, 1992). In addition, the initial depositional porosity of sediments has been liked to sorting, with very well- to well-sorted sands having depositional porosities > 40 % Pryor (1973). The studied Forties sandstones, however, are moderately to well sorted, and the initial depositional porosities of 36 and 43 % have been reported in the literature (Allsop, 1994; Whyatt et al., 1992). Consequently, an average of 40 % initial depositional porosity was used. The plot of porosity loss due to compaction against porosity loss due to cementation demonstrates that porosity loss is primarily driven by compaction (Figure 11).

Furthermore, the extent of compaction in the Forties Sandstone Member was assessed based on burial history plots (Figure 3A & B), petrographic observation of grain contacts, grains rearrangements and fracturing, ductile deformation of grains (mica, mudclasts, and rock fragments), and extent of carbonate cementation. Although the burial history plots of the

Forties Sandstone Member in proximal and distal fan are similar, sandstones in the distal fan have suffered higher impact of mechanical compaction due to greater burial depths (Figure 3B) than those in the proximal fan (Figure 3A). Grain contact consists of point, long, concavo-convex, floating, and ductile deformation (Figure 12A-D). While the impact of mechanical compaction in sandstones with point, long and floating grain contacts is low (Figure 12A & B), sandstones with concavo-convex and ductile deformation have suffered moderate to high impact of mechanical compaction, respectively (Figure 12C & D). Even though sandstones with floating-grain contacts (due to early, blocky carbonate cementation; Figure 12B) show less impact of mechanical compaction, their porosity loss is mainly due to cementation rather than compaction.

4.5.2. Clay minerals

4.5.2.1. Pore-filling clays

In the Forties Sandstones Member studied, pore-filling clays occur in two forms: detrital and authigenic. Detrital pore-filling clays mainly consists of mixed-layer smectitic clays (Figure 6B-E). Mixed layer illite/smectite (I/S) mainly occurs as a pore-filling cement (Figure 13A) and is mostly replaced by illite (Figure 13A). Percentages of I/S decrease with depth, possibly due to transformation to illite and/or chlorite.

Diagenetic pore-filling clays consists of chlorite and illite (which are formed from transformation of detrital smectite) and kaolinite (Figure 13B & C). Diagenetic chlorite occurs as pore-filling (Figure 13B) and grain-replacive cement. Grain-replacive chlorite is formed from alteration of volcanic rock fragment and biotite, reducing secondary intragranular porosity. SEM observation revealed that authigenic pore-filling illite is formed from illitization of kaolinite (Figure 13D) and mixed-layer illite-smectite (Figure 13A).

Authigenic kaolinite, which is identified by its vermicular or booklet form (Figure 13C), occurs as both grain-replacive and pore-filling cement (Figure 13C). Vermicular kaolinite ranges in diameter from 2µm to 20 µm. Grain-replacive kaolinite occurs as replacement of unstable, dissolved feldspar and mica grains, whereas pore-filling kaolinite precipitates adjacent to leached feldspar and mica grains (i.e., in open pores). Occasionally, the kaolinite transforms into illite (Figure 13D), or changes to its higher temperature form (dickite) at depth (Figure 13C & E).

4.5.2.2. Clay coats

Diagenetic, grain-coating clays consists of chlorite, illite, illite-smectite. Authigenic chlorite occurs as grain-coating (2µm to 10 µm) (e.g. Figure 13E) and pore-lining (Figure 13F) cement. In many samples, petrographic and SEM observations revealed that authigenic chlorite seems to have formed after the first phase of quartz cementation (e.g., Figure 14A), and that subsequent phase(s) of quartz overgrowths have been impeded by grain-coating chlorite or illite/illite-smectite. Additionally, SEM observations show that, where grain-coating chlorite/illite-smectite are absent on quartz grains, quartz overgrowths develop, thereby reducing porosity (e.g., Figure 14B). Pore-lining chlorite precipitated parallel to detrital grains (Figure 13F). Occasionally, thick, well-developed pore-lining chlorite transforms into pore-filling chlorite (Figure 13F).

Grain-coating illite/illite-smectite (2µm to 12 µm) commonly occur as thick and continuous coatings on grain embayments (Figures 13D & E and 14C). The coatings were thought to have been inherited from shelf, transitional or continental environments (Bahlis and de Ros, 2013; Yezerski and Shumaker, 2018), which were transformed from smectites during diagenesis.

4.5.3. Carbonate cements and stable isotopes

4.5.3.1. Early carbonate cements

Petrographic evidence revealed that early carbonate cements consists non-ferroan calcite, dolomite, and siderite. The early carbonate cements occur in sandstones with point and floating grain contacts (Figure 12B), suggesting formation during shallow burial. The cements occur mainly as pore-filling. Non-ferroan calcite occurs as patchy (Figure 14D) and as blocky, poikilotopic (Figure 12B) cement. The blocky calcite commonly shows evidence of pervasive dissolution, and the resulting porosity are either fairly connected and well-preserved or are completely filled by late ferroan calcite (Figure 14E). Authigenic siderite commonly occurs in loosely packed sandstones as scattered rhombs (Figure 14F) and are often associated with dolomite and/or pyrite. Siderite is also found in the vicinity of dissolved mica grains, which probably serve as the principal source of Fe required for the formation (Mansurbeg et al., 2008). The cement commonly undergoes dissolution, with secondary porosity generation (Figure 14F), probably due to influx of acidic pore fluids. Dolomite occurs as pore-filling cement and as replacement of dissolved, detrital mica grains, filling dissolution pores. They occur in close association with siderite and pyrite.

Results of stable carbon and oxygen isotopes indicate that the non-ferroan calcite cements have $\delta\ ^{13}C$ values ranging from -8.66 to -2.32 ‰ and $\delta\ ^{13}O$ values ranging from -13.55 to -4.99 ‰, whereas siderite cements have $\delta\ ^{13}C$ values ranging from +0.26 to +9.48 ‰ and $\delta\ ^{13}O$ values ranging from -5.88 to -9.30 ‰ (Table 2). Dolomite cements have $\delta\ ^{13}C$ values ranging from -3.40 to +0.59 ‰ and $\delta\ ^{13}O$ values ranging from -6.25 to -5.99 (Table 2).

4.5.3.2. Late carbonate cement

Occurring mainly as patchy and pore-filling, ferroan calcite is a late carbonate cement in the sandstones, replacing pervasively dissolved non-ferroan calcite and/or feldspar grains (Figure 14E). In addition, the cement also engulfs (and thus postdates) quartz overgrowths.

Ferroan calcites have $\delta\ ^{13}C$ values ranging from -20.45 to -8.53 ‰ and $\delta\ ^{13}O$ values ranging from -13.10 to -8.62 ‰ (Table 2).

4.5.4. Quartz cement

Quartz overgrowths occur as euhedral and syntaxial overgrowths around quartz grains (Figure 14A & B). In the sandstones, the quartz cements occur as partial to complete cover around detrital quartz grains, and either partially or pervasively fills primary intergranular porosity. Under petrographic light microscope, the boundary between a quartz overgrowth and a detrital quartz grain is usually delineated by dust rim or thin clay coatings. It has been observed that quartz overgrowths are more abundant or well-developed in sandstones with clean quartz grain surfaces compared to those characterised by the presence of grain-coating clays.

4.5.5. Mineral dissolution

Dissolution of feldspars, mica, and carbonate cements has resulted in the formation of secondary porosity in most of the sandstones, notably in the amalgamated sandstones facies. Analysed samples show partial to complete dissolution of K-feldspar and plagioclase grains, resulting in the formation of secondary intragranular porosity. In addition, the feldspars often undergo complete dissolution, forming moldic, open pores. Authigenic chlorite, kaolinite, ferroan and non-ferroan calcites, illite, and pyrite have, in some samples, precipitated in feldspars and micas that have undergone partial and/or complete dissolution. Mica grains undergo dissolution to form both grain-coating and grain-replacive chlorite. Dissolution of carbonate bioclasts and cements is common and results in the development of open pores that are either well-preserved (e.g., Figure 14F) or later filled by late authigenic cements (such as ferroan calcite) (Figure 14E).

4.6. Clay-coat coverage

The percentage of grain-coating chlorite and illite/illite-smectite coverage on detrital quartz grains was measured on 50 randomly selected quartz grains in 50 Forties Sandstone samples, based on the established facies schemes. Average Clay-coat coverage in the selected samples ranges from 18 to 61 %. Plots of average clay-coat coverage against porosity and permeability (Figure 15A & B) show both porosity (helium and optical) and permeability increase relatively with increasing clay-coat coverage. Sandstones with >40 % clay-coat coverage retain higher porosity and permeability values (Figure 15A & B). Additionally, quartz overgrowths seem to decrease with increasing clay-coat coverage (Figure 15C), and clay-coat coverage of >40 % is required to lower the quartz cement significantly.

However, there is seemingly lack of an excellent inverse relationship between quartz cement volume and clay-coat coverage in some samples in Figure 15C. From the plot, it has been observed that, while some samples have low quartz cements volume (< 2%) despite having low clay-coat coverage (< 40 %) (blue circle), others have relatively high quartz cement (≥ 6 %) despite having high clay-coat coverage (> 40 %) (purple circle). This is probably because in the former, the samples are characterized by high pore-filling clay matrix, which is also effective in preventing quartz cementation as it covers the surface area of grains (Porten et al., 2019; Shaw and Conybeare, 2003). In the latter samples, on the other hand, grain-coating clays have formed after the formation of quartz cement (e.g., Figure 14A); nonetheless, the clay coats would arrest further quartz cementation in such sandstones.

In general, positive relationship between clay-coating coverage and porosity and permeability (Figure 15A & B) may partly be due to the combination effect of depositional facies and primary depositional character and diagenesis are having on reservoir quality.

5. Discussion

5.1. Impact of depositional processes on reservoir quality

Our study shows that depositional processes exert a key control on the distribution of sedimentary facies, grain size, and clay content, which result in spatial variation in reservoir quality of submarine fan deposits (Bell et al., 2018; Marchand et al., 2015; Porten et al., 2016;

Stammer, 2014). The Forties Sandstones Member studied have porosities ranging from 1.9 to 28.4 % and permeabilities ranging from 0.01 to 500 mD (Figure 16A), with a decrease in permeability with depth (Figure 16B) higher in magnitude than that of porosity (Figure 16C). This is probably because an increase in clay content with depth results in pore throats blockage, lowering permeability and increasing microporosity that contributes to overall porosity. A multi-disciplinary approach involving core description, measured petrophysical properties, and petrographic observations employed in this study has shown that the proximal fan, amalgamated sandstones channel facies have the best reservoir quality because of the coarser grain size (Figure 17A & B), lowest amount of pore-filling clays (Figures 10A, 17C & D), least amount of ductile grains (Figure 10B), and lowest total amount of cements (Figure 17E & F), which lead to higher porosities and permeabilities (Figure 16A). The distal fan, mud-prone heterolithic facies have the poorest reservoir quality due to the finer grain size (Figure 17A & B), abundance of pore-filling clays (Figures 10A, 17C & D), highest amount of ductile grains (Figure 10B), and highest total amount of pore-filling cements (Figure 17E & F), resulting in lower porosities and permeabilities (Figure 16A). Total pore-filling clays between 10 and 30 % have a deleterious effect on reservoir quality, reducing porosities and permeabilities to generally < 10 % and < 1 mD, respectively (Figure 17C & D). The overlap in the porosity and permeability (Figure 16A) suggests reservoir heterogeneity even within the same depositional facies, presumably due to variation in detrital compositions and diagenetic evolution pathways. The depositional facies are characterized by variations in detrital smectitic clays matrix and authigenic kaolinite, which have abundant microporosity that contribute to total porosity. Additionally, isolated intragranular pores could contribute to total porosity but little (if any) to permeability.

Overall, the decrease in sandstones thickness (N:G) (Figure 1B), degree of sandstone amalgamation, and increase in clay content from proximal to distal fan (Figures 10A and 17C & D) show that the amalgamated sandstones facies have the highest connectivity and, hence, the best reservoir quality (Porten et al., 2016). The rapid decrease in grain size and increase in clay content from sand-prone heterolithic facies to mud-prone heterolithic facies (Figure 17A, B, C & D) result in the deterioration of reservoir quality, indicating that the mud-prone heterolithic facies are unlikely to form a significant/good quality hydrocarbon reservoir (Figure 17A & B) (Bell et al., 2018; Fildani et al., 2018).

Sediments undergo textural and compositional segregation during transport in turbidity currents based on competency and capacity of flows, resulting in fan-scale spatial variations in reservoir quality (Kane et al., 2017; Kuenen and Sengupta, 1970; Marchand et al., 2015). An experimental study of turbidity currents by Stammer (2014) shows that particles are spatially fractionated based on grain density and shape, which result in large-scale spatial variations in texture and composition of the deposits. During sediment transport from submarine channel to lobe axis and lobe off axis settings, coarser-grained sediments fraction settles first at the base of high-density turbidity flows in the channel and lobe axis areas, whereas the finer-grained, less-dense fraction remains in the flow and are progressively deposited in the lobe off-axis depositional settings (Huang et al., 2020; Marchand et al., 2015). In this study, textural and petrographic data have indicated that turbidity flows segregate particle by both grain size and composition (Figure 10A & B), and have had a significant impact on their reservoir quality. Ductile grains content, consisting of mica and mudclasts, are more abundant in lower-energy deposits of channel margin and lobe margin/fringe, and tend to increase with decreasing grain size (Figure 10B), which enhances mechanical compaction (e.g. Figure 12D). This is similar to the findings of the study of the Paleogene deep-water reservoirs of the US Gulf of Mexico (Marchand et al., 2015).

Therefore, the proximal to distal fan change in lithofacies associations in the Forties Fan system suggests transformation of turbidity currents from high- to low-density/debris flows. The transformation commonly occurs at a transition zone in channel-lobe areas (Ito, 2008). Turbidity flows erode and incorporate muddy fines as they move downslope, resulting in suppression of turbulence and conversion of turbulent flows into laminar flows (Ito, 2008; Kane et al., 2017; Talling et al., 2012).

5.2. Origin of carbonate cements

The origin of carbonate cements can be established based on carbon isotopic compositions of the cements (Irwin et al., 1977; Ma et al., 2017; Mao et al., 2019; Stewart, 1995). The $\delta^{13}C$ values for the carbonate cements in the sandstones range from -21.12 ‰ to +9.48 ‰ (average -7.04 ‰; Table 2; Figure 18), suggesting a wide range of sources for carbon including both organic and inorganic sources (Figure 18). Based on the carbon isotope values (Table 2), non-ferroan calcites cements were sourced from mixed meteoric input and/or carbonate bioclasts (Figure 18). In the Paleocene sands of the Central North Sea, the relative fall in sea level and delta progradation shortly after deposition of the sands could have led to meteoric flushing, dissolution of detrital carbonate bioclasts, and precipitation of the non-ferroan calcite (Den Hartog Jager et al., 1993; Mudge and Copestake, 1993; Stewart, 1995) (Figure 18). However, results of the carbon isotopic compositions for late ferroan calcite indicate that they were sourced mainly from decarboxylation (Figure 18), presumably due to influx of late acidic pore fluids in the sandstones (Stewart, 1995; Stewart et al., 2000). The decarboxylation is interpreted to have been influenced by proximity to heat-conducting salt diapirs and/or due to vertical transfer of fluid by leak-off from overpressured, deeply-buried Jurassic reservoirs through faults created by salt domes (Darby et al., 1996; Stewart, 1995; Stewart et al., 2000). The carbon isotope values for dolomite and siderite indicate that the cements might have been derived from fermentation and/or recrystallization of bioclastic carbonates (Figure 18). Fermentation of organic matter in the sandstones is believed to have occurred in meteoric pore fluids that are lacking in available sulphate (Stewart, 1995).

5.3. Role of provenance, depositional processes, and diagenetic alterations on grain-coating clays and coat coverage

The occurrence of grain-coating clays in deep-water sandstones can be linked to provenance, depositional, and diagenetic processes (Bahlis and de Ros, 2013; Porten et al., 2019; Yezerski and Shumaker, 2018). Sand grains can develop precursor clay coats in continental, transitional or shallow marine/shelf environments (Bahlis and de Ros, 2013; Yezerski and Shumaker, 2018) before being transported to deep-water environments. Although the precursor clay coats may be partly or pervasively abraded during transport to deep-water environments, grains characterized by embayments preserve clay coatings as they are resistant to abrasion (Figure 14C). Furthermore, grain-coating clays are emplaced in deep-water sediments during sediment dewatering (Houseknecht and Ross, 1992; Porten et al., 2019) (e.g., Figure 4B), due to the escape of entrapped pore fluids as overlying beds are deposited. Diagenetic clay coatings, on the other hand, are formed from direct precipitation (Dutton et al., 2018; Kordi, 2013; Worden et al., 2020) and/or through alteration of precursor clays (e.g. kaolinite or smectite) (Bahlis and de Ros, 2013) (e.g. Figures 13D & 14C).

Deposited in proximal fan setting and characterized by sediment dewatering structures (e.g., Figure 4B), the amalgamated sandstones facies in the Forties Sandstone Member are characterized by high clay-coat coverage (26-61 %) (Figure 15A & B). Their close proximity to shelf edge, notably in sand-rich systems, suggests that precursor coats in this facies are less susceptible to abrasion during transport. Additionally, the coarser grain size might facilitate fluid escape, thereby increasing the amount coatings emplacement due to sediment dewatering in the sandstones. The distal fan, mud-prone heterolithic facies, in contrast, have the least clay coating coverage (18-33 %) (Figure 15A & B), presumably due to intense abrasion of precursor coatings during long transport and/or lack of dewatering structures in the sandstones.

5.4. Implications for proximal to distal fan fields

Reservoir quality in the Forties Sandstone Member is mainly controlled by depositional facies, paleotopographic highs, and salt-induced highs (Collins et al., 2015; Eldrett et al., 2015; Hempton et al., 2005; Kunka et al., 2003; McKie et al., 2015; Scott et al., 2010; Whyatt et al., 1992). The proximal fan settings (e.g. Nelson field) have the best reservoir quality due to coarser grain size, lower detrital clay matrix, and higher degree of channelization, and net to gross (Figures 1B & 17A-D). The distal fan settings (e.g. Blane field), in contrast, have the poorest reservoir quality due to finer grain size, higher detrital clay matrix, and lower degree of channelization, and net to gross (Figures 1B & 17A-D).

In addition, the Forties Sandstone Member is interpreted to have been deposited between the paleotopographic highs of the Lista Formation and highs created by rising salt diapirs (Figure 19A-C), thereby influencing the sandstones depositional architecture, depositional facies, and, thus, reservoir quality (Hempton et al., 2005; Scott et al., 2010). These highs created channel-like features that often extend to the margins of the fan (Den Hartog Jager et al., 1993; Kessler et al., 1980) (Figure 19A), causing flows to speed up and depositing high-density channel sandstones in an otherwise distal fan setting (e.g. Pierce field; Figure 19B) (Eldrett et al., 2015). However, while there is absence of baffles and barriers to fluid flow in the channel-dominated proximal-fan setting, due to sand amalgamation, the heterolithic sandstones of the distal fan, lobe-dominated areas are characterized by increasing shale interbeds, argillaceous sandstones, and mudstones, which could act as baffles to flow (Figure 19C). Additionally, the instability created by the rising salts diapirs develop slumps, debrites, and sand injectites, which significantly cause reservoir heterogeneity in the sandstones (e.g. Figure 19C).

5.5. Implications of clay coats on reservoir quality

Understanding of quartz cementation is important for pre-drill prediction of porosity in deeply-buried sandstones (Bukar, 2013; Porten et al., 2019). The amount of quartz cement formed is determined by the time and temperature history of the sandstone, the amount of nucleation surface area available for quartz cementation, and the presence of dissolved silica (Lander et al., 2008; Lander and Walderhaug, 1999; Walderhaug, 1996, 1994; Walderhaug and BjØrkum, 2003). The rate of quartz cementation in sandstones increases exponentially with increasing temperature, resulting in a decrease in porosity in basins characterized by high heat flows (Taylor et al., 2010; Walderhaug, 2000, 1996). The burial and temperature history plots for the proximal (Nelson field) and distal fan (Blane field) (Figure 3A & B) suggest that, while the former attained a temperature of 120 ˚C during the Late Miocene to present, the latter attained a temperature of 130 ˚C during the same period. However, low volumes of quartz cement have been recorded in both proximal and distal fan, with the average of 3.62 % and 1.78 % respectively. This could be attributed to the relatively shallow burial depths of the sandstones (2200-3100 m true vertical depth subsea), short residence times in the quartz cementation domain (>1.5 km), or due to the moderately good clay-coat coverage (40 to 50 %; Figure 15C). Nevertheless, the observed dissolution of feldspars and the evidence of the conversion of smectite to illite, which supply silica as by-product (Worden and Morad, 2003), indicate the likely presence of silica in the system, but has been largely inhibited from precipitating as quartz cement by the good clay-coat coverage. Additionally, the low quartz cement recorded in the distal fan is presumably due to the increased pore-filling clays, which are also effective in preventing quartz cementation as they cover the surface of grains (Shaw and Conybeare, 2003).

5.6. Diagenetic and reservoir quality evolution

Reservoir quality in sandstones is controlled by depositional characteristics and diagenetic processes, including grain size, sorting, clay content, compaction, cementation, dissolution (Bell et al., 2018; Bjørlykke and Jahren, 2010; Ma et al., 2017; Oluwadebi et al., 2018; Porten et al., 2016). The diagenetic alterations have been achieved during both eodiagenesis (< 2 km; < 70 ˚C) and mesodiagenesis (> 2 km; > 70 ˚C) (Morad et al., 2010) (Figure 20). In the studied sandstones, compaction is the main diagenetic process that controlled the reservoir quality followed by cementation. Petrographic evidence has shown that the sandstones are characterized by point and concavo-convex grain contacts (Figures 12A & C), with ductile grains compacted around rigid grains (Figures 12D). Additionally, a plot of compactional porosity loss against cementational porosity loss (Figure 11) has shown that compaction is the main driver for porosity loss than cementation. The impact of mechanical compaction on reduction of porosity was more important in the distal fan sandstones due to finer grain size (Figure 10A), and relatively higher amount of ductile grains (Figure 10B) than in the proximal fan sandstones.

Apart from compaction, cementation has also played a significant role in reducing the reservoir quality of the sandstones through the formation of clay minerals and carbonate cements (mainly early non-ferroan calcite and siderite and late ferroan calcite) (Figure 20). Diagenetic clay minerals can significantly influence sandstones reservoir quality. The formation of authigenic chlorite, kaolinite, and illite has greatly contributed to the reduction in reservoir quality of the sandstones. Pore-filling chlorite occludes porosity and reduces pore throat diameter, preventing fluid flow (Figures 13B & 20). Vermicular kaolinite tends to sit between detrital grains, filling pores and blocking pore throats, resulting in destroying reservoir quality (Figure 13C). Additionally, flaky and fibrous illite occludes intergranular porosity and blocks pore throats, decreasing reservoir quality of the sandstones (e.g. Figures 13A & 20). Nonetheless, grain-coating chlorite and illite, mainly from smectite, have relatively inhibited the development of quartz overgrowths in the sandstones (Figures 13E, 14A, & 20).

Quartz cement has been identified as the main cause of porosity destruction in several sandstone reservoirs (Blatt, 1979; Ehrenberg, 1990; McBride, 1989). Nevertheless, quartz overgrowths in the Forties Sandstone Member occur in moderate amount (average 2.73 % for all samples), suggesting that the cement has little effect on reservoir quality, presumably due, in part, to clay coats.

Early calcite and siderite, where well-developed, completely filled intergranular porosity, thereby preventing fluid migration (Figures 12B & 20). Late ferroan calcite replaces early non-ferroan calcite, destroying porosity (Figures 14E & 20). The dissolution of early carbonate cement and feldspars has created secondary porosity, thereby enhancing the reservoir quality of the sandstones (e.g. Figure 14F).

6. Conclusions

Establishing the link between depositional facies with diagenetic processes in sandstone reservoirs is crucial for understanding their controls on reservoir quality evolution. This is exemplified by the Tertiary, deep-sea turbidite sandstones of the Forties Member of Sele Formation, North Sea Central Graben. This study found that:

- Three main lithofacies associations were identified based on depositional environments and core description: (1) amalgamated sandstone facies (channel and proximal lobe), (2) sand-prone heterolithic facies (lobe off-axis), (3) mud-prone heterolithic facies (lobe margin/fringe)

- The Forties Sandstones Member are very fine- to medium-grained, poorly- to moderately well-sorted, mainly arkose to subarkose, and deposited in submarine fan settings. The sandstones have considerable reservoir heterogeneity due to variations in facies and mud content, with a wide range of porosity from 1.9 to 28.4 % and permeability from 0.01 to 500 mD.
- The proximal fan, amalgamated sandstones facies have the best reservoir quality due to coarser grain size, lower detrital clays, and lower ductile grains content. The distal fan, mud-prone facies have the poorest reservoir quality due to finer grain size, higher detrital clays, and higher ductile grains content. Total pore-filling clays between 10 and 30 % have a deleterious effect on reservoir quality, reducing porosities and permeabilities to generally < 10 % and < 1 mD, respectively.
- Diagenetic alterations of the Forties Sandstones Member have been achieved during early and late diagenesis. Key diagenetic processes and alterations include mechanical compaction, formation of smectite (and illite/smectite), kaolinite, illite, chlorite and quartz overgrowth, calcite (ferroan and non-ferroan). Minor diagenetic alterations include dissolution of feldspar, mica and carbonate cement cements and precipitation of dolomite and pyrite.
- Measurements of grain-coating clays, consisting of chlorite and illite/illite-smectite, coverage have shown that the clay-coat coverage to arrest quartz cementation and preserve reservoir quality at the present-day burial depths of Forties Sandstone Member (2200-3100 m true vertical depth subsea) ranges from 40 to 50 %. The clay coats have relatively maintained reservoir quality in both the amalgamated and heterolithic sandstones facies by inhibiting the development of quartz cementation. Macroporosity and permeability are preserved in the reservoir facies due to the grain-coating clays.

Acknowledgements

The work contained in this paper was conducted during a PhD study funded by Nigerian Federal Government, through Petroleum Technology Development Fund (PTDF), whose financial support is gratefully acknowledged. The authors would like to thank Philip Milstead, Tom Taylor, and three other anonymous reviewers for their constructive comments and suggestions towards improving the quality of the manuscript. We sincerely thank the Associate Editor Luca Caracciolo for his invaluable comments and encouragement.

Figure Titles

Figure 1. (A) Regional map of the Forties submarine fan system. The figure shows the distribution of the main fan (NW-SE) and location of the wells sampled for this study (modified from Hempton et al., 2005). (B) GR logs showing reservoir lithologies and thicknesses in some selected wells from proximal to distal fan used in the study.

Figure 2. Regional stratigraphic chart for the Paleogene Central Graben (modified from Charles and Ryzhikov, 2015). The main focus of the study is the Upper Forties Sandstone Member (T-70 and T-75). The sequences represent periods of sustained clastic sediment input into the basin from the shelf, which are marked by maximum flooding surfaces (MFS).

Figure 3. Burial and thermal history plots for the Forties Sandstones Member. (A) Proximal fan (Nelson field); (B) Distal fan (Blane field). See Figure 1 for location of fields.

Figure 4. Sedimentary core lithofacies scheme established for the study. (A) Structureless sandstone (St) facies. (B) Dewatered sandstones facies (Sd). (C) Structureless, interbedded sandstones facies (Si). (D) Parallel laminated sandstones facies (Sp). (E) Wavy, ripple laminated sandstones facies (Sr). (F) Slump facies (Sl). (G) Sand injection facies (Sin). (H) Laminated mudstones facies (Ml). (I) Hemipelagic mudstones facies (M). Note: black and white scale = 0.3 ft (~ 9 cm).

Figure 5. Example sedimentary logs for the three key facies and lithofacies associations as recognised and used in this study. (A) Amalgamated sandstones facies is dominated by stacked sandstones up to ~20 m thick; (B) Sand-prone heterolithic facies. The sandstones are similar to those in (A), but are interbedded with mudstones and siltstones. Sand bed thickness is substantially less than those in facies (A) and typically < 1 m thick; (C) Mud-prone heterolithic facies. In contrast, the mud-prone heterolithic facies comprises mainly mudstones, siltstones, and interbedded sandstones up to a maximum of 0.5 m thick and typically below standard logging tool resolution.

Figure 6. (A) QFR plot (after Folk, 1980) showing the compositional mineralogy of the Forties Sandstones Member for all the wells used in this study. Most of the sandstones are arkosic to subarkosic, with a smaller proportion represented by lithic arkoses. (B) PPL photomicrograph of moderately high refringence, greenish to brown smectitic clay matrix filling intergranular porosity. Pierce field, well 23/27-5, 2728.26 m TVDSS; (C) XPL image of (B); (D) Greenish

to brown, smectitic detrital clay matrix destroying intergranular porosity. Pierce field, well 23/27-5, 2728.26 m TVDSS; (E) XPL photomicrograph of grain-coating chlorite illite-smectite. Blane Field, well 30/03a-1, 3097 m TVDSS.[PPL= plane polarized light; XPL= cross polarized light].

Figure 7. Sedimentary log demonstrating amalgamated sandstones facies in well 22/11-8 (Nelson field); (B-C) Vertical variation in mean grain size and mud content determined by petrographic point counting, respectively. The vertical changes show that a decrease in grain size leads to an increase in detrital mud content and vice versa; (D-E) Thin-section photomicrographs showing finer and coarser grain size for amalgamated sandstones facies association, respectively.

Figure 8. Sedimentary log demonstrating sand-prone heterolithic facies in well 23/16c-8 (Arran field); (B-C) Vertical variation in mean grain size and mud content determined by petrographic point counting, respectively. The vertical changes show that a decrease in grain size leads to an increase in detrital mud content and vice versa; (D-E) Thin-section photomicrographs showing finer and coarser grain size for sand-prone heterolithic facies association, respectively.

Figure 9. Sedimentary log showing mud-prone heterolithic facies in well 23/16b-9 (Arran field); (B-C) Vertical variation in mean grain size and mud content determined by petrographic point counting, respectively. The vertical changes show that a decrease in grain size leads to an increase in detrital mud content and vice versa; (D-E) Thin-section photomicrographs showing finer and coarser grain size for mud-prone heterolithic facies association, respectively.

Figure 10. Relationship between mean grain size and detrital clay matrix showing that the coarser-grained, proximal-fan sandstones have lower detrital clay matrix, and the finer-grained, distal-fan sandstones have higher detrital clay matrix; (B) Plot of ductile grains contents (mica and mudclasts) against mean-grain size showing that, that the coarser-grained, proximal-fan sandstones have low ductile grains content (and thus less mechanical compaction), and the finer-grained, distal-fan sandstones have higher ductile grains content (and hence higher impact of mechanical compaction).

Figure 11. Plot of compactional porosity loss against cementational porosity loss for the Forties Sandstone Member (calculated after Lundegard, 1992). The plot shows that more porosity is lost due to compaction than due to cementation.

Figure 12. Thin-section photomicrographs illustrating the examples of compaction and cementation, in the Forties Sandstone Member. (A) Point- and long-grain contacts. Nelson field, well 22/11-8, 2570.68 m TVDSS; (B) Less mechanical compaction due to floating grains in an early, non-ferroan calcite. Pierce field, well 23/27-8, 2479.85 m TVDSS; (C) Photomicrograph of concavo-convex grain contact, suggesting moderate impact of mechanical compaction. Arran field, well 23/16c-8, 2580.74 m TVDSS; (D) Ductile deformation of mica (muscovite) grain, bending around detrital grains due to intense compaction. Pierce field, well 23/27-5, 2727.05 m TVDSS; [TVDSS= True Vertical Depth Subsea].

Figure 13. BSEM images showing examples of grain-coating, pore-filling, cement-replacing, and pore-lining clays within the Forties Sandstone Member studied. (A) BSEM image showing illite-smectite being replaced by illite. Pierce field, well 23/27-5, 2733.75 m TVDSS; (B) BSEM image of pore-filling chlorite occluding intergranular porosity and blocking pore throat. Everest field, well 22/14a-2, 2616 m TVDSS. (C) BSEM image of pore-filling kaolinite and dickite occluding intergranular porosity and blocking pore throat. Everest field, well 23/27-5, 2726.74 m TVDSS; (D) BSEM image showing kaolinite being replaced by illite. Blane field, well 30/03a-1, 3096 m TVDSS; (E) BSEM image showing grain-coating chlorite and illite-smectite preventing quartz cementation, and where the clays are absent, quartz overgrowth develops (light blue arrow). Everest field, well 22/14a-2, 2616 m TVDSS; (F) BSEM image showing pore-lining chlorite. Everest field, well 22/14a-2, 2616 m TVDSS. [BSEM = Backscattered Scanning Electron Image].

Figure 14. Clay minerals, quartz overgrowths, and carbonate cements in the Forties Sandstone Member (A) Grain-coating chlorite postdating quartz cementation. Arran field, well 23/16c-8, 2580.74 m TVDSS; (B) Well-developed quartz overgrowth on clean detrital grain. Note the absence of quartz cement on a grain with clay coat. Everest field, well 22/10a-T6, 2437 m TVDSS; (C) Grain-coating illite preventing quartz cementation. Nelson field, well 22/11-8, 2508.17 m TVDSS; (D) Formation of patchy non-ferroan calcite adjacent to gastropod shell. Everest field, well 22/10a-T6, 2476.5 m TVDSS; (E) Photomicrograph showing late ferroan calcite replacing dissolved, early non-ferroan calcite cement. Note the remnants of the early non-ferroan calcite. Arran field, well 23/16b-9, 2696 m TVDSS; (F) Photomicrograph showing dissolved siderite cement, creating secondary intergranular porosity. Pierce field, well 23/27-6, 2900.48 m TVDSS.

Figure 15. (A) Optical and helium porosities increasing with an increase in clay-coat coverage (B) An increase in permeability with an increasing clay-coat coverage; (C) An inverse relationship between quartz cement volume and clay-coat coverage.

Figure16. (A) Plot of core permeability against core porosity for the studied Forties sandstone reservoirs. The higher permeabilities in the 10 to >100 mD range and porosities >20 % are predominantly for the proximal amalgamated sandstones facies (see Figure 5A). This compares markedly to the sand-prone and mud-prone heterolithic facies where permeabilities can be >0.1 mD and porosities frequently >10 %. (B) Plot of helium porosity against depth, showing a general decrease in porosity with depth. (C) Plot of permeability against depth, showing a general decrease in permeability (by up to two orders of magnitude) with depth. This is due increase in pore-filling clays, total cements, and compaction from proximal to distal fan.

Figure 17. Impact of grain size, clay content, and total cements on reservoir properties of the Forties Sandstone Member. (A) Plot of core porosity against mean grain size. Porosity increases relatively with increasing grain size; (B) Plot of core permeability against mean grain size. Reservoir permeability increases with increasing grain size; (C) Plot of helium porosity against pore-filling detrital and authigenic clays. High pore-filling clays lower the porosity, but they have more deleterious effect on permeability; (D) Plot of core permeability against pore-filling detrital and authigenic clays. Permeability is significantly lowered with increasing pore-filling clays; (E) Plot of helium porosity against total pore-filling clays and carbonate cements. The higher the cements, the lower the porosity; (F) Plot of core permeability against total pore-filling clays and carbonate cements. Permeability significantly decreases with increasing total clays and carbonate cements.

Figure 18. Scatterplot of delta ^{13}C carbon and delta ^{18}O oxygen isotopic compositions showing the various sources of carbon for precipitation of carbonate cements in the Forties Sandstones Member. The plot shows that mixed meteoric and carbonate bioclasts are the main sources of carbon for the cements.

Figure 19. (A) The Forties Sandstone Member isochrones on a 3D representation of the Lower Forties (T65) showing areas of paleotopographic highs and sediment fairways through the Pierce area (modified from Scott et al. 2010). (B) Conceptual model of sandbody architecture of the Forties reservoirs in channel-dominated areas of salt diapirs (modified after Eldrett et al. 2015). (C) Conceptual model of sandbody architecture of the Forties reservoirs in lobe-dominated areas of salt diapirs (modified after Eldrett et al. 2015).

Figure 20. Schematic conceptual model for the facies control and diagenesis of the Forties Sandstones Member and reservoir quality evolution. The model shows the types of diagenetic alterations and products that have affected the reservoir quality of the Forties Sandstones Member.

Tables

Table 1. Sedimentary facies classification, description, and interpretation of predominant processes and depositional environments.

Table 2. Stable carbon and oxygen isotopes data for carbonate cements.

Table 3. Supplementary data (Appendix).

References

Allsop, T., 1994. Early compaction history of marine siliciclastic sediments. Durham University.

Bahlis, A.B., de Ros, L.F., 2013. Origin and impact of authigenic chlorite in the Upper Cretaceous sandstone reservoirs of the Santos Basin, eastern Brazil. Pet. Geosci. 19, 185–199.

Bell, D., Kane, I.A., Pontén, A.S.M., Flint, S.S., Hodgson, D.M., Barrett, B.J., 2018. Spatial variability in depositional reservoir quality of deep-water channel-fill and lobe deposits. Mar. Pet. Geol. 98, 97–115.

Bjorlykke, K., Aagaard, P., 1992. Clay Minerals in North Sea Sandstones. In: Houseknecht, D.W. and Pittman, E.D. (Ed.), Origin, Diagenesis, and Petrophysics of Clay Minerals in Sandstones. Spec. Pub. Soc. Econ. PaleontoL Mineral, pp. 65–80.

Bjørlykke, K., Jahren, J., 2010. Sandstones and sandstone reservoirs. In: Bjørlykke, K. (Ed.), Petroleum Geoscience: From Sedimentary Environments to Rock Physics, Second Edition. Springer- Verlag, Berlin Heidelberg, pp. 113–140.

Blatt, H., 1979. Diagenetic` Processes in Sandstones. Soc. Econ. Paleontol. Mineral. 26, 141–157.

Bloch, S., Lander, R.H., Bonnell, L., 2002. Anomalously high porosity and permeability in deeply buried sandstone reservoirs: Origin and predictability. Am. Assoc. Pet. Geol. Bull. 86, 301–328.

Bouma, A.H., 1962. Sedimentology of Some Flysch Deposits. Elsevier, Amsterdam 168, 168.

Bowman, M.B.., 1998. Cenozoic. In: Glennie, K.W. (Ed.), Petroleum Geology of the North Sea. pp. 350–375.

Brennand, T.P., Van Hoorn, B., James, K.H., Glennie, K.W., 2009. Historical review of north sea exploration, Petroleum Geology of the North Sea: Basic Concepts and Recent Advances: Fourth Edition.

Bukar, M., 2013. Does oil emplacement stop diagenesis and quartz cementation in deeply buried sandstone reservoirs. University of Liverpool.

Charles, R., Ryzhikov, K., 2015. Merganser Field: managing subsurface uncertainty during the development of a salt diapir field in the UK Central North Sea. Geol. Soc. London, Spec. Publ. 403, 261–298.

Chen, B., Wang, F., Shi, J., Chen, F., Shi, H., 2019. Origin and Sources of Minerals and Their Impact on the Hydrocarbon Reservoir Quality of the PaleogeneLulehe Formation in the Eboliang Area, Northern Qaidam Basin, China. Minerals 9, 436.

Chudi, O.K., Lewis, H., Stow, D.A.V., Buckman, J.O., 2016. Reservoir quality prediction of deep-water Oligocene sandstones from the west Niger Delta by integrated petrological, petrophysical and basin modelling. Geol. Soc. Spec. Publ. 435, 245–264.

Collins, J., Kenyon-Roberts, S., Cullen, B., White, J., Bordas-Le Floch, N., Downey, J., 2015. Arran Field: A complex heterolithic reservoir on the margins of the Forties Fan System. Geol. Soc. Spec. Publ. 403, 185–217.

Darby D., Haszeldine, R.S. & Couples, G., 1996. Pressure Cells and Pressure Seals in the Central North Sea. Mar. Pet. Geol. 13, 865ÿ878.

Davis, C., Haughton, P., McCaffrey, W., Scott, E., Hogg, N., Kitching, D., 2009. Character and distribution of hybrid sediment gravity flow deposits from the outer Forties Fan, Palaeocene Central North Sea, UKCS. Mar. Pet. Geol. 26, 1919–1939.

Davison, I., Alsop, I., Birch, P., Elders, C., Evans, N., Nicholson, H., Rorison, P., Wade, D., Woodward, J., Young, M., 2000. Geometry and late-stage structural evolution of Central Graben salt diapirs, North Sea. Mar. Pet. Geol. 17, 499–522.

Deegan, C.E., Scull, B.J., 1977. A proposed standard lithostratigraphic nomenclature for the Mesozoic of the central and northern North Sea, Mesozoic of the Northern North Sea Symposium.

Den Hartog Jager, D., Giles, M.R., Griffiths, G.R., 1993. Evolution of Paleogene submarine fans of the North Sea in space and time. Pet. Geol. Conf. Proc. 4, 59–71.

Dos Anjos, S.M.C., De Ros, L.F., De Souza, R.S., De Assis Silva, C.M., Sombra, C.L., 2000. Depositional and diagenetic controls on the reservoir quality of Lower Cretaceous Pendencia sandstones, Potiguar rift basin, Brazil. Am. Assoc. Pet. Geol. Bull. 84, 1719–1742.

Dutton, S.P.; Hutton, M.E.; Ambrose, W.A.; Childers, A.T.; Loucks, R.G., 2018. Preservation of reservoir quality by chlorite coats in deep Tuscaloosa Sandstones, Central Louisiana, USA. Gulf Coast Assoc. Geol. Soc. 7, 46–58.

Dutton, S.P., 2008. Calcite cement in Permian deep-water sandstones, Delaware Basin, west Texas: Origin, distribution, and effect on reservoir properties. Am. Assoc. Pet. Geol. Bull. 92, 765–787.

Ehrenberg, S.N., 1990. Relationship between diagenesis and reservoir quality in sandstones of the Garn Formation, Haltenbanken, mid-Norwegian Continental Shelf. Am. Assoc. Pet. Geol. Bull. 74, 1538–1558.

Ehrenberg, S.N., 1993. Preservation of anomalously high porosity in deeply buried sandstones by grain-coating chlorite: examples from the Norwegian Continental Shelf 77, 1260–1286.

Ehrenberg, S.N., 1997. Influence of Depositional Sand Quality and Diagenesis on Porosity and Permeability: Examples from Brent Group Reservoirs, Northern North Sea. SEPM J. Sediment. Res. Vol. 67, 197–211.

Eldrett, J., Tripsanas, E., Davis, C., Mckie, T., Vieira, M., Osterloff, P., Sandison, T., 2015. Sedimentological evolution of Sele Formation deep-marine depositional systems of the Central North Sea. Tert. Deep. Reserv. North Sea Reserv. North Sea 403.

Fildani, A., Clark, J., Covault, J.A., Power, B., Romans, B.W., Aiello, I.W., 2018. Muddy sand and sandy mud on the distal Mississippi fan: Implications for lobe depositional processes. Geosphere 14, 1051–1066.

Folk, R.L., 1980. Petrology of sedimentary rocks. Hemphill Publishing Company, Austin, Texas.

Haughton, P.D.W., Barker, S.P., McCaffrey, W.D., 2003. "Linked" debrites in sand-rich turbidite systems - Origin and significance. Sedimentology 50, 459–482.

Heald, M.T., and Larese, R.E., 1974. Influence of Coatings on Quartz Cementation. SEPM J. Sediment. Res. Vol. 44, 1269–1274.

Hempton, M., Marshall, J., Sadler, S., Hogg, N., Charles, R., Harvey, C., 2005. Turbidite reservoirs of the Sele formation, Central North Sea: Geological challenges for improving production. Pet. Geol. Conf. Proc. 6, 449–459.

Houseknecht, D.W., Ross, L.M., 1992. Clay Minerals in Atokan Deep-Water Sandstone Facies, Arkoma Basin: Origins and Influence on Diagenesis and Reservoir Quality. Orig. Diagenesis, Petrophysics Clay Miner. Sandstones 227–240.

Huang, Y., Kane, I.A., Zhao, Y., 2020. Effects of sedimentary processes and diagenesis on reservoir quality of submarine lobes of the Huangliu Formation in the Yinggehai Basin, China. Mar. Pet. Geol. 120.

Irwin, H., Curtis, C., Coleman, M., 1977. Isotopic evidence for source of diagenetic carbonates formed during burial of organic-rich sediments. Nature 269, 209–213.

Ito, M., 2008. Downfan transformation from turbidity currents to debris flows at a channel-to-lobe transitional zone: The lower Pleistocene Otadai Formation, Boso Peninsula, Japan. J. Sediment. Res. 78, 668–682.

Jennette, D.C., Garfield, T.R., Mohrig, D.C., Cayley, G.T., 2000. The Interaction of Shelf Accommodation, Sediment Supply and Sea Level in Controlling the Facies, Architecture and Sequence Stacking Patterns of the Tay and Forties/Sele Basin-Floor Fans, Central North Sea. In: Weimer, P., Bouma, A.H. and Perkins, B.F. (Ed.), Deep-Water Reservoirs of the World: 20th Annual. 3–6 December, Houston, USA, pp. 402–421.

Jones, D.W., Large, S., McQueen, A., Helmi, A., 2015. Reservoir geology of the Paleocene Forties Sandstone Member in the Fram discovery, UK Central North Sea. Geol. Soc. Spec. Publ. 403, 219–246.

Kane, I.A., Pontén, A.S.M., Vangdal, B., Eggenhuisen, J.T., Hodgson, D.M., Spychala, Y.T., 2017. The stratigraphic record and processes of turbidity current transformation across deep-marine lobes. Sedimentology 64, 1236–1273.

Kessler, L.G., Zang, R.D., Englehorn, J.A., Eger, J.D., 1980. Stratigraphy and sedimentology of a Palaeocene submarine fan complex, Cod Field, Norwegian North Sea. Sediment.

North Sea Reserv. Rocks. NPF Artic. 8.

Kilhams, B., Morton, A., Borella, R., Wilkins, A., Hurst, A., 2014. Understanding the provenance and reservoir quality of the Sele Formation sandstones of the UK Central Graben utilizing detrital garnet suites. Geol. Soc. Spec. Publ. 386, 129–142.

Knox, R.W.O., Holloway, S., 1992. Paleogene of the central and northern North Sea. In: Knox, R.W.O'B. and Cowdey, W.G. (Ed.), Lithostratigraphic Nomenclature of the UK North Sea. British Geological Survey, Nottingham, p. 206.

Kordi, M., 2013. Characterization and prediction of reservoir quality in chlorite-coated sandstones: evidence from the Late Cretaceous Lower Tuscaloosa Formation at Cranfield Field, Mississippi, U.S.A. The University of Texas at Austin.

Kuenen, P.H., Sengupta, S., 1970. Experimental marine suspension currents, competency and capacity. Geol. en mijnbouw. 49, 89–118.

Kunka, J.M., Williams, G., Cullen, B., Boyd-Gorst, J., Dyer, G.R., Garnham, J.A., Warnock, A., Wardell, J., Davis, A., Lynes, P., 2003. The Nelson Field, Blocks 22/11, 22/61, 22/7, 22/12a, UK North Sea. In: Gluyas, J.G. and Hichens, H.M. (Ed.), Geological Society Memoir. Geological Society, London, London, pp. 617–646.

Lander, R.H., Larese, R.E., Bonnell, L.M., 2008. Toward more accurate quartz cement models: The importance of euhedral versus noneuhedral growth rates. Am. Assoc. Pet. Geol. Bull. 92, 1537–1563.

Lander, R.H., Walderhaug, O., 1999. Predicting porosity through simulating sandstone compaction and quartz cementation. AAPG Bull. (American Assoc. Pet. Geol. 83, 433–449.

Lien, T., Midtbø, R.E., Martinsen, O.J., 2006. Depositional facies and reservoir quality of deep-marine sandstones in the Norwegian Sea. Nor. Geol. Tidsskr. 86, 71–92.

Lowe, D.R., 1982. Sediment gravity flows: II. Depositional models with special reference to the deposits of high-density turbidity currents. J. Sediment. Petrol. 52, 279–297.

Lundegard, P.D., 1992. Sandstone porosity loss - a "big picture'' view of the importance of compaction." J. Sediment. Petrol. 62, 250–260.

Ma, B., Cao, Y., Eriksson, K.A., Jia, Y., Gill, B.C., 2017. Depositional and diagenetic controls on deeply-buried Eocene sublacustrine fan reservoirs in the Dongying Depression, Bohai Bay Basin, China. Mar. Pet. Geol. 82, 297–317.

Mansurbeg, H., Morad, S., Salem, A., Marfil, R., El-ghali, M.A.K., Nystuen, J.P., Caja, M.A., Amorosi, A., Garcia, D., La Iglesia, A., 2008. Diagenesis and reservoir quality evolution of palaeocene deep-water, marine sandstones, the Shetland-Faroes Basin, British continental shelf. Mar. Pet. Geol. 25, 514–543.

Mao, S.W., Bao, Z.D., Wang, X.X., Gao, Y.S., Song, J., Wang, Z.C., Liu, W., Zhang, L., Wei, M.Y., Bao, Y.F., 2019. Origin of carbonate cements and reservoir evolution of tight sandstone in the Upper Triassic Yanchang Formation, Ordos Basin, China. Aust. J. Earth Sci. 66, 1175–1194.

Marchand, A.M.E., Apps, G., Li, W., Rotzien, J.R., 2015. Depositional processes and impact on reservoir quality in deepwater Paleogene reservoirs, US Gulf of Mexico. Am. Assoc. Pet. Geol. Bull. 99, 1635–1648.

McBride, E.F., 1989. Quartz cement in sandstones: a review. Earth Sci. Rev. 26, 69–112.

McKie, T., Rose, P.T.S., Hartley, A.J., Jones, D.W., Armstrong, T.L., 2015. Tertiary deep-marine reservoirs of the North Sea region: An introduction. Geol. Soc. Spec. Publ. 403, 1–16.

Middleton, G. V, Hampton, M.A., 1973. Part I. Sidement gravity flows: mechanics of flow and deposition. In: Middleton, G.V.; Bouma, A.H. (Ed.), Turbidites and Deep Water Sedimentation. Soc. Econ. Paleontol. Mineral., Pac. Sect., Short Course, p. 38.

Morad, S., Al-Ramadan, K., Ketzer, J.M., De Ros, L.F., 2010. The impact of diagenesis on the heterogeneity of sandstone reservoirs: A review of the role of depositional fades and sequence stratigraphy. Am. Assoc. Pet. Geol. Bull. 94, 1267–1309.

Morad, S., Ketzer, J.M., De Ros, L.R., 2000. Spatial and temporal distribution of diagenetic alterations in siliciclastic rocks: Implications for mass transfer in sedimentary basins. Sedimentology 47, 95–120.

Mudge, D.C. and Copestake, P., 1993. A revised Lower Palaeogene lithostratigraphy for the Outer Moray Firth. Mar. Pet. Geol. 9, 53–69.

Mudge, D.C., 2015. Regional controls on Lower Tertiary sandstone distribution in the North Sea and NE Atlantic margin basins. Geol. Soc. Spec. Publ. 403, 17–42.

Neal, J.., 1996. A summary of Paleogene sequence stratigraphy in northwest Europe and the North Sea. In: Knox, R.W.O'B., Corfield, R.M. and Dunay, R.E. (Ed.), Correlation of the Early Paleogene in Northwest Europe. Geological Society, London, Special Publications, pp. 15–42.

Oluwadebi, A.G., Taylor, K.G., Dowey, P.J., 2018. Diagenetic controls on the reservoir quality of the tight gas Collyhurst Sandstone Formation, Lower Permian, East Irish Sea Basin, United Kingdom. Sediment. Geol. 371, 55–74.

Paxton, S.T., Szabo, J.O., Ajdukiewicz, J.M., Klimentidis, R.E., 2002. Construction of an intergranular volume compaction curve for evaluating and predicting compaction and porosity loss in rigid-grain sandstone reservoirs. Am. Assoc. Pet. Geol. Bull. 86, 2047–2067.

Pittman, E.D., Larese, R.E., Heald, M.T., 1992. Clay Coats: Occurrence and Relevance To Preservation of Porosity in Sandstones. In: Housenknecht, D W. and Pittman, E. (Ed.), Origin, Diagenesis, and Petrophysics of Clay Minerals in Sandstones. SEPM, Special Publication, pp. 241–255.

Porten, K.W., Kane, I.A., Warchoł, M.J., Southern, S.J., 2016. A Sedimentological Process-Based Approach To Depositional Reservoir Quality of Deep-Marine Sandstones: An Example From the Springar Formation, Northwestern Vøring Basin, Norwegian Sea. J. Sediment. Res. 86, 1269–1286.

Porten, K.W., Warchoł, M.J., Kane, I.A., 2019. Formation of detrital clay grain coats by dewatering of deep-water sands and significance for reservoir quality. J. Sediment. Res. 89, 1231–1249.

Pryor, W.A., 1973. Permeability-Porosity Patterns and Variations in Some Holocene Sand Bodies. Am. Assoc. Pet. Geol. Bull. 57.

Scott, E.D., Gelin, F., Jolley, S.J., Leenaarts, E., Sadler, S.P., Elsinger, R.J., 2010.

Sedimentological control of fluid flow in deep marine turbidite reservoirs: Pierce Field, Uk Central North Sea. Geol. Soc. Spec. Publ. 347, 113–132.

Shaw, H.F., Conybeare, D.M., 2003. Patterns of Clay Mineral Diagenesis in Interbedded Mudrocks and Sandstones: An Example from the Palaeocene of the North Sea. In: R.H Worden and S. Morad (Ed.), Clay Mineral Cements in Sandstones. International Association of Sedimentologists, pp. 129–145.

Stammer, J.G., 2014. Hydrodynamic fractionation of minerals and textures in submarine fans: Quantitative analysis from outcrop, experimental, and subsurface studies. ProQuest Diss. Theses. Colorado School of Mines.

Stewart, R.N.., 1995. Regional diagenetic porosity change in palaeocene oilfield sandstones, U.K. North Sea. University of Glasgow.

Stewart, R.N.T., Haszeldine, R.S., Fallick, A.E., Wilkinson, M., Macaulay, C.I., 2000. Regional distribution of diagenetic carbonate cement in Palaeocene deepwater sandstones: North Sea. Clay Miner. 35, 119–133.

Stricker, S., 2016. Influence of fluid pressure on the diagenesis of clastic sediments. Durham University, UK.

Stricker, S., Jones, S.J., 2018. Enhanced porosity preservation by pore fluid overpressure and chlorite grain coatings in the Triassic Skagerrak, Central Graben, North Sea, UK. Geol. Soc. Spec. Publ. 435, 321–341.

Stricker, S., Jones, S.J., Sathar, S., Bowen, L., Oxtoby, N., 2016. Exceptional reservoir quality in HPHT reservoir settings: Examples from the Skagerrak Formation of the Heron Cluster, North Sea, UK. Mar. Pet. Geol. 77, 198–215.

Swarbrick, R.E., Osborne, M.J., Grunberger, D., Yardley, G.S., Macleod, G., Aplin, A.C., Larter, S.R., Knight, I., Auld, H.A., 2000. Integrated study of the Judy Field (Block 30/7a) - an overpressured Central North Sea oil/gas field. Mar. Pet. Geol. 17, 993–1010.

Talling, P.J., Amy, L.A., Wynn, R.B., Peakall, J., Robinson, M., 2004. Beds comprising debrite sandwiched within co-genetic turbidite: Origin and widespread occurrence in distal depositional environments. Sedimentology 51, 163–194.

Talling, P.J., Masson, D.G., Sumner, E.J., Malgesini, G., 2012. Subaqueous sediment density flows: Depositional processes and deposit types. Sedimentology 59, 1937–2003.

Tang, L., Gluyas, J., Jones, S., 2018. Porosity preservation due to grain coating illite/smectite: Evidence from Buchan Formation (Upper Devonian) of the Ardmore Field, UK North Sea. Proc. Geol. Assoc. 129, 202–214.

Taylor, T.R., Giles, M.R., Hathon, L.A., Diggs, T.N., Braunsdorf, N.R., Birbiglia, G. V., Kittridge, M.G., MacAulay, C.I., Espejo, I.S., 2010. Sandstone diagenesis and reservoir quality prediction: Models, myths, and reality. Am. Assoc. Pet. Geol. Bull. 94, 1093–1132.

Thompson, P.J., Butcher, P.D., 1990. The geology and geophysics of the Everest Complex. Am. Assoc. Pet. Geol. Bull. 74, 778.

Ulmer-Scholle, D.S., Scholle, P.A., Schieber, J., Raine, R.J., 2015. A Color Guide to the Petrography of Sandstones, Siltstones, Shales and Associated Rocks, A Color Guide to the Petrography of Sandstones, Siltstones, Shales and Associated Rocks. AAPG.

Vining, B.A., Ioannides, N.S., Pickering, K.T., 1993. Stratigraphic relationships of some Tertiary lowstand depositional systems in the Central North Sea. In: Parker, J.R. (Ed.), Petroleum Geology Conference Proceedings. Geological Society, London, pp. 17–29.

Walderhaug, O., 1994. Precipitation rates for quartz cement in sandstones determined by fluid-inclusion microthermometry and temperature-history modeling. J. Sediment. Res. A Sediment. Petrol. Process. 64 A, 324–333.

Walderhaug, O., 1996. Kinetic modeling of quartz cementation and porosity loss in deeply buried sandstone reservoirs. Am. Assoc. Pet. Geol. Bull. 80, 731–745.

Walderhaug, O., 2000. Modeling quartz cementation and porosity in Middle Jurassic Brent Group sandstones of the Kvitebjørn Field, northern North Sea. Am. Assoc. Pet. Geol. Bull. 84, 1325–1339.

Walderhaug, O., BjØrkum, P.A., 2003. The effect of stylolite spacing on quartz cementation in the Lower Jurassic StØ Formation, Southern Barents Sea. J. Sediment. Res. 73, 146–156.

Waples, D.W., Pacheco, J., Vera, A., 2004. A method for correcting log-derived temperatures in deep wells, calibrated in the Gulf of Mexico. Pet. Geosci. 10, 239–245.

Whyatt, M., Bowen, J.M., Rhodes, D.N., 1992. The Nelson Field: A successful application of a development geoseismic model in North Sea exploration. Geol. Soc. Spec. Publ. 67, 283–305.

Wooldridge, L.J., Worden, R.H., Griffiths, J., Utley, J.E.P., 2017. Clay-Coated Sand Grains In Petroleum Reservoirs: Understanding Their Distribution Via A Modern Analogue. J. Sediment. Res. 87, 338–352.

Wooldridge, L.J., Worden, R.H., Griffiths, J., Utley, J.E.P., 2019. How to quantify clay-coat grain coverage in modern and ancient sediments. J. Sediment. Res. 89, 135–146.

Worden, R.H., Griffiths, J., Wooldridge, L.J., Utley, J.E.P., Lawan, A.Y., Muhammed, D.D., Simon, N., Armitage, P.J., 2020. Chlorite in sandstones. Earth-Science Rev. 103105.

Worden, R.H., Morad, S., 2003a. Clay Minerals in Sandstones: Controls on Formation, Distribution and Evolution. Clay Miner. Cem. Sandstones 1–41.

Worden, R.H., Morad, S., 2003b. Clay Minerals in Sandstones: Controls on Formation, Distribution and Evolution. In: Clay Mineral Cements in Sandstones. Blackwell Publishing Ltd., Oxford, UK, pp. 1–41.

Xia, C., Wilkinson, M., 2017. The geological risks of exploring for a CO2 storage reservoir. Int. J. Greenh. Gas Control 63, 272–280.

Yezerski, D.J., Shumaker, N., 2018. PS Improving Prediction of Porosity Preservation in Thermally-Stressed Deep Marine Sandstones: A Synthesis of Grain-Coating Chlorite Observations*. In: AAPG 2017 Annual Convention and Exhibition. Search and Discovery Article, Houston, Texas.