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Sedimentology and Depositional Environments in the Mesozoic, West of Shetland

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Front cover

Erosive contact between two beds of oil-stained sandstone. Well 204/28-1 (192.50 m – 1928.69 m)

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Sedimentology and Depositional Environments in the Mesozoic, West of Shetland

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Executive Summary

As part of Phase 3 of the Faroe-Shetland Consortium project on the UK sector of the Faroe-Shetland Basin, BGS completed detailed (10 cm-scale) sedimentary logging of 604.77 m of conventional core recovered from 19 wells, drilled between 1974 and 1995. The project originally focussed solely on Jurassic-aged sediments, as identified in BGS held well databases. In reality, the project examined a suit of sediments ranging from the Triassic, Jurassic and Lower Cretaceous. In addition, a suite of complementary palynological sampling was completed. The goal was to provide additional depositional environment information from palyno-facies analysis, along with age determination for the sediments. Together, the two new datasets form an integrated re-assessment of the Mesozoic-aged depositional environments located to the West of Shetland.

The Triassic-aged deposits of the Papa Group record deposition in a fluvial environment, whereby the fluvial systems display meandering to braided characteristics. In places, particularly in the upper parts of the cored Triassic-aged strata, the sediments display evidence for nearshore, wave-working processes. The nearshore working may be evidence for a transgression event at the top of the cored Triassic interval; something which should be investigated further in the future.

Within the Jurassic-aged succession, two main groups were analysed: the Skerry Group and the Humber Group. Sediments within the Skerry Group were deposited within a fully marine, shelfal environment (the Stack Skerry Formation) and a relatively deeper-water, outer shelf to bathyal environment (the Sule Skerry Formation). Late Jurassic-aged sediments from the Humber Group are represented by the Rona Member, the Solan Sandstone Member and the Ridge Conglomerate Member. BGS has subdivided the Rona Member into five “facies”, largely on the basis of depositional environment. These include: Rona R1 (Fluvial), Rona R2 (Fan Delta), Rona R3 (Marginal Marine), Rona R4 (Shoreface/Littoral) and Rona R5 (Shallow Marine). Deposits of the Rona R4 facies represent good hydrocarbon reservoir targets, whilst the Rona R3 facies has the potential to form a sourcing lithology. The Solan Sandstone Member, interpreted to be contemporaneous with the deposition of the Rona Member, was deposited in a deep-marine, turbidite fan system. The Kimmeridge Clay Formation is encountered in a number of wells, typically represented by a dark grey- to black-coloured, hemi-pelagic mud-prone succession.

The Early Cretaceous-aged Cromer Knoll Group is also present in the core data, represented by: turbidite fan deposits, formed in a deep marine environment (204/19-1 & 205/21-1A); and by shoreface/littoral deposits representative of a marine setting (205/26a-2). These sediments appear to rest unconformably on the Kimmeridge Clay Formation.

1 Introduction

This study documents the results of a sedimentological analysis of 604.77 m of conventional core, from "Jurassic"-aged strata, West of Shetland. The cores were logged at the BGS core store in Keyworth. All depths quoted are measured depth below Kelly Bushings in metres. No core shifts have been made. The report outlines the methodologies that were used, the sedimentary logs and a detailed group/formation/member-based analysis of the sedimentary environments, using biostratigraphy to provide control. The summaries for each individual section are included in the main report, entitled "Jurassic stratigraphy of the Faroe-Shetland region: implications for the evolution of the proto-NE Atlantic margin" (Andrews et al., 2018), which forms the final deliverable for the Jurassic Project for the Phase 3 of the Faroe-Shetland Consortium.

2 Stratigraphy

2.1 TRIASSIC

Triassic strata West of Shetland are represented by the Papa Group (***Figure 1***). The sediments were deposited in fluvial, alluvial, lacustrine and aeolian environments (Herries et al., 1999); reflecting extension, the northwards movement of Pangaea away from the equator and an overall lack of marine influence throughout this period.

2.2 EARLY JURASSIC

In the Faroe-Shetland region, the Early Jurassic is represented by the deposits of the Skerry Group. This comprises two formations: the Stack Skerry Formation; and the Sule Skerry Formation (***Figure 1***). These are thought to have been deposited in a "shallow marine, inner shelf" (Stack Skerry Formation) to "shallow marine" (Sule Skerry Formation) environment (Ritchie et al. 1996).

2.3 MID TO LATE JURASSIC

In the study area, deposits of the Mid to Late Jurassic are represented by the Humber Group, comprising the Heather Formation and the Kimmeridge Clay Formation (***Figure 1***). The Heather Formation contains one member: the Fair Sandstone Member, interpreted as being deposited in a submarine fan setting (Haszeldine et al., 1987). In the study area, the Kimmeridge Clay Formation comprises: the Rona Member; the Solan Sandstone Member and the Ridge Conglomerate Member. The Rona Member is considered to represent a number of environmental settings, ranging from debris flow deposits to shallow marine sedimentation (Verstralen et al., 1995). The Solan Sandstone Member has been interpreted as turbidites deposited on a marine shelf or basinal environment (Herries et al., 1999), or as gully-fill deposits (Verstralen, 1996). The Ridge Conglomerate Member has been interpreted as submarine scree deposits, derived from an active fault scarp (Haszeldine et al., 1987).

2.4 EARLY CRETACEOUS

In the study area, the Early Cretaceous is represented by deposition of the Cromer Knoll Group, representing the post-Kimmeridge Clay Formation Lower Cretaceous sequence. The Cromer Knoll Group records deposition in a range of sedimentary environments, including shallow marine to paralic, through to deepwater settings (see Ritchie et al., 2011 and references therein), and has been discussed more recently in Stoker et al., (2017).

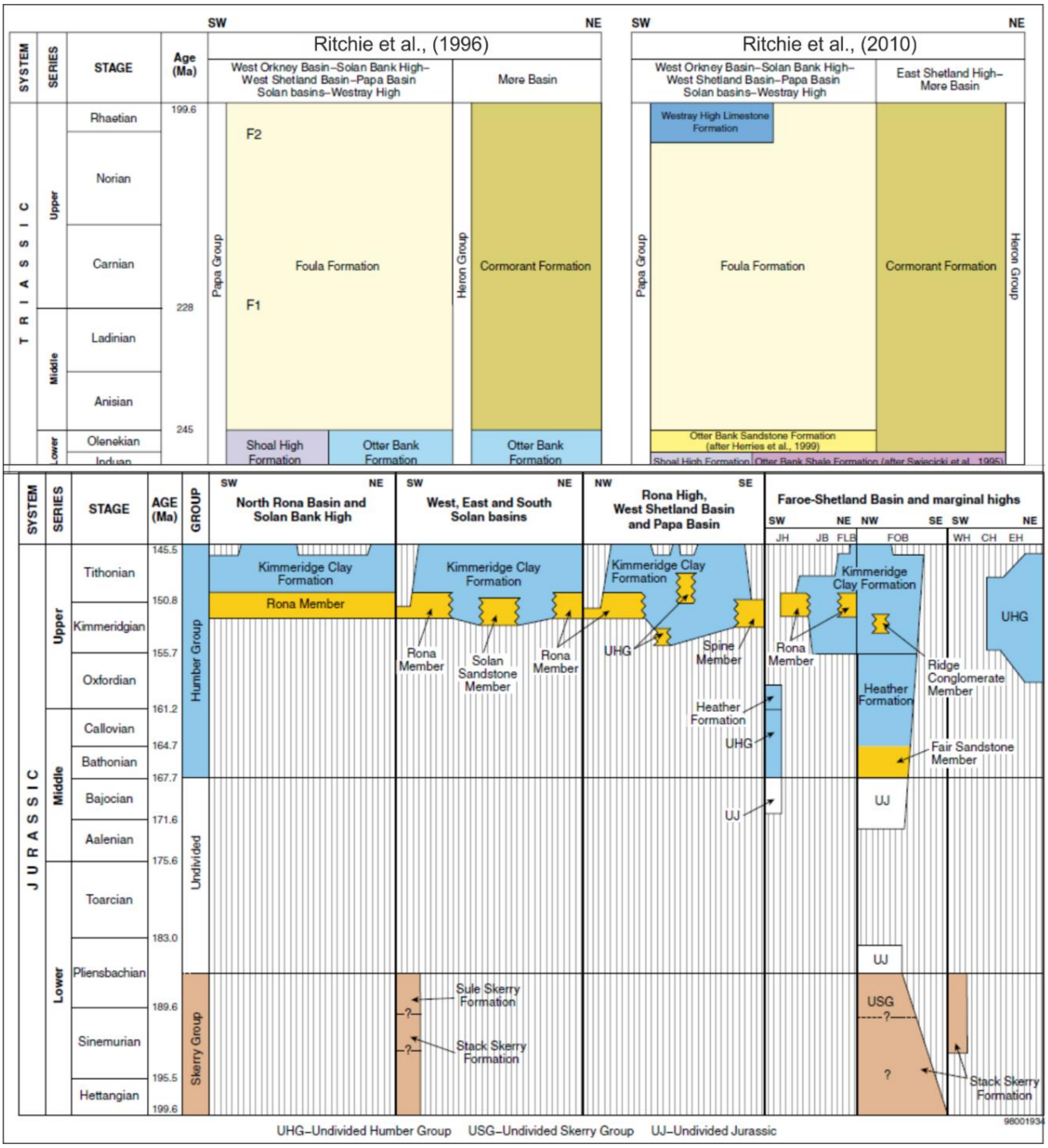

Figure 1 Lithostratigraphical nomenclature for Triassic and Jurassic, West of Shetland (modified after Ritchie et al., 2011).

3 Methodology

The aim of this assessment was to examine a suite of conventional core data, identified as being of “Jurassic” in age, in order to determine depositional environments in the Jurassic, West of Shetland. The sedimentological analysis was completed alongside palynological sampling, in order to provide information concerning the environment of deposition (palynofacies) and, where key microfossils are present, critical age dating. The results of the palynological studies are contained within a series of complementary well reports (see Riding 2018a-i; Thomas, 2018a-j). Furthermore, a seismic interpretation study was completed, which assesses the distribution and thickness of Jurassic-aged strata, West of Shetland (see Quinn, 2018)

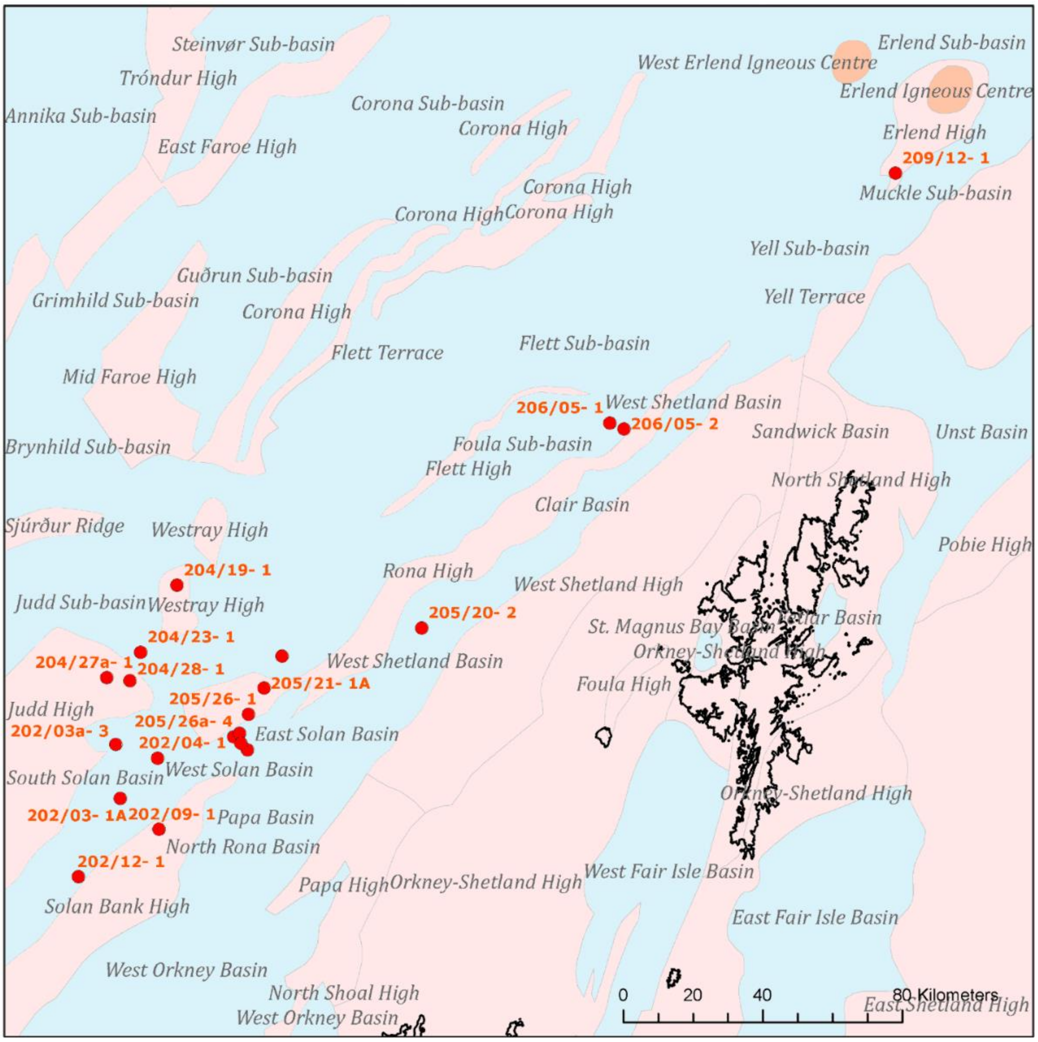

Figure 2 Well locations of the 19 wells, from which 604.77 m of core data that were examined.

A suite of conventional cores were selected from a database on the basis that the wells had been assigned to the "Jurassic". By the end of the study it was apparent that not all of the cores selected for this study were actually of Jurassic age. Both Triassic-aged and Early Cretaceous-aged sediments were also found within this dataset and their depositional environments have been interpreted and discussed in separate sections. The broad stratigraphic subdivisions of sediments in core data, examined as part of this study, are summarised in ***Table 1***. In total, 604.77 m of conventional core data, containing sedimentary rocks, from 19 separate wells (***Figure 2***) were examined.

Well Number	**Precambrian (Crystalline Basement - Lewisian)**	**Triassic (Papa Group)**	**Lower Jurassic (Skerry Group)**	**Middle Jurassic (Heather Formation)**	**Upper Jurassic (Rona Member)**	**Upper Jurassic to Lower Cretaceous (Kimmeridge Clay Formation) Solan Sandstone Member (S) or Ridge Conglomerate Member (RC)**	**Lower Cretaceous (Cromer Knoll Group)**
202/03-1A							
202/03a-3							
202/04-1							
202/09-1							
202/12-1							
204/19-1							

204/27a-1							
204/28-1							
205/20-2							
205/21-1A							
205/22-1A							
205/26-1							
205/26a-2							
205/26a-4						S	
205/26a-5Z						S	
205/26a-6							
206/05-1						RC	
206/05-2							
209/12-1							

Table 1 Stratigraphy represented in core data from 19 wells, examined as part of this study.

Detailed sedimentological logging was undertaken in order to capture information on grain size, lithology and sedimentary structures, to a 10 cm-scale of resolution. The interpretation of the sedimentary logs was completed independently of the analysis of the palynology information. The sedimentary cores were subsequently divided into lithostratigraphical packages (group/formation/member) based on their characteristics, principally controlled by the environment of deposition (Appendix 1). Where possible, (new) dating was used to constrain the lithostratigraphical model. The following sections discuss each lithostratigraphical sub-division.

4 Crystalline Basement (Lewisian – Precambrian)

Crystalline basement rocks (Lewisian - Precambrian) were encountered in three wells examined as part of this study (***Table 2***). Sedimentary logs (***Figure 3***) show that it is unconformably overlain by Late Jurassic-aged deposits of the Rona Member R2 (see section 7.2.1.2). These sediments were logged at a 10 cm-scale of resolution (Appendices 8, 11 & 12).

Well Number	Top Depth (m)	Base Depth (m)	Underlain by in core	Overlain by in core	Comments
205/21-1A	1353.81	1365.50	None	Rona Member R2	16 cm weathered
205/22-1A	3222.34	3226.00	None	Rona Member R2	30 cm weathered
204/27a-1	2128.90	2138.00	None	Rona Member R2	+3.5 m weathered

Table 2 Depth of core data through the crystalline basement (Lewisian – Precambrian).

Description

In 205/21-1A, the succession is composed of up to 10 m of green, red and blue-coloured, crystalline rock. The rock displays a shiny lustre and contains interwoven granitic lithologies. The uppermost 30 cm displays visible signs of a weathering/alteration profile.

In 205/22-1A, the succession is composed of 3.5 m of light green, light red and white-coloured, hard, crystalline rock. The upper 16 cm documents a weathering profile, with some tentative bioturbation and or pedogenic alteration textures observed.

In 204/27a-1, the core documents >3.5 m of intensely weathered/altered crystalline rock, with an "appearance" of highly mixed sediment. It contains at least one example of a well-preserved pollen spore (Riding, 2018b) and, in some places, displays calcite which infills a "vuggy" texture.

Interpretation

In 205/22-1A, the top 16 cm of crystalline basement appears to be altered, suggesting that it was not as exposed (or not exposed at all) when compared with the basement in 204/27a-1. The same is clear in 205/21-1A, with only the upper 30 cm of basement being affected by weathering/erosion. In contrast, the 3.5 m of altered crystalline basement at the base of 204/27a-1 was likely weathered for a prolonged period of time, indicating a significant period of exposure at the surface. The lack of a deep-weathering profile in wells 205/21-1A and 205/22-1A suggests little or no exposure of the basement rocks prior to the deposition of the Jurassic-aged sedimentary cover. Another possibility is the basement block of the Rona High (where 205/21-1A and 205/22-1A were drilled; see ***Figure 2***) was submerged before being covered by the overburden.

Conversely, the basement rocks observed in 204/27a-1 were almost certainly exposed for a protracted period of time before the overburden was deposited. Well 204/27a-1 was drilled on the edge of the Judd High, on the Judd Terrace (***Figure 2***). This provides an indication that the Judd Terrace formed an emergent feature up until at least Late Jurassic times. The deep weathering profile observed in 204/27a-1 might suggest that although the area of the Judd High and Judd Terrace was an emergent feature, it was most likely a palaeo-low.

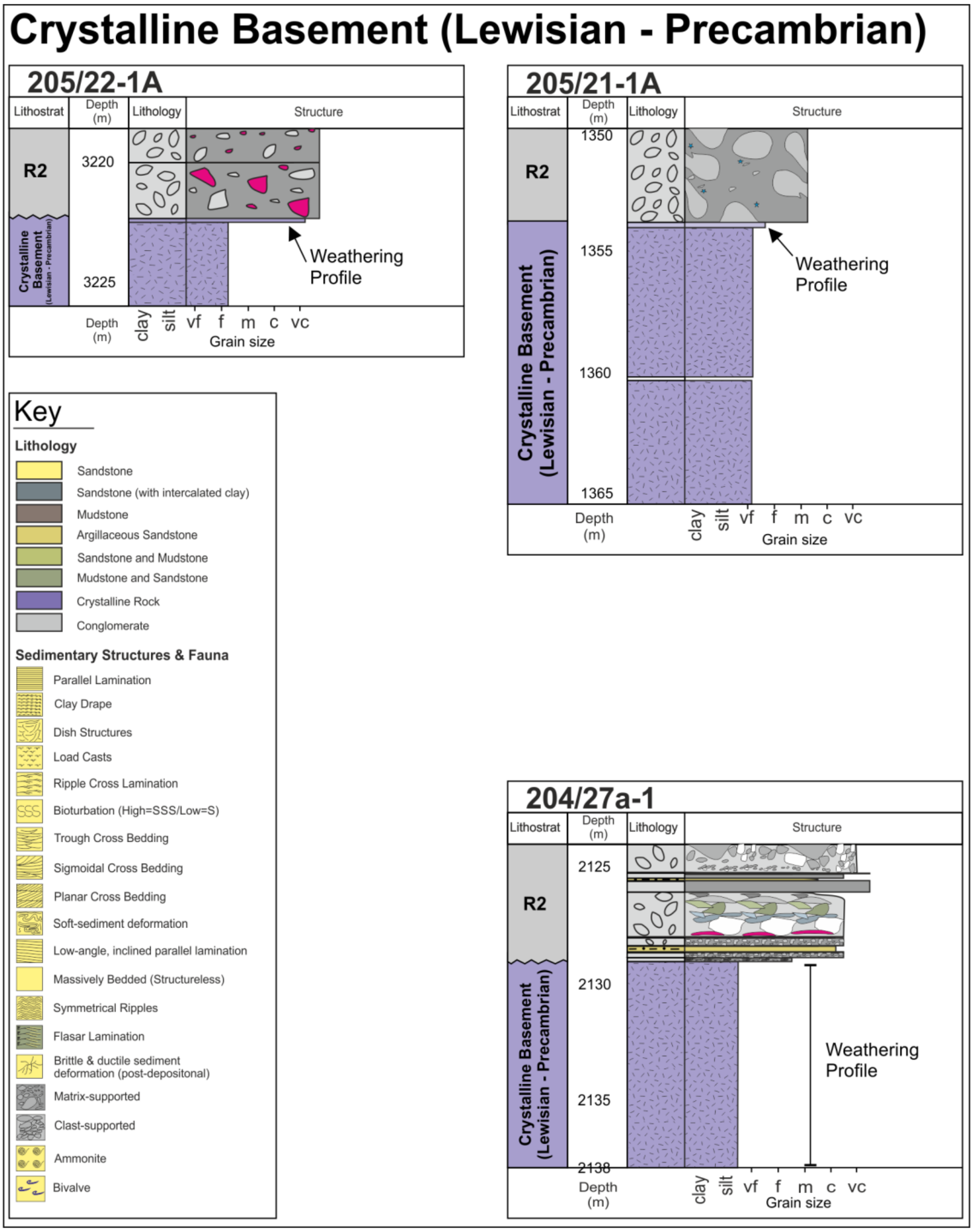

Figure 3 Sedimentary logs through the Crystalline Basement (Lewisian, Precambrian) and the overlying Rona R2 facies, representing fan delta deposition directly onto basement.

Summary

Crystalline basement (Lewisian, Precambrian) was encountered in three of the wells (205/21-1A, 205/22-1A and 204/27a-1) logged as part of this study (***Figure 3***). In all three cases, the basement rocks are overlain, unconformably, by Late Jurassic-aged deposits of Rona Member R2 (fan delta deposits). Variability exists within the crystalline basement, particularly the depth and degree of palaeo-weathering. The basement displays a much deeper weathering profile in well 204/27a-1 (>3.5 m-thick), than compared with wells 205/21-1A and 205/22-1A, where it is much thinner (16 cm and 30 cm, respectively). Well 204/27a-1 was drilled on the Judd Terrace and displays a deep weathering profile, suggesting prolonged exposure, potentially in a wet, palaeo-low setting. In comparison, thin weathering profiles at the top of the crystalline basement from wells 205/21-1A and 205/22-1A, drilled on the south-eastern corner of the Rona Ridge, may suggest relatively shorter periods of exposure.

5 Sedimentology of the Papa Group (Triassic)

The Triassic-aged Papa Group sediments were encountered in two wells examined as part of this study (***Table 3***). These sediments were logged at a 10 cm-scale of resolution (Appendices 10 and 15) and have been summarised (***Figure 4***).

Well Number	Top Depth (m)	Base Depth (m)	Underlain by in core	Overlain by in core	Comments
205/20-2	2983.87	3001.31	None	Rona Member R3	None
205/26a-4	2469.23	2501.25	None	Kimmeridge Clay Formation	None

Table 3 Depth of core data through the Papa Group (Triassic).

Description

In 205/20-2, sediments are characterised as a 13 m-thick succession of fine to medium-grained, fining-upwards, planar cross-bedded and trough cross-bedded, erosively based, reddy brown-coloured sandstones. Occasionally, beds display sub-angular, lithic and granitic clasts, typically sorted along cross beds sets. Basal scours are also present, often showing granitic and lithic pebble lags, along with intra-formational mudstones and siltstone clasts. Interbedded with this are very fine-grained, ripple cross-laminated or parallel-laminated, argillaceous sandstones. There is an uppermost zone within the core (above 2988.00 m; ***Figure 4***) where sediments change from a reddy-brown colour into a yellow-coloured sandstone. The lithofacies does not change across this interface.

In 205/26a-4, a thick succession of 1-2 m-thick, normally graded, trough cross-bedded to planar cross-bedded, quartz and k-spar-rich sandstone is present. The beds display very coarse-grained, granitic and lithic pebble-rich basal lags, along with well-developed trough cross-bedding. Trough cross-bedding typically develops into planar cross-bedding towards the top of the bed. An inversely graded unit (at 2491.12 m; ***Figure 4***) marks a change in the lithofacies, with beds above this point becoming much thinner (0.25 - 0.5 m vs. 0.5 m – 2.5 m). This is accompanied by a reduction in thickness of the basal lags and out-sized granitic and lithic clast sizes. In addition, very fine- to fine-grained sandstone bed become more regular, often displaying well-developed parallel-laminations and elevated clay concentrations within the matrices. Beds become thicker, with better-developed trough cross-bedding upwards from this point. The upper section in 205/26a-4 (above 2479.00 m; ***Figure 4***) documents an important change in terms of clast composition. There is an immediate reduction in the size and percentage concentration of granitic clasts within the matrix. These beds have a comparably lower matrix grain size than compared with units below. The granitic clasts, along with the alkali feldspars within the matrix, are gradually worked-out of the sediments and are almost completely absent from the upper 1-2 m of Triassic-aged core. Along with the compositional change, the sediments form coarsening-upwards, fine to medium-grained, moderately sorted packages of sandstone. They typically contain rafted intra-formational mud clasts, concentrated on bed tops, and evidence for soft-sediment slumping or de-watering.

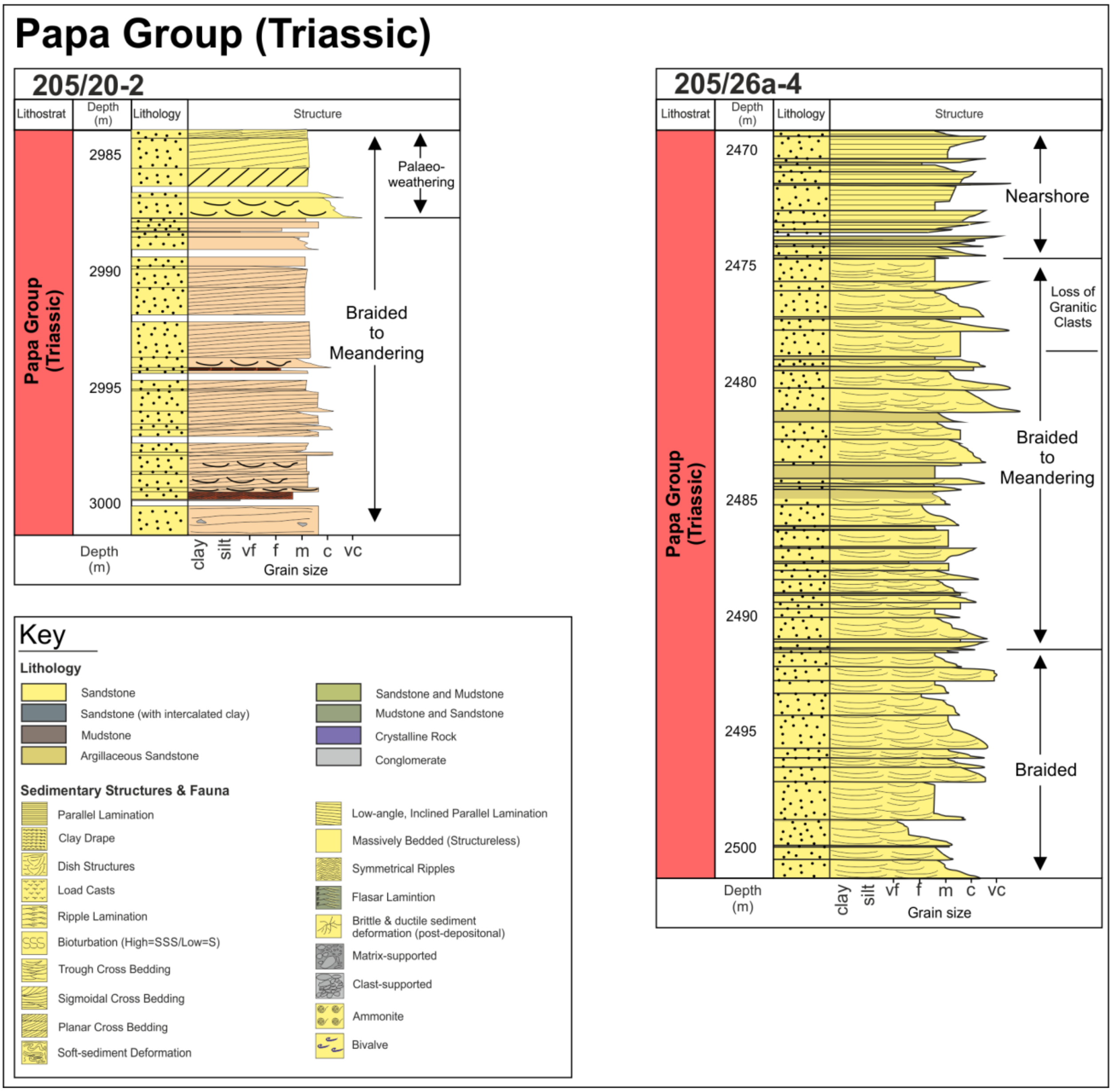

Figure 4 Sedimentary logs through the Papa Group (Triassic).

Interpretation

In 205/20-2, fluvial processes dominate, typified by vertically stacked successions of fluvial channel to point bar deposition. Fluvial channel elements are represented by vertically-stacked successions of medium to coarse grained, trough cross bedded sandstone that often display erosive basal contacts, normal grading and contain pebble lags. Point bar deposition is represented by stacked beds of planar cross bedded sandstone. Generally, preserved point bar elements are more dominant over deposition of channel elements. These deposits are interpreted to represent a braided to meandering system. Granitic clasts, particularly within the channel lags may have been sourced from a hinterland composed of crystalline basement rocks (Lewisian – Precambrian). The pervasive red-brown colouration, likely caused by primary oxidation, provides a general indication of terrestrial deposition. The switch to yellow-coloured sediments in the upper portion of the core suggests the presence of a palaeo-weathering surface. During this period of exposure, a considerable succession of Triassic sediments may have been eroded and removed.

In 205/26a-4, the basal section of this well comprises stacked, amalgamated fluvial channel deposits. Above this is a very definite change in the stacking pattern, and sediments within the fluvial system become thinner bedded. The uppermost section (above 2479.00 m) is interpreted to represent littorally-worked sediments, deposited in a nearshore setting. This is marked by fluvial processes beginning to show stacked, coarsening-upwards packages of trough cross-bedded to low-angle, inclined, parallel-laminated sandstones, suggesting wave-working of the sediment. This is interpreted as representing a transgression (of unknown scale) located at the top of the Triassic-aged core in well 205/26a-4. The loss of granitic clasts is a key observation, as it suggests that sediment supply from the hinterland was altered/reduced, most likely through the flooding of the shelf. This was followed by a "working-out" of feldspar-rich material in a nearshore environment.

Summary

In 205/20-2 and 205/26a-4, sediments were deposited in a fluvial environment that exhibited braided to meandering characteristics (***Figure 4***). There is evidence for both unconfined fluvial deposits and confined fluvial channel fills. The confined fluvial channel fills tend to transition into point bar deposits, with very little preserved overbank deposition, suggesting a braided to meandering system. The dark red to brown colouration of the sediments, associated with oxidation processes, provides additional support for deposition in a subaerial, terrestrial setting. In 205/26a-4, the top of the fluvial sediments documents a transition from fluvial processes into nearshore wave processes, suggesting a progressive transgression at the top of the Triassic core. In contrast, the upper 4 m of 205/20-2 has been altered to a yellow colour (from a reddy-brown colour), likely through a reduction of iron during a period of prolonged exposure. This may represent a discontinuity surface (i.e. an unconformity).

6 Sedimentology of the Skerry Group (Lower Jurassic)

6.1 SKERRY GROUP

The Skerry Group comprises two formations: the Stack Skerry Formation and the Sule Skerry Formation. Both formations were encountered in one well (***Table 4***), well 202/03a-3 which was divided into an "upper section" and "lower section". These sediments were logged at a 10 cm-scale of resolution (Appendix 3) and are summarised below (***Figure 5***).

Well Number	Top Depth (m)	Base Depth (m)	Underlain by in core	Overlain by in core	Comments
202/03a-3 Sule Skerry Formation	1784.00	1819.70	None	None	"upper section"
202/03a-3 Stack Skerry Formation	2050.00	2066.93	None	None	"lower section"

Table 4 Depth of core data through the Skerry Group (Lower Jurassic).

6.1.1 Stack Skerry Formation

Description

In 202/03a-3 (Fig. 5), the lowermost 13 m of core (2054.18 – 2066.93 m) comprises hemi-pelagic siltstones and mudstones. These sediments are thinly interbedded with "clean", ripple laminated, parallel-laminated, and well-sorted sandstones. Mudstones and siltstones commonly display moderate to intense bioturbation and range between 0.5-1 m in thickness. In general, bioturbation is ubiquitous throughout much of the succession. The overlying succession (2050.00 - 2054.18 m) is composed of thickly bedded sandstones that are "very clean", well-sorted, massively bedded (structureless), with some evidence for de-watering in the form of dish structures, particularly near bed bases. Individual sandstone beds range from 10 cm to 100 cm in thickness, forming a 4 m-thick, amalgamated package. Occasionally, 2-3 cm-thick bed tops are composed of a carbonaceous-clast-rich, parallel-laminated, asymmetrically ripple laminated, argillaceous sandstone. Within these beds, clay concentrations increase upwards, along with well-developed normal grading. In addition, mud clasts and carbonaceous material is typically concentrated within these bed tops (***Figure 6***a). Abundant ammonite macrofossils have been encountered within this well (***Figure 5*** and ***Figure 6***b), dated as late Sinemurian (Thomas, 2018b)

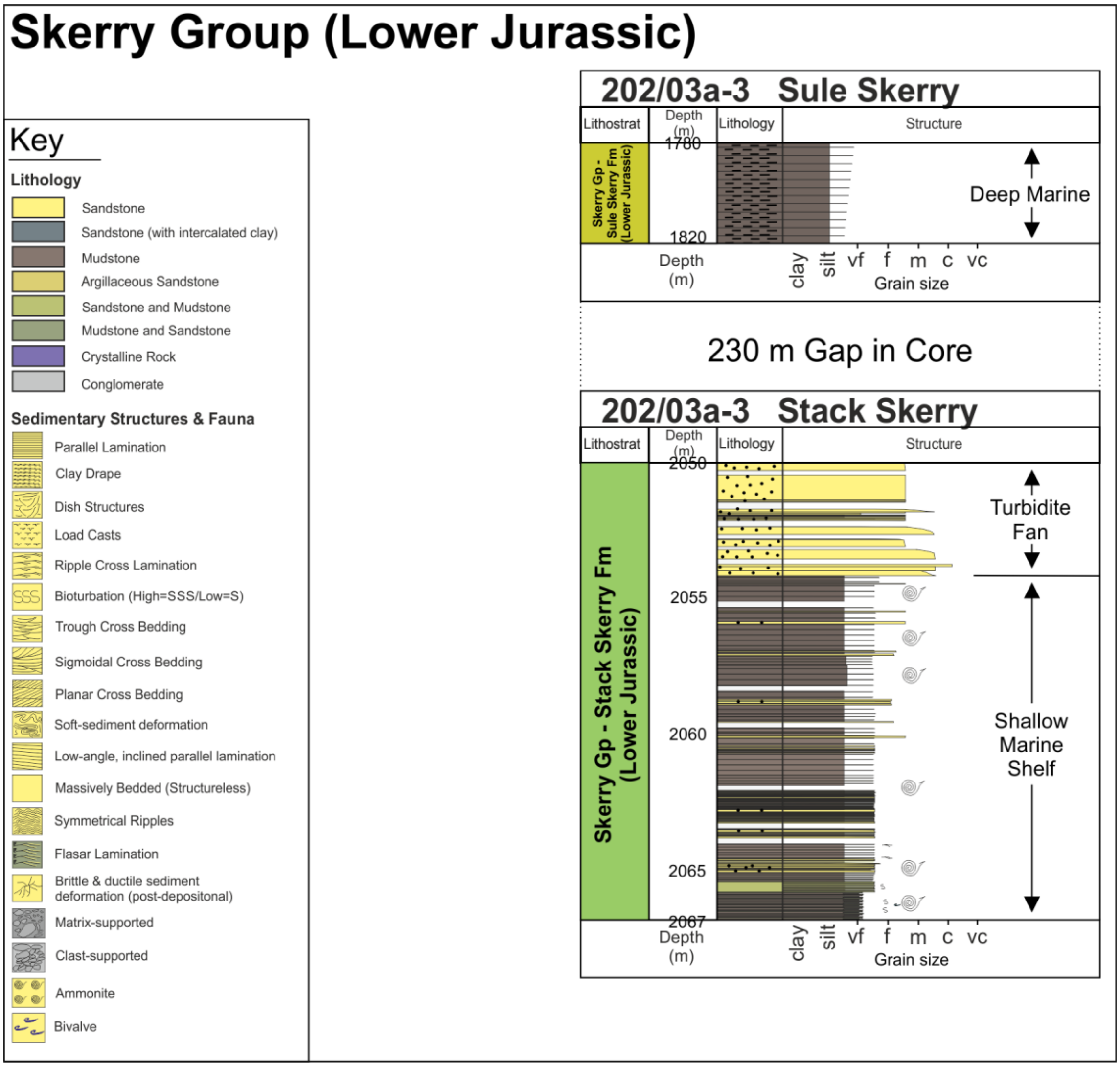

Figure 5 Sedimentary logs through the Skerry Group (Lower Jurassic), including the Stack Skerry Formation and Sule Skerry Formation.

Interpretation

In 202/03a-3, the depositional environment is interpreted as a shallow-marine, shelfal environment. The lower portion of core (2054.1 – 2066.93 m) represents "normal" background deposition on a marine shelf. This is evidenced by the deposition of parallel laminated, hemi-pelagic mudstones, interbedded with thin beds of well-sorted, clean sandstone. The sandstones display loaded bases, parallel laminations, ripple lamination (asymmetrical) and can be interpreted as low-density (dilute) turbidites. The low-density turbidites may have been fed from fluvial systems draining into a shelfal area and indicate relatively constant delivery of clastic material into this setting. The evidence for a "marine" shelf (opposed to freshwater) is provided by numerous ammonite fossils encountered throughout the lower portion of core (***Figure 5***; Thomas, 2018b).

Following the relatively quiescent condition of the shelfal succession, the deposition of overlying, thickly bedded, well-sorted sandstones marks the activation of a turbidite fan (***Figure 5***). Deposition occurred through a mixture of high-density turbidite flows and hybrid event beds. Hybrid event beds are represented by a lowermost massive (structureless), sometimes normally-graded sandstone; and an uppermost mud-rich bed top (***Figure 6***a). They represent the product of a flow that exhibited mixed flow behaviour (Haughton et al., 2009). The thick, sandstone-prone succession is interbedded with hemi-pelagic mudstones, which represents periods of quiescence in deposition within the fan, suggesting a fan fringe depositional location. Turbidite fan activation is typically linked to relative sea level variations, with sand input into the shelfal areas occurring during periods of relative lowstand (Catuneanu, 2006 and references therein).

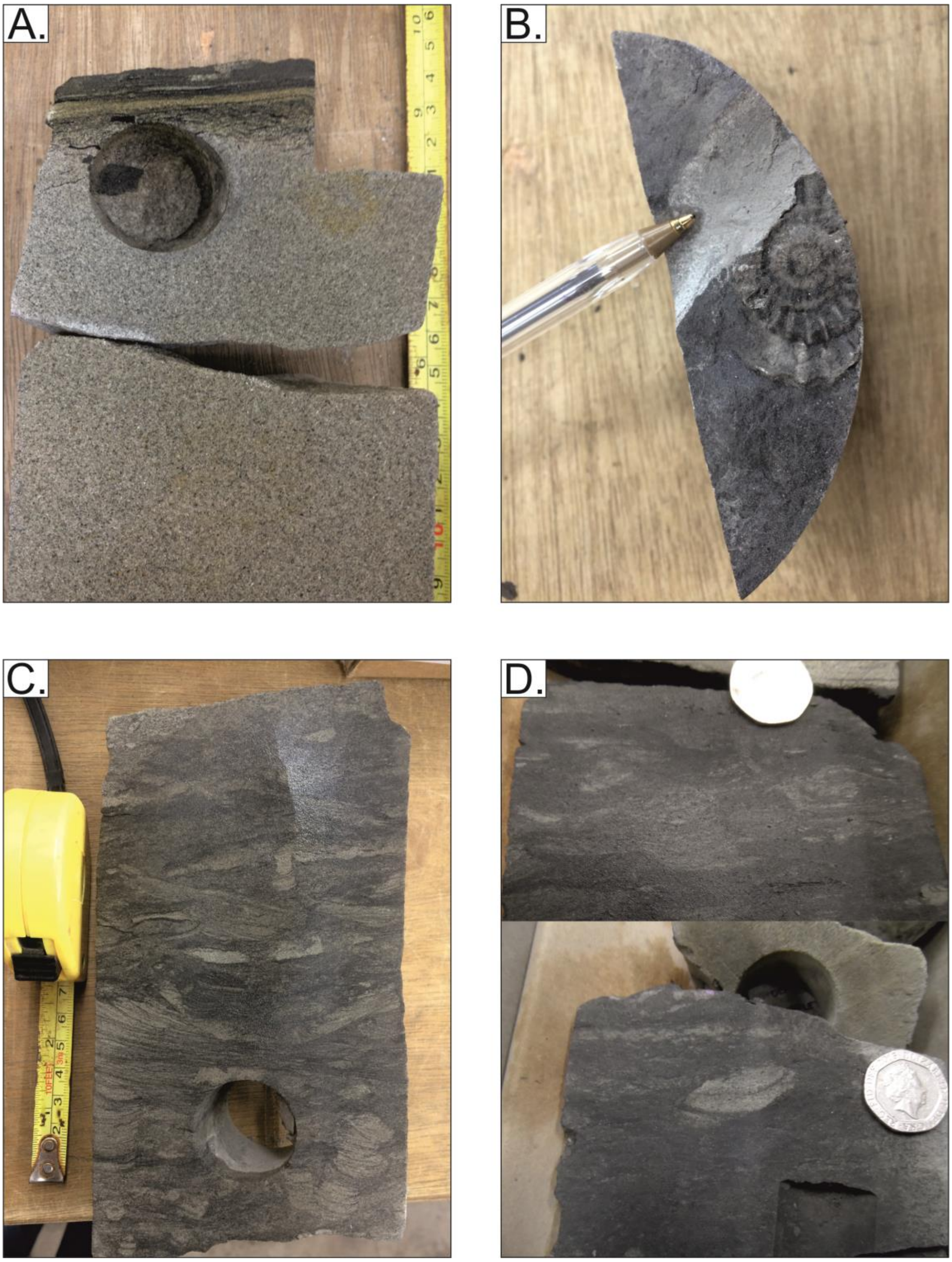

Figure 6 Images of core from 202/03a-3, a) A normally graded, structureless sandstone, with a clay-rich bed top, interpreted to represent a hybrid event bed (in 202/03a-3, at 2052.77 m). b) an ammonite macrofossil, assigned to the Echioceras raricostatum ammonite zone, dated as latest Sinemurian. c) An example of Teichicnus and Skolithos ichnogenera in intensely bioturbated sandstones and mudstones (in 202/03-a3 at 2054.60 m). d) An example of Teichicnus ichnogenera (in 202/03a-3, at 2053.70 m).

Ammonites were encountered within this well (***Figure 6***b; Thomas, 2018b). Ammonites typically live in the water column, predominantly along the continental shelf, in marine basins. The presence of ammonite fossils supports the interpretation of a marine, shelfal environment. In addition, the intensity of bioturbation (***Figure 6***c), within the background siltstones and mudstones, suggests a well-oxygenated environment. The presence of feeding burrows representing the *Teichicnus* Ichnogenera (***Figure 6***c and ***Figure 6***d), of the *Cruziana* ichnofacies, suggests a sublittoral, lower shoreface to offshore (shelf) setting (Seilacher, 2007; Pemberton et al., 2012).

Summary

The lower portion of core representing the Stack Skerry Formation comprises hemi-pelagic, dark-grey coloured, moderate to intensely bioturbated mudstones, thinly interbedded with fine to very fine-grained, parallel to ripple laminated sandstones, interpreted as the product of low-density turbidity currents. These sediments are typical of deposition on a shelfal setting. The low-density turbidites were likely sourced from an in-draining river system, located along a margin. The presence of *Teichicnus* ichnogenera, of the *Cruziana* ichnofacies, suggests a sublittoral, shelfal setting. The occurrence of ammonite fossils supports a marine shelf. The upper section of core is composed of thickly bedded, medium to fine grained, well sorted, structureless sandstones deposited by a mixture of high density turbidity flows and hybrid event beds. Hybrid event beds are marked by the presence of clay-rich bed-tops, typically with high concentrations of mudclasts and carbonaceous fragments. The high density turbidites and hybrid event beds were active within a turbidite fan; one which may have been linked to a period of lowstand in the basin.

6.1.2 Sule Skerry Formation

Description

In 202/03a-3, sediments comprise c. 36 m of homogenous, dark grey to chocolate-coloured, parallel-laminated mudstones (***Figure 5***). The only visible heterogeneities are scattered patches of light grey-coloured laminae, where the grain size is very fine-grained sand. These laminae also display an elevated micaceous component within the matrices. There is a complete lack of nodules, pyrite or bioturbation within these mudstones.

Interpretation

The mudstone-prone succession, encountered at the top of well 202/03a-3, was deposited as hemi-pelagic fall-out within the water column, most likely within a deep-marine setting. The observed laminations are formed through vertical suspension fall-out within the water column, with the white/coarser-grained laminae forming through a combination of increased productivity or through ?volcanic input, in the form of ash. The lack of bioturbation or shell material within these sediments suggests an anoxic/dysaerobic bottom water. There is a general lack of coarse-grained clastic material. A deep marine, bathyal depositional environment is an appropriate interpretation.

Summary

In 202/03a-3, sediments comprise a c. 36 m thick succession of homogeneous, dark grey to brown coloured, parallel laminated mudstones. The parallel laminated mudstones are interpreted as the product of suspension fall-out within the water column (hemi-pelagic). There is a lack of bioturbation or shell material throughout, suggesting the bottom waters were anoxic or dysaerobic. In addition, the lack of clastic input into the environment suggests a relative distance or disconnection from the shelf/hinterland. Consequently, the depositional environment for the Sule Skerry Formation is interpreted as a deep marine setting. An assessment of palynological samples has provided an age determination of Early Jurassic for these sediments (Thomas, 2018b).

7 Sedimentology of the Humber Group (Middle Jurassic to Lower Cretaceous)

The Humber Group is divided into the Heather Formation and the Kimmeridge Clay Formation (KCF; ***Figure 1***). The type section for the Heather Formation is in well 206/05-1 (***Figure 2***; Ritchie et al. 1996) and contains one member; the Fair Sandstone Member.

In the study area, the KCF comprises three members: the Solan Sandstone Member, the Ridge Conglomerate Member and the Rona Member. Various authors have proposed differing stratal relationships between the Solan Sandstone Member and the Rona Member (Herries et al., 1999; Ritchie and Varming, 2011). In this study, we propose that the Rona Member and the Solan Sandstone Member are contemporaneous. The Rona Member (section 7.2.1) represents a terrestrial to shelfal succession (R1-R5 facies) and the Solan Sandstone Member (section 7.2.2) a deep-marine setting. The Ridge Conglomerate Member (section 7.2.3) was deposited in a deep marine, subaqueous debris cone setting that may be slightly older than the Solan Sandstone Member. A palynological sample recovered from within the Ridge Conglomerate Member provided an age determination of “Oxfordian to Volgian”(see MPA 67629 in Riding 2018g). The Ridge Conglomerate Member is considered as “Kimmeridgian” in Ritchie et al. (1996).

7.1 HEATHER FORMATION – FAIR SANDSTONE MEMBER

The Mid Jurassic sediments of the Fair Sandstone Member of the Heather Formation, were encountered in one well, examined as part of this study (***Table 5***). These sediments form a 3.86 m thick section of core that was logged at a 10 cm-scale of resolution (Appendix 18).

Well Number	Top Depth (m)	Base Depth (m)	Underlain by in core	Overlain by in core	Comments
206/05-1	3901.14	3904.00	none	Kimmeridge Clay Formation	Limited thickness of core sample (<3 m). This makes for a challenging interpretation.

Table 5 Depth of core data through the Fair Sandstone Member of the Heather Formation (Mid Jurassic).

Description

In 206/05-1, the core comprises a single, three meter thick bed of fine-grained, well to very well-sorted, sub-rounded, quartz-rich, massive, calcite-cemented, indurated sandstone (Appendix 1). The sandstone displays a sugary texture, a patchy, shiny lustre and grain boundaries/shapes are often difficult to observe.

Interpretation

In 206/05-1, the sediments are interpreted as the deposits of high density turbidite flows, most likely in a deep-water setting. The main evidence for this is the relatively mature nature of the sediment, which has been well worked, showing evidence for enhanced sorting processes. In addition, the lack of identifiable structures within the bed suggests that it was deposited relatively rapidly. The presence of a sugary texture and a shiny lustre, along with poorly-defined grain boundaries, indicates these sediments are altered and indurated. Consequently, they were likely exposed to substantial pressure and/or temperatures during their burial history.

Summary

In 206/05-1, sediments comprise relatively mature, well-sorted, sub-rounded, quartz-rich sandstone. The massive bedding suggests they were deposited rapidly. The observations permit an interpretation of a high-density turbidite, which may have formed in a deepwater setting (although this lithofacies could form in a range of sedimentary environments). The sediments are heavily indurated, evidenced by: a sugary texture; a shiny lustre and poorly-defined grain boundaries/shapes. This suggests exposure to substantial pressures or temperatures during burial. It is possible that sedimentary structuring has been over-printed by the effects of the induration process. No BGS palynological samples were taken from these sandstones.

7.2 KIMMERIDGE CLAY FORMATION

In this study the Kimmeridge Clay Formation was encountered in eight wells, examined as part of this study (***Table 6***). They were logged at a 10 cm-scale of resolution (Appendices 6, 8, 11, 12, 15, 16, 17 and 18) and have been summarised in representative sedimentary logs (***Figure 7***; Appendix 1).

Well Number	Top Depth (m)	Base Depth (m)	Underlain by in core	Overlain by in core	Comments
205/26a-4	2454.85	2501.25	Papa Group	None	Solan Sandstone Member
205/26a-5Z	2928.00	2961.26	None	None	Solan Sandstone Member in-
205/26a-6	2574.00	2576.12	Rona Member R1	None	None
202/12-1	1356.00	1361.54	None	Rona Member R1	None
205/21-1A	1339.71	1344.08	Cromer Knoll Group	Rona Member R2	None
205/22-1A	3176.00	3179.00	Rona Member R4	None	None
204/27a-1	2043.00	2043.70	Rona Member R5 (shallow marine – shelf)	None	? check the top against comp log
206/05-1	3148.00	3276.60	Heather Formation Fair Sandstone Member	None	None

Table 6 Depth of core data through the Kimmeridge Clay Formation.

Description

In 205/26a-4 (***Figure 7***), the base is marked by a 1.5 m-thick, fining-upwards, bioturbated, shell-rich, massively bedded (structureless) sandstone. This is overlain by a 13 m-thick succession of parallel-laminated, homogenous, shell-rich, dark grey to black-coloured mudstone. Shells are thin-walled and typically comprise broken, scattered fragments. Occasionally, they are interbedded with 2-40 cm-thick, well to very well-sorted, fine-grained, normally graded, quartz-rich sandstones that display mud-rich beds tops. In addition, there is one example (2459.50 m) of a discreet, 40 cm-thick, very fine-grained, poorly sorted, argillaceous sandstone. This bed contains a concentration of both mud clasts and carbonaceous clasts, along with scattered crinoid vesicles and shelly material; no clast sorting is present.

In 205/26a-5Z (***Figure 7***), the KCF is represented by 3.5 m of parallel-laminated, homogenous, dark grey to black-coloured, pyritic mudstones at the base of the core and by 5 m of mudstones at the top of the core (encasing the Solan Sandstone Member). The pyrite in the uppermost interval ranges from 1-8 mm in width and is cubic in nature. Scattered, thin-walled, broken shelly fragments are present in both the lower and upper mudstones within the core.

In 205/26a-6 (***Figure 7***), the base of the KCF is marked by a 66 cm-thick, normally graded, poorly sorted, structureless, intensely bioturbated, argillaceous sandstone. The sandstone contains rounded, lithic clasts, along with a high concentration of broken shelly material along bed tops. This is overlain by c. 1.5 m of dark grey to dark brown-coloured, parallel-laminated, homogenous mudstones. The mudstones display fine-grained sand laminae, which occurs alongside weak bioturbation, in the form of horizontal burrows. The mudstones are otherwise non-bioturbated throughout.

In 202/12-1 (***Figure 7***), the KCF is represented by a c. 6 m-thick, homogenous, parallel-laminated, dark grey to black-coloured mudstones. Occasionally, these mudstones display 1-2 mm-thick, white to light grey-coloured, silt-grade, calcitic laminae, which appear to be evenly spaced, every 20 cm throughout the mudstone. In addition, the core appears to be “shrunken/contracted”.

In 205/21-1A (***Figure 7***), the KCF is composed of a c. 4 m-thick succession of dark grey to dark brown coloured, clay-to-silt grade, parallel laminated, homogenous mudstones. Bioturbation is absent from these deposits.

In 205/22-1A (***Figure 7***), the KCF is represented by a 3 m-thick succession of homogenous, dark grey to black-coloured, parallel-laminated mudstones. The lower half (3177.60 – 3179 m) contains interlaminations of very fine-grained sand, along with a persistent, moderate bioturbation. The upper half (3176.00 – 3177.60 m) displays a lower concentration of inter-laminated, very fine-grained sand and instead contains scattered patches of a white-coloured, ?nodular material, possibly composed of carbonate rock (chalk).

In 204/27a-1 (***Figure 7***), the KCF is represented by a 30 cm-thick, ripple laminated, parallel-laminated, shell-rich, very fine-grained, argillaceous sandstone.

In 206/05-1 (***Figure 7***), the KCF is represented by a c. 4 m-thick succession of dark grey to black-coloured, homogenous, parallel-laminated mudstones at the base of the core and a 30 m-thick succession of dark brown to black-coloured, homogenous, parallel-laminated mudstones at the top. Sandstones of the Solan Sandstone Member are encased within the two intervals. The mudstones are interbedded with 1-2 cm-thick, well-sorted sandstones and bioturbation is completely absent.

Interpretation

In 205/26a-4, the 1.5 m-thick, bioturbated, shell-rich, massively bedded sandstone, at the base of KCF, is interpreted as a transgressive lag deposit (“T-Lag” in ***Figure 7***; ***Figure 9***). The main evidence for this is the density of shell material within a poorly sorted, clay-rich sandstone. In addition, the high degree of bioturbation in these deposits is typical of a marine flooding surface, with an increase in faunal abundance common during a shift to deeper water facies (Pemberton et al., 2001). Following this, the general lack of coarser-grained clastic material in the thick succession of hemi-pelagic mudstones; coupled with very little evidence for bioturbation, suggests deposition occurred in a deep-water environment. Thin (2-45 cm-thick) sandstones are rarely interbedded within the mudstones, which are interpreted as isolated occurrences of hybrid events beds (Haughton et al., 2003; 2009). These periodically punctuate an otherwise low-energy, hemi-pelagic depositional environment. In addition, the 40 cm-thick, mud-rich, fine-grained, poorly sorted, carbonaceous and mud clast- rich bed (at 2459.00 m) represents the deposits of a subaqueous debris flow (a debrite).

In 205/26a-5Z, the mudstones encountered above and below the Solan Sandstone Member were deposited by hemi-pelagic processes, in a deepwater environment. The homogenous nature, in particular the lack of interbedded sandstone, indicates there was very little in way of clastic input into the system during this time.

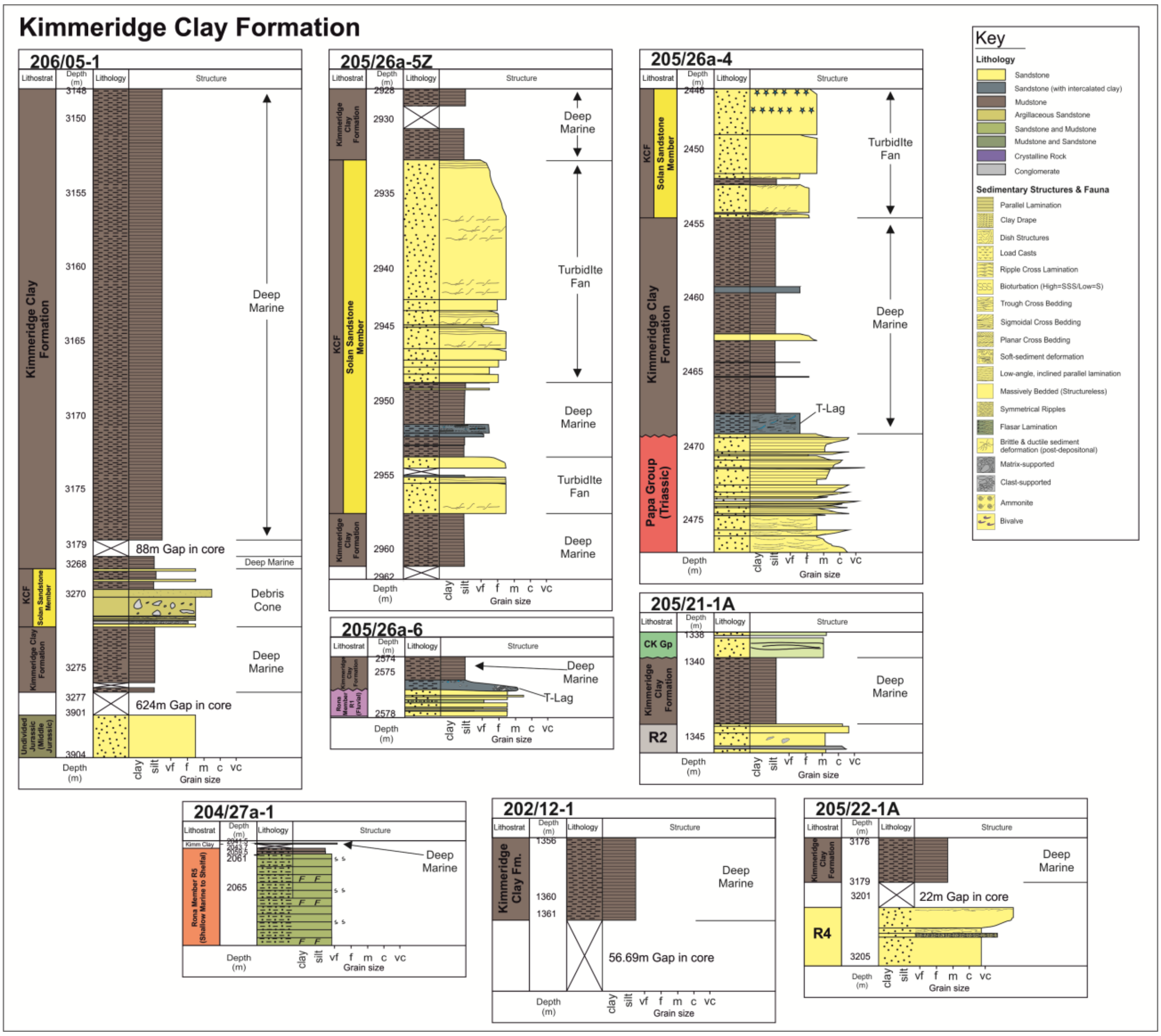

Figure 7 Sedimentary logs through the Kimmeridge Clay Formation, including deposits of the Solan Sandstone Member.

In 205/26a-6, the basal bed, composed of argillaceous sandstone, is interpreted as a transgressive lag deposit ("T-Lag" in ***Figure 7***). The base of the lag contains a concentration of rounded, lithic clasts, likely reworked by wave energy during the transgression. The concentration of shell material within a poorly sorted sandstone, along with the high degree of bioturbation, is typical of the deposits of a marine flooding surface. Furthermore, an increase in faunal abundance, leading to intense bioturbation, is typically observed during a shift to deeper water facies (Pemberton et al., 2001).The mudstones overlying this transgressive lag are interpreted as deposited in a deepwater environment, by hemi-pelagic processes. Occasionally, thin beds of sandstone represent small turbidites deposited in the deepwater basin. The turbidity currents brought in fauna along with them; the burrows of which are observed in association with the coarser-grained sand laminae. Bioturbation is not present in the rest of the mudstone succession, suggesting anoxic/dysaerobic bottom water conditions.

In 202/12-1, the mudstones of the KCF represent hemi-pelagic sedimentation, likely in a deepwater environment. The white-coloured, calcitic laminae, scattered throughout the mudstones, may represent short periods of elevated productivity in the water column, likely formed during algal blooms. This increased the carbonate material in suspension, which was then deposited in the deepwater setting. The “shrunken/contracted” nature of the core may indicate the presence of swelling clay minerals (e.g. smectite).

In 205/21-1A, the dark grey to brown coloured, homogenous, parallel laminated mudstones are interpreted to have been deposited as hemi-pelagite in a deepwater setting. The dark colouration suggests the mudstones are organic-rich. The absence of bioturbation may suggest bottom water anoxia was present during deposition. The lack of other heterogeneities, in the forms of coarser-grained beds or laminae, indicates suggesting a relatively distally-located setting, potentially within a deepwater environment.

In 205/22-1A, mudstones of the KCF were deposited by hemi-pelagic processes, most likely in a deepwater environment. The lower half (3177.60 – 3179.00 m) contains coarser-grained clastic laminae, along with moderate bioturbation. This might indicate slightly shallower, more oxygenated waters, with clastic material derived from the hinterland. The upper half (3176.00 – 3177.60 m) documents a relative shut-down of this clastic supply, which may have permitted the in-situ formation of carbonate material.

In 204/27a-1, the thin interval of very fine-grained, argillaceous sandstone, at the top of the core, represents a setting where the environment transitioned from an outer shelf setting to a deeper water, likely bathyal environment. This example would represent the most proximal facies of the Kimmeridge Clay Formation, with the contemporaneous Rona Member R5 facies (see section 7.2.1.5) sitting immediately upslope.

In 206/05-1, mudstones of the KCF represent deposition in a deepwater environment, where low energy, settling processes dominated. There is little evidence for coarser-grained clastic input from the hinterland during this time. The dark brown to black colouration of the shale, lack of clastic input and absence of bioturbation, suggest an anoxic or dysaerobic bottom water.

Summary

The Kimmeridge Clay Formation (KCF) is composed of homogenous, dark grey to dark brown to black-coloured, parallel-laminated, occasionally pyritic mudstones deposited in an anoxic/dysaerobic, deepwater environment. The mudstones are inter-laminated with very fine grained sand and calcitic laminae. Deposition occurred through suspension fall-out within the water column, forming vertically-aggrading laminae. Bioturbation is largely absent throughout, suggesting anoxic bottom waters. Occasionally, 1-2 cm-thick, turbiditic or debritic sandstones interrupt the otherwise low energy deposition. In 205/26a-5Z, the mudstones are rich in cubic pyrite and in 205/22-1A nodular carbonate/?chalk is present. In wells 205/26a-4 and 205/26a-6, the base of the Kimmeridge Clay Formation is marked by an intercalated, clast-rich, shell-rich sandstone and claystone bed, interpreted as a transgressive lag deposit. This provides evidence for an abrupt transgression of the shelf at the base of the Kimmeridge Clay Formation.

In general, there is lack of clastic input into the deepwater environment, signified by an absence of thin interbeds of sandstone within the thicker deposits of mudstone. When significant clastic input into the basin does occur, it forms abrupt, c. 25 m-thick packages of turbiditic sandstone of the Solan Sandstone Member; or coarse-grained subaqueous debris cone deposits of the Ridge Conglomerate Member. These sediments were brought into the basin by a variety of subaqueous flow processes, which tend to be more active during periods of lowstand within a basin.

7.2.1 Rona Member

"The Rona Member" was first defined as: "a clastic sequence deposited on and adjacent to the present-day structural highs… on a varied pre-mid Jurassic sub-crop", with an age ranging from early to late Volgian (Verstralen et al., 1995). In this study, the Rona Member has been encountered in 14 cored wells (***Table 1***) and has been sub-divided on the basis of broad depositional environments. Each core was logged sedimentological and interpreted in terms of sedimentary processes. Five different depositional environments were recognised, these include: fluvial, fan delta, marginal-marine, shoreface/littoral and shallow-marine to shelfal. The various environment of deposition are recorded in the Rona Member R1-R5 facies. The description and interpretation of the various facies; the wells and depths in which they occur; and the summary of deposits, is detailed in the following sections.

7.2.1.1 Rona Member R1 –Fluvial (Meandering)

The Late Jurassic-aged Rona Member R1 sediments were encountered in three wells, examined as part of this study (***Table 7***). These sediments were logged at a 10 cm-scale of resolution (Appendices 6, 14 and 17) and have been summarised (***Figure 8***).

Well Number	Top Depth (m)	Base Depth (m)	Underlain by in core	Overlain by in core	Comments
202/12-1	1418.23	1447.50	none	Kimmeridge Clay Formation	None
205/26a-2	2157.37	2158.29	none	50 m gap in core then Cromer Knoll	None
205/26a-6	2576.12	2578.00 (deeper core was not logged)	none	Kimmeridge Clay Formation	Late Jurassic or younger, from dates obtained in new BGS palynological sampling (see 10 dates from 2578.00 – 2611.00m)

Table 7 Depth of core data through Rona Member R1.

Description

In 202/12-1, sediments comprise thickly bedded (0.5-2 m), moderate to well-sorted, fine- to coarse-grained, massively bedded (structureless) sandstone. The sandstones are sub-arkosic and contain 1-3 mm wide, spherical, orange-coloured nodules of ?siderite. These are typically overlain by up to 1 m-thick beds of planar cross-bedded and parallel-laminated sandstone, which are less well-sorted and commonly contain intra-formational mud clasts. Occasionally, the bed bases are deeply erosive, with scours filled with a pebble lag. The pebble lags are composed of granitic clasts, lithic clasts and intraformational mud clasts, within a poorly sorted, coarse-grained matrix. Lags are present in around c. 50% of the beds in the lower interval of core. Bed amalgamation is typical, with up to seven, normally graded, vertically stacked, erosively based sandstone packages present. Some beds are massively bedded (structureless), whilst others display trough cross-bedding, with parallel-laminated bed tops. The upper succession of sandstones (above c. 1433 m) are thinner, lack erosive bases/pebble lags and display massive bedding, planar cross-bedding and occasional parallel laminations. Overlying this succession is a 3 m-thick interval of dark red and green-coloured, ripple laminated (symmetrical) and parallel-laminated, bioturbated, argillaceous sandstones and siltstones, containing flaser lamination (***Figure 9***a) and parallel laminations. These beds become finer grained and begin to develop parallel lamination. Above this (c. 1425 m) is a second coarser-grained succession of erosively based, sub-arkosic, well-sorted sandstones. These erosively cut into the finer-grained, bioturbated siltstones and very fine-grained sandstones. The lowermost bed is massively bedded (structureless) and contains a high concentration of green-coloured mud clasts at the bed base. The composition of the mud clasts is lithologically identical to that of the underlying mudstones and siltstones.

In 205/26a-2, the lowermost portion of the core comprises bioturbated, parallel-laminated, clay to silt grade mudstones. These are overlain by thinly bedded (<10 cm), parallel-laminated, ripple laminated (asymmetrical), very fine- to fine-grained, very well-sorted, quartz-rich, argillaceous sandstones.

In 205/26a-6, sediments comprise fine-grained, moderately sorted, sub-angular to sub-rounded, quartz-rich, parallel-laminated, occasionally trough cross-bedded sandstone. Some beds comprise very fine grained, ripple laminated (asymmetrical), argillaceous sandstone. The uppermost bed displays planar cross-bedding, with a concentration of green-coloured, silt-grade, elongate, rounded, intraformational mud clasts. The upper contact is unconformable, marked by an clast-rich, argillaceous sandstone (***Figure 9***b). The underlying succession (below 2578 m) was not logged as part of this study.

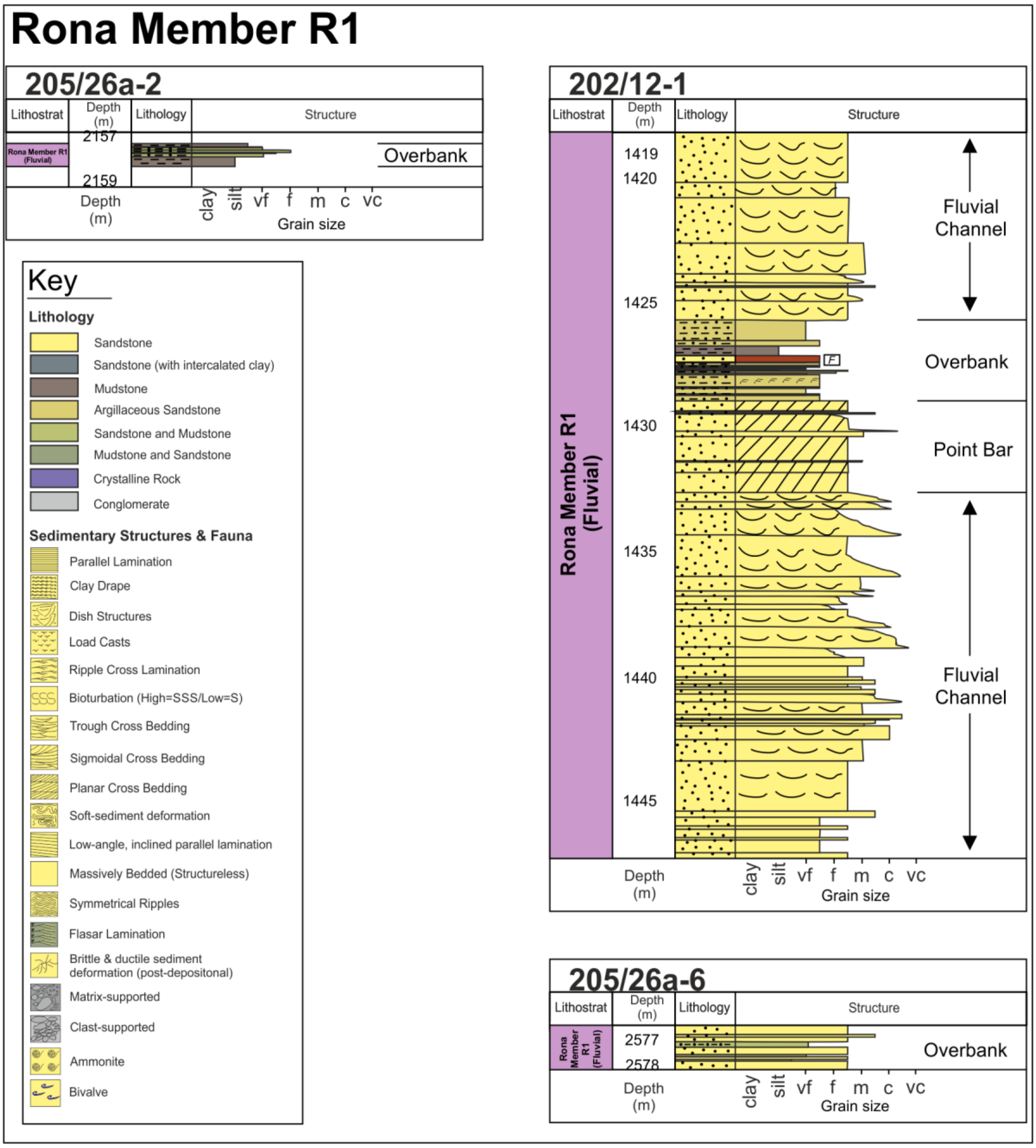

Figure 8 Sedimentary logs through the Rona R1 facies (Fluvial).

Interpretation

In 202/12-1, the lowermost c. 15 meters represents the deposits of a fluvial channel (***Figure 8***), typified by stacked, erosively based, trough cross-bedded, sub-arkosic sandstones. Directly above this lies vertically-stacked, planar cross bedded sandstones, representing fluvial point bar deposits. These sediments typically accrete at the edge of the fluvial channel and suggest the presence of a meandering fluvial system. Above this, rests a thin interval that records a transition from point bar into overbank deposition. This is evidenced by low energy deposition and by a complex redox interaction, providing the sediments with a patchy, green to red colouration. Above this rests the deposits of a second fluvial channel, which avulsed across the underlying system. Intraformational rip-up mud clasts within the basal scour of the uppermost fluvial channel suggest upstream erosion of overbank deposits. The lack of structuring in these deposits suggests high sediment concentrations within the fluvial system. The fluvial system may have been sourced from a recently uplifted, actively eroding hinterland.

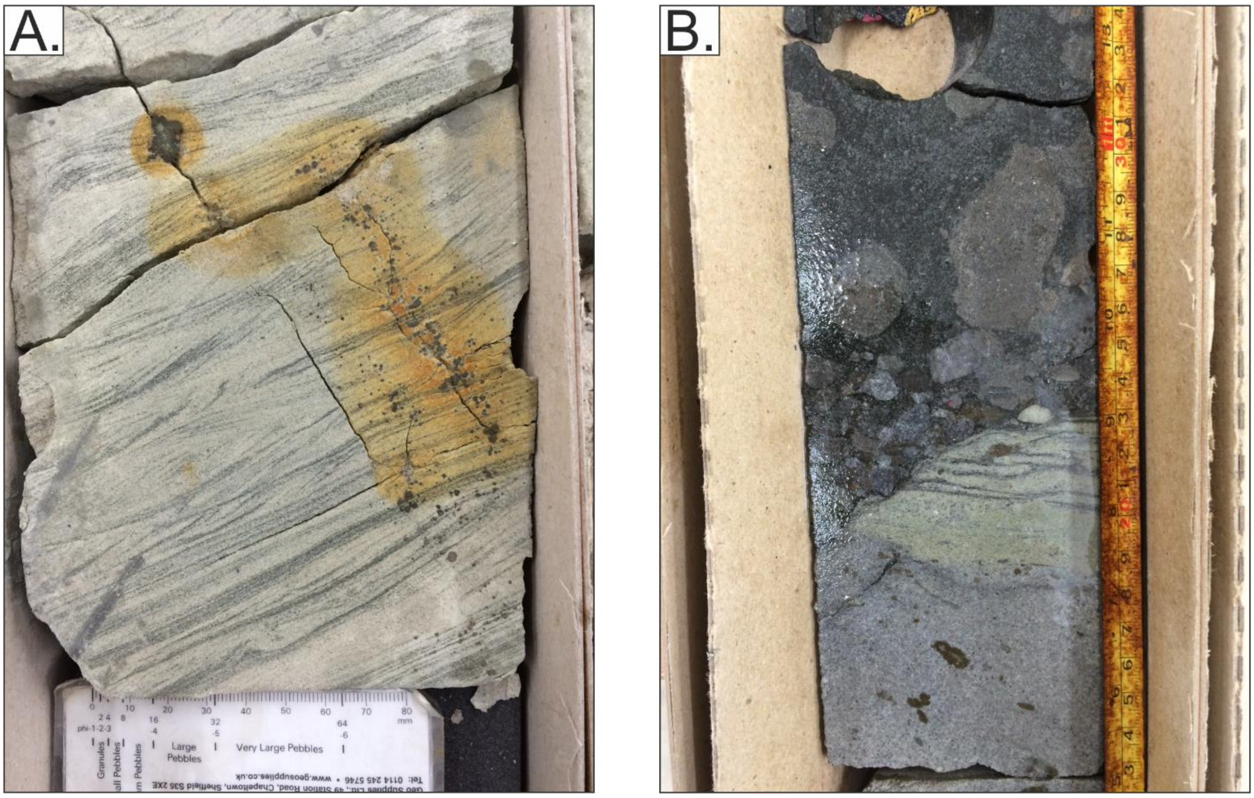

Figure 9 Images of core from wells 202/12-1 and 205/26a-6. a) Flaser laminated sandstone (in 202/12-1, at 1428.10m) b) Clast-rich, argillaceous sandstone, representing a transgressive lag deposit, resting on a well-sorted, fluvial sandstone (in 205/26a-6, at 2476.35 m).

In 205/26a-2, deposition is interpreted to have occurred in a low-energy, standing body of water; potentially in an oxbow cut-off or pond, located in an overbank area. The parallel-laminated, clay to silt-grade mudstones likely formed as a result of suspension fall-out, within the standing bodies of water. The very fine-grained, well-sorted, parallel-laminated to ripple laminated (asymmetrical) sandstones represent fluidal, low-density flows. These may have been sourced from crevasse splays, which broke out onto the floodplains, feeding sediment-rich waters into the small ponds of the overbank areas.

In 205/26a-6, sediments of Rona R1 above 2578 m, represent fluvial-style deposition, within an overbank location, adjacent to a fluvial channel. The fine-grained, occasionally medium-grained, parallel-laminated, well-sorted sandstones represent deposition of crevasse splays. The clay-rich matrices, along with intraformational mud clasts (rip-up clasts), indicate the presence of a low-energy setting immediately up-stream, which was eroded into during high flow/flood conditions. Silt to very fine-gained, clay-rich beds generally follow “cleaner”, parallel-laminated sandstones of the crevasse splay deposits. These are interpreted as deposition in standing/slack water left after the flood conditions of the river system (sometimes referred to as clay plugs). This style of deposition may suggest a fluvial system whereby discharge was variable, resulting in a “flashy regime”. The underlying succession (below 2578 m) was not logged as part of this study as it was originally thought to be Triassic in age. However, subsequent palynological age determinations completed as part of an accompanying study (Thomas, 2018i), re-date the succession below 2578 m as representing Upper Jurassic sedimentation. In order to properly define the environment of deposition for this lowermost interval, these sediments should logged and interpreted in a similar style, in future studies.

Summary

In 202/12-1, Rona R1 sediments comprise thickly bedded (0.5-1.5 m), fine- to coarse-grained , moderately sorted, trough cross bedded, normally-graded, sub-arkosic sandstones with subordinate mudstones. Sandstone bases are typically erosional, displaying pebble-grade basal lags, composed of granitic and mixed lithic clasts. In places, amalgamated packages of planar cross bedded, moderately sorted sandstone, represent thin development of point bar deposits, forming at the edge of the fluvial channel. Very fine-grained, occasionally medium grained, well-sorted, parallel laminated sandstones, interbedded with clay to silt-grade mudstones represent deposition within adjacent overbank areas. Clay to silt-grade mudstones were likely deposited in standing bodies of water (e.g. oxbow cut-offs), within overbank areas, formed laterally adjacent to the fluvial channels. Within the channel elements, entrained intraformational rip-up mud clasts also suggest the upstream development of overbank deposits. Occasionally, coarser-grained, fine to medium grained, well-sorted, planar cross bedded, parallel-laminated, ripple laminated sandstones interrupt the low energy deposition. These sediments are interpreted as crevasse splay deposits, formed on overbank areas during periods of high river discharge (flood conditions). The frequency of crevasse splay deposits may suggest a fluvial system that documents variable discharge ("a flashy regime").

In summary, sediments of the Rona R1 facies are interpreted as being deposited in a meandering fluvial environment. The preservation of a 20 m-thick succession of fluvial channel, point bar and overbank deposits, permits the interpretation of a meandering fluvial system. The presence of two/multiple fluvial channel elements is core from well 202/12-1 (c. 1447.5 – 1433 m and 1426 – 1418 m) suggests a laterally avulsing fluvial system. Intraformational mudclasts, present within the base of sandstone beds, suggests the system was actively eroding mud-prone overbank deposits developed in upstream locations. Beds of structureless sandstone, typically observed at the base of fluvial channel elements, indicate high sediment loads within the fluvial system. In general, sediment maturity is low, suggesting the sediments were being sourced from an actively eroding hinterland, composed of granitic/igneous terranes.

7.2.1.2 Rona Member R2 - Fan Delta

The Late Jurassic-aged Rona R2 sediments were encountered in five wells examined as part of this study (***Table 8***). These sediments were logged at a 10 cm-scale of resolution (Appendices 8, 9, 11, 12 and13) and have been summarised (***Figure 10***).

Well Number	**Top Depth (m)**	**Base Depth (m)**	**Underlain by in core**	**Overlain by in core**	**Comments**
205/21-1A	1344.18	1353.81	Crystalline Basement (Lewisian)	Cromer Knoll Group	Verstralen, et al., 1995 commented on this. 30 cm-thick weathering profile
205/22-1A	3208.59	3222.34	Crystalline Basement (Lewisian)	Rona Member R4	Verstralen, et al., 1995 showed a log of this and used it for the facies model
204/27a-1	2117.47	2128.91	Crystalline Basement (Lewisian)	Rona Member R4	Definitely a subaerial fan delta, roots + sheet flows
204/28-1	1938.91 and 1928.21	1939.60 and1934.63	None	Interdigitates with Rona Member R4	Two sections of fan delta – Interdigitating of fan delta and shoreface/littoral deposits.

205/26-1	2013.15	2104.64	none	Rona Member R4	None

Table 8 Depth of core data through the Rona Member R2 facies.

Description

In 205/21-1A (***Figure 10***), the lowermost bed is composed of a c. 4 m-thick, matrix-supported conglomerate. Directly overlying this is a stacked succession of 1-2 m-thick beds of normally graded, coarse-grained, grading to fine-grained, moderate to well-sorted, sub-rounded to rounded, quartz-rich sandstone. These are typically massively bedded (structureless) and display sub-rounded to rounded, 1-8 cm wide lithic clasts. The clasts are not concentrated within any particular part of a bed and are floated throughout the matrix. Interbedded with are a number of thin (5-50 cm-thick), well-sorted, fine to medium-grained, quartz-rich, matrix-supported, erosively based conglomerates. In these conglomerates, clasts tend to be sub-rounded to rounded and comprise various lithic lithologies.

In 205/22-1A (***Figure 10***), the base is composed of a c. 4 m-thick succession of lithic and granitic clast-rich, matrix supported conglomerates. The lowermost bed contains immature, angular clasts and the uppermost bed has more mature, rounded clasts. Both beds contain clasts composed of lithic and granitic lithologies. Above a 5.62 m gap in core, rests a normally-graded, medium-grained to very fine-grained, moderately sorted, quartz-rich, lithic clast-rich sandstone. The clasts display sorting, with large clasts at the base and smaller clasts at the top of the bed. Above this is a c. 2 m-thick clast-supported conglomerate, which is followed by a well-sorted, dark grey-coloured, erosively based, planar cross-bedded, carbonaceous sandstone succession.

In 204/27a-1 (***Figure 10***), the base is marked by a 5 m-thick, interbedded succession of both matrix and clast supported conglomerates and massively bedded, poorly sorted sandstones. The poorly sorted sandstones occasionally contain parallel laminations, developed along the bed tops. Directly above these deposits rests a 50 cm-thick, massively bedded, mottled sandstone, on which sits a stacked succession of normally graded sandstones and matrix supported conglomerates. These contain smaller, sub-rounded to rounded, slightly more mature clasts. This is overlain by a single, 20 cm-thick, parallel-laminated siltstone, followed by a 1 m-thick, coarsening-upwards, parallel-laminated, argillaceous sandstone succession.

In 204/28-1 (***Figure 10***), the Rona Member R2 is present within two intervals (between 1938.91-1939.60 and 1928.21 – 1934.63). The lower most interval comprises a 1.5 m-thick succession of clast-supported conglomerates, matrix-supported conglomerates and fine-grained, well-sorted sandstones. The uppermost interval comprises very fine-grained to medium-grained, moderately sorted, clast-rich and clast-poor sandstones. Bed bases are quite commonly erosional and display a thin pebble lag. Sandstone beds are often massively bedded (structureless), with normal grading and parallel laminations also developing in places. Clasts are present in c. 50% of the beds, comprise lithic lithologies, range from 2-8 cm in width and are sub-rounded to rounded.

In 205/26-1 (***Figure 10***), the Rona R2 facies comprises a 1.51 m-thick bed of matrix-supported conglomerate, containing sub-rounded to rounded, granitic and lithic clasts that range from 5-30 cm in diameter. The matrix is composed of fine to medium-grained, moderate to well-sorted, quartz-rich, sub-rounded sand.

Interpretation

In 205/21-1A, the basal succession represents a 3 m-thick, matrix-supported, rounded-lithic-clast-rich, ungraded conglomerate, deposited by a cohesive debris flow (DF in ***Figure 10***). Debris flows tend to have limited transport distances; and clasts in the matrix are relatively large (up to 15 cm wide); they were likely sourced quite locally. Above this is an amalgamated package of concentrated sediment gravity flow deposits, containing a high concentration of lithic casts and well-sorted sandstones. Interbedded with this are a number of thin (7-19 cm-thick), matrix-supported, ungraded conglomerates. These were most likely deposited by cohesive, yet fluidal flows. This succession it typical of a fan delta setting, whereby deposition occurred through flows exhibiting a range of sediment concentrations (typically high concentrations). High sediment concentrations are evidenced by the “floating” of lithic clasts within the matrix and by unsorted, matrix-supported conglomerates. The presence of thickly bedded, well-sorted sandstones suggests a considerable amount of water in the system. The sub-rounded to rounded nature of the lithic clasts suggests a periods of wave working in a shoreface/littoral environment. An appropriate interpretation would be an actively eroding basement, sourcing a fan delta system that prograded into a body of water.

In 205/22-1A, the conglomerates and thinly interbedded sandstones are representative of deposition through a mixture of processes, the most dominant being debris flows. The lowermost bed of debris flow conglomerate (DF in ***Figure 10***) is immature, with large, angular, granitic and lithic clasts, suggesting close proximity to the sediment source. The overlying conglomerate displays more rounded clasts, indicating higher levels of working/transport. Unfortunately, the following six-meter gap in core likely records an important interval of deposition. The following clast-rich sandstone displays well developed normal grading and clast-sorting, indicating elevated levels of water in the system. The overlying clast-supported conglomerates represent successive debris flow events that show evidence for water winnowing of fines. Importantly, a thin, very well-sorted sandstone is observed, draping on top of these conglomeratic beds, characteristic of the deposition by sheet flows. The succession, comprising clast-supported, debris flows conglomerates, capped by well-sorted sheet flow sandstones, suggests subaerial deposition. On balance, a subaerial, fan delta environment is the most appropriate interpretation for these deposits. The intermittent presence of immature conglomerates may signify developing uplift and exposure of the hinterland/eroding escarpment, potentially related to fault activity.

In 204/27a-1, the lowermost succession (2124 – 2129 m) represents the deposits of subaerial debris flows, sheet-flows and winnowed sieve conglomerates, likely deposited within a proximal fan delta depositional environment (***Figure 10***). Mottled sandstones are interpreted as palaeosol development, which supports a subaerial setting. The middle section (2124 - 2122 m) records the transition from debris flow and sheet flow deposits of the proximal fan, into the medial to distal parts of the fan delta. This is indicated by the presence of pedogenically-altered sheet flow sandstones, interbedded with thin debris flow deposits. In addition, there is evidence for interbedded, wave worked sediments near to the top of this interval. Overlying this (between 2117 - 2122.2 m), coarsening-upwards packages record wave-working processes in a shoreface/littoral environment, with reworking of clasts sourced from the underlying fan delta. The upper-most deposits (>2118 m in ***Figure 10***) record the transition from the Rona R2 facies into the overlying Rona R4 facies (see section 7.2.1.4).

In 204/28-1, the lowermost section (“lower section” in ***Figure 10***) is interpreted as the product of debris flows, which transported and deposited thinly-bedded, matrix-supported conglomerates. These are interbedded with clast-supported conglomerates, overlain by well-sorted, parallel-laminated sandstones. The clast-supported conglomerates are interpreted as water-winnowed tops, with the overlying, well sorted, parallel-laminated sandstones representing sheet flow deposits. These facies association is typically observed in alluvial fan/fan delta environments and are referred to as sieve deposits (McPherson et. al., 1987). The sheet flow deposits display erosive basal contacts, pebble-rich basal lags and are massively bedded (structureless) or parallel-laminated in nature. The lack of trough cross-bedding within these deposits indicates unconfined, sheet-like processes. These deposits suggest dominance of fluidal processes, occurring in the distal part of a fan delta system, over that of the nearshore processes during this time.

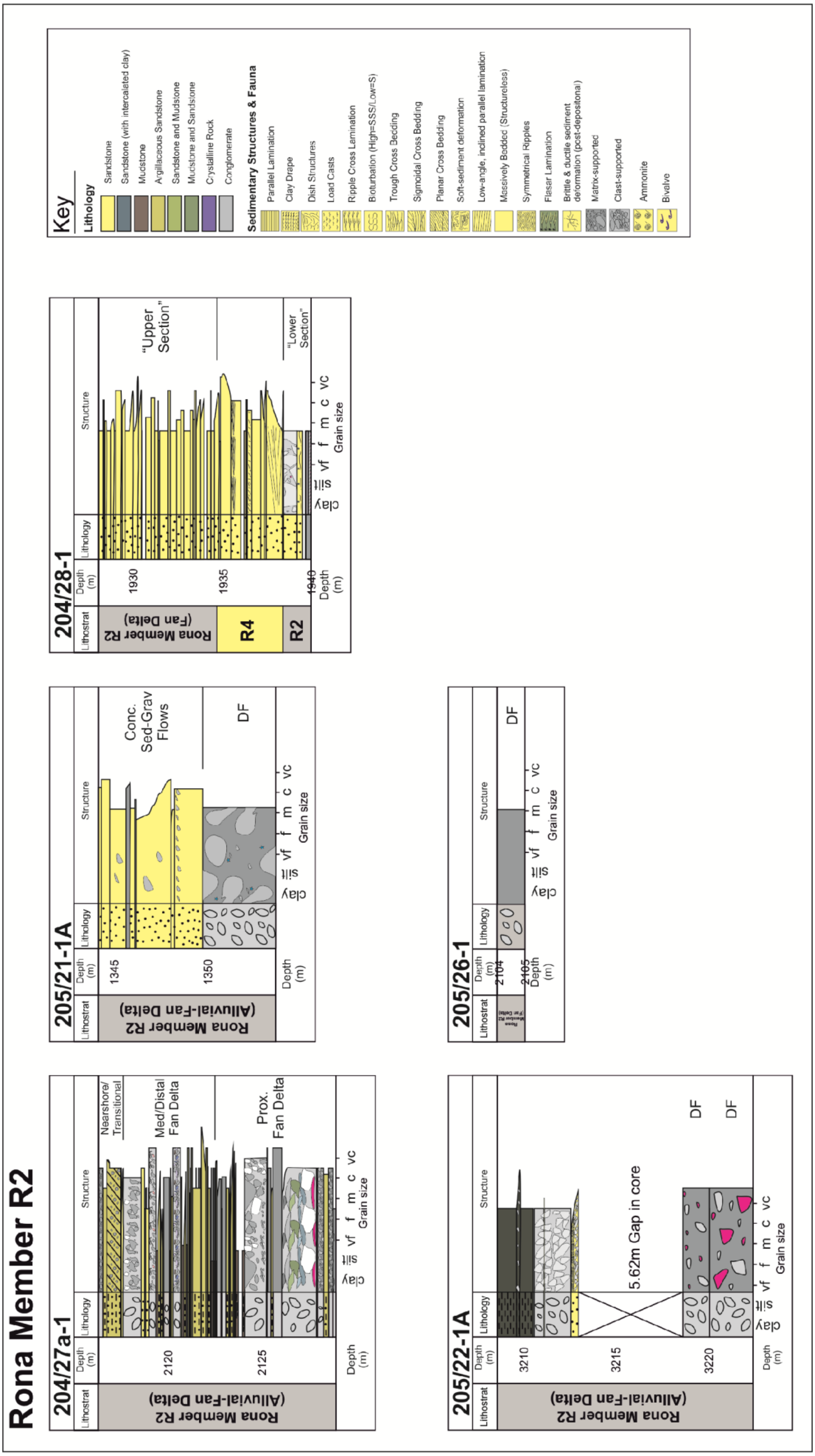

Figure 10 Sedimentary logs through the Rona R2 facies.

In 205/26-1, the single bed of matrix-supported conglomerate represents the products of a debris flow, which brought 5-30 cm-wide, lithic clasts from an actively eroding hinterland and deposited them within a fine- to medium-grained, well-sorted sandstone matrix. The matrix-supported nature of the conglomerates provides evidence for water-laden sedimentary flow process. Debris flows can form in a range of environments, including subaerial fan deltas or subaqueous debris cones; it is often impossible to determine the correct setting from sedimentary observations alone.

Summary

The deposits of the Rona R2 facies record deposition within a fan delta environment, draining into a marine basin. Sediments typically include: fine to coarse-grained, matrix-supported conglomerates; clast supported conglomerates; and very fine to medium-grained, structureless, occasionally parallel-laminated, normally-graded sandstones. Clasts within the conglomerates are composed of various lithic and granitic lithologies, are between 2 - 50 cm in width and tend to be sub-rounded to rounded, although occasionally are angular. Matrix supported conglomerates, particularly those that contain immature clasts and no matrix grading, represent debris flow deposits. Clast-supported conglomerates are interpreted as water-winnowed debris flow deposits. These are commonly overlain by moderate to well-sorted, fine to medium-grained sandstones, representing sheet-flow deposits. Examples of medium grained sandstone beds in 204/27a-1 display evidence for pedogenic texturing, indicating subaerial deposition within that part of the fan delta.

The presence of immature, clast-rich debris flows deposited in a fan delta setting, suggests developing relief, potentially linked to fault activation in the Late Jurassic, West of Shetland. The input of immature, debris flow conglomerates has been linked to fault activation in the areas from which fan deltas are sourced (McPherson et al., 1987). Unconfined flow deposits (fluidised processes, commonly found in fan deltas) are observed in 204/28-1. These form thickly bedded, erosively based, clast-rich, typically structureless sandstones. The fan delta deposits of Rona R2 are overlain by deposits of the Rona R4 facies (section 7.2.1.4) and, in 204/28-1, are observed to interdigitate. The vertical association of Rona R2 and Rona R4 (***Table 8***) suggests there was a spatial link between an in-draining fan delta and a shoreface/littoral setting (***Figure 14*****).**

7.2.1.3 Rona Member R3 - Marginal Marine

The Late Jurassic-aged Rona R3 sediments were encountered in 5 wells examined as part of this study (***Table 9***). These sediments were logged at a 10 cm-scale of resolution (Appendix 4, 5, 10, 19 and 20) and have been summarised (***Figure 11***).

Well Number	Top Depth (m)	Base Depth (m)	Underlain by in core	Overlain by in core	Comments
205/20-2	2955.67	3001.31	Papa Group (Triassic)	Rona Member R4	None
202/04-1	1862.07	1898.00	None	None	None
202/09-1	840.34	860.21	None	None	None
206/05-2	3169.31	3174.18	None	None	None
209/12-1	3467.41	3469.54	None	None	None

Table 9 Depth of core data through the Rona Member R3 facies.

Description

In 205/20-2, sediments comprise very fine- to fine-grained, occasionally medium-grained, well-sorted, quartz-rich, sub-rounded sandstone that displays carbonaceous flecks scattered throughout. The sandstones display erosive bases, weak to intense bioturbated, parallel lamination, trough cross-bedding, planar cross-bedding and occasionally have ripple laminated (asymmetrical) bed tops. They form coarsening-upwards successions, which are often capped by bioturbated and parallel-laminated mudstones. Sandstones tend to "clean-upwards", with abundant intraformational mud clasts, concentrated near the bed bases or in bed tops. Some beds develop trough cross bedding and/or planar cross bedding in the upper parts. In addition, very fine to fine-grained, poorly sorted, bioturbated, parallel-laminated, argillaceous sandstones are also present. These tend to contain concentrations of 1-10 cm long, 1-5 cm wide, angular, carbonaceous clasts; along with 1-2 cm wide, both angular and rounded, intraformational mud clasts.

In 202/04-1, sediments comprise fine to coarse-grained, poorly sorted to moderately sorted, sub-angular to sub-rounded, quartz-rich, planar cross-bedded, low-angle parallel-laminated, reversely graded, occasionally trough cross bedded sandstones (***Figure 11***). Occasionally root structures are observed in the sandstones beds, with one particular example of an 80 cm long, 6 cm wide, carbonaceous-filled root structure. Trough cross bedded sandstones sometimes display irregular foreset angles and reactivation surfaces; which are typically associated with clay-drapes on laminae. The coarser-grained successions are interbedded with very fine and fine-grained, ripple laminated and parallel-laminated, bioturbated sandstones. In addition, beds of medium to fine-grained, normally graded, erosively based, moderately sorted, quartz-rich, trough cross-bedded sandstone are present. The coarse-grained successions are always capped by an erosively based, structureless, occasionally parallel-laminated, soft-sediment deformed, argillaceous sandstone that range between 5 and 40 cm in thickness. Between each coarse-grained succession, 1.2 m – 3.5 m-thick, parallel-laminated, burrowed, bioturbated mudstones are present. There are eight separates cycles of these deposits within the core, with each successive coarse-grained interval documenting comparably coarser-grained, less mature sediments. The two, uppermost coarse-grained successions contain abundant shelly material within sandstones and cubic pyrite within the mudstones.

In well 202/09-1, sediments comprise 20 cm to 3 m-thick, moderate to well-sorted, sub-angular to sub-rounded sandstones that display massive bedding (structureless), occasionally trough cross-bedding, reverse grading, weak to moderate bioturbation and one example of root structures (at 843.20 m; ***Figure 11***). 1-4 cm wide, sub-rounded to rounded, lithic clasts are present within sandstone beds in the lower half of the core. The sandstones are interbedded with, parallel-laminated, often bioturbated, very fine-grained, argillaceous sandstones and dark grey-coloured, moderately bioturbated, parallel-laminated mudstones. Occasionally, normally graded, coarse-grained to very fine-grained, moderate to well-sorted, erosively based sandstones erode into well-sorted, quartz-rich sandstones, sometimes depositing a thin, lithic-clast-rich pebble lag. An upwards increase in argillaceous and carbonaceous material within matrices is common and argillaceous and carbonaceous material is ubiquitous throughout all of the sediments. This includes up to 10 cm long, elongate, carbonaceous wood fragments within much of the sediments.

In 206/05-2, sediments comprise 30 cm to 2 m-thick, coarsening-upwards, cleaning upwards, fine-grained to coarse-grained, moderately sorted, sub-angular sandstones (***Figure 11***). The sediments are weak to completely bioturbated throughout, resulting in a complete destruction of primary sedimentary structures in places. Root structures are observed in some beds. Most of the sand-prone intervals are capped by a 4–5 cm-thick bed composed of poorly sorted, carbonaceous-clast-rich, erosively based, argillaceous sandstones. The coarse-grained succession is interbedded with 10 - 20 cm-thick, clay- to silt-grade, moderate to intensely bioturbated, parallel-laminated mudstones.

In 209/12-1, the basal portion of this core comprises dark grey coloured, carbonaceous-clast-rich, weakly bioturbated mudstones, interbedded with very fine-grained, poorly sorted, sub-angular, argillaceous sandstones (***Figure 11***). Overlying this is thicker succession of fine to medium-grained, well-sorted, argillaceous sandstone. Other than crude parallel laminations developed at bed tops, these sandstones tend to be massively bedded (structureless). The sediments seem to be well-indurated, with poorly defined grain boundaries. The only heterogeneity present is in the form of calcite-filled "vugs" within the sandstone, which represent replacement of detritus of unknown origin (likely shell material or other organic fragments). The uppermost bed is composed of silt-grade to very fine-grained, moderately bioturbated sandstones, with interbedded mudstones.

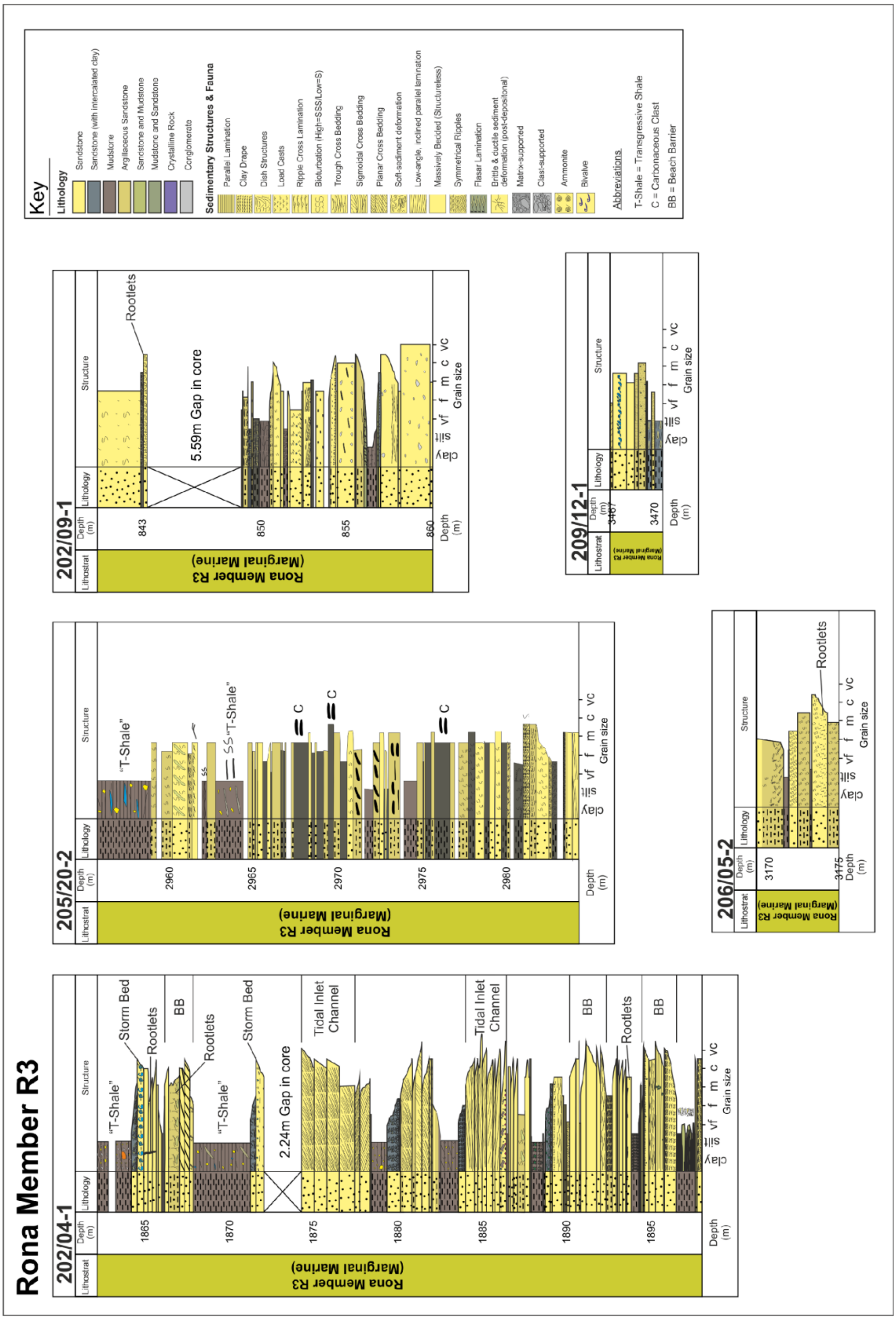

Figure 11 Sedimentary logs through the Rona R3 facies.

Interpretation

In 205/20-2, deposition occurred within a marginal marine, barrier-beach and back barrier/lagoonal environment. The barrier-beaches protected a low energy, restricted depositional environment, most likely an inter-tidal bay, lagoon or marsh. The restricted environment is evidenced by the high concentration of organic matter, with organic-rich sandstone matrices and large carbonaceous clasts/wood fragments present throughout the succession. This suggests a strong influence of terrigenous input into the marginal marine system at this location. The erosively based, clean, well-sorted, trough cross-bedded sandstones represent small distributary channels that cut through the lagoon, bringing in coarser-grained sediments and terrestrially derived organic matter from the hinterland. Near to the top of the barrier/lagoon succession (above 2965 m in ***Figure 11***) lies a thick (3 m-thick), slightly pyritic, partially parallel-laminated siltstone that contain carbonaceous flecks within the matrix. The pyritic nature of these mudstones may suggest a transgression of the lagoon. Above this lies a 1-3 m-thick barrier succession, suggesting temporary re-adjustment of relative sea level. This is followed by deposition of a >3 m-thick pyritic, homogenous, dark grey to black-coloured mudstone. This is interpreted as representing a significant marine transgression and downing of the marginal marine, back-barrier/lagoonal environment; this marks the top of Rona Member R3.

In 202/04-1, sediments represent a marginal marine, barrier-beach and back-barrier/lagoonal depositional environment. The planar cross-bedded, low-angle inclined laminated, parallel-laminated, sometimes reversely graded sandstones represent wave-worked deposits of the barrier-beach, typically found at the base of the coarser-grained intervals. In a few of the coarse-grained successions (c. 1875 m and 1885 m in ***Figure 11***), a number of stacked erosional surfaces filled with trough cross-bedded, moderately sorted, quartz-rich sandstones occur. These display irregular trough cross foresets and reactivation surfaces and are interpreted as deposition in tidal inlet channels that cut through the barrier-beach system. The beds of argillaceous sandstone at the top of each coarser grained interval marks the abandonment or migration of the barrier-beach, likely during a storm event. The intervening mudstones are interpreted as deposits of a protected lagoon, lying just behind the barrier-beach system. The cyclic association between coarser-grained barrier-beach deposits and intervening mudstones, is interpreted to represent migration or storm-related abandonment of bar systems in the marginal marine setting. This may have been controlled by fluctuations in relative sea level and downing of barrier-beach systems or simply migration/re-position of the bars along the margin.

The interbedded mudstones document a low-energy, protected environment, in which moderate to intense bioturbation of the substrate occurred. Sediment input into this protected setting occurred through washover deposition, formed during storm events. These deposits comprise interbedded, very fine-grained sandstones within the thick mudstone successions. The uppermost coarser-grained deposits display an increase in the prevalence of storm-generated, shell-rich deposits. The intervening mudstones exhibit an upwards increase in pyrite concentration, potentially indicating a progressive marine transgression of the shelf during this time. An overall upwards increase in energy/storm activity can be interpreted within the core.

In 202/09-1 (***Figure 11***), sediments represent deposition in marginal marine, barrier-beach and back barrier/ lagoonal depositional environment. Coarse-grained sandstones represent the deposits of the barrier beaches that protected a back barrier/lagoon. Argillaceous sandstone beds, located at the top of coarse-grained successions, represent abandonment or migration of the barrier-beach. Intervening, weak to moderately bioturbated mudstones represent deposition within a low-energy, lagoonal environment. Erosively based sandstones represent washover deposits or tidal inlet channels. The quantity of carbonaceous clasts, within both the barrier-beach and the lagoonal deposits, suggests elevated terrigenous input into this system.

In 206/05-2 (***Figure 11***), the sediments record a marginal marine, barrier-beach and back-barrier/lagoonal depositional setting. The presence of rooting indicates very shallow, possibly subaerial conditions, suggesting relatively stable barrier-beach. The argillaceous, carbonaceous, erosively based, poorly sorted sandstones represent abandonment/migration of the barrier system. The interbedded, bioturbated mudstones represent deposition within the low energy, back-barrier/lagoonal setting.

In 209/12-1, the well-sorted, quartz-rich sandstones are massively bedded, indicating they are have been well worked and were deposited quite rapidly. The coarser-grained succession in the centre of the core (3467.55 m - 34639.50 m in ***Figure 11***) displays a cleaning-upwards pattern, with argillaceous sandstone at the base and cleaner sandstone at the top. The presence of bioturbation throughout suggests deposition occurred in an oxygenated water column. Furthermore, the presence of calcite-filled "vugs" suggests that these sandstones originally contained either shelly material or other organic fragments, which were later replaced. The observation of well worked, bioturbated sandstones; along with shelly material permits an interpretation of a marginal-marine setting. A barrier-beach and back-barrier/lagoonal depositional environment would be appropriate for these sediments.

Summary

The Rona R3 facies represents deposition in a marginal-marine, barrier-beach and back barrier/lagoon depositional environment. Sediments comprise moderate to well-sorted, very fine to coarse-grained, sub-angular to sub-rounded, reversely graded, inclined laminated (low angle), parallel-laminated, planar cross-bedded, quartz-rich sandstones. Both the sandstones and mudstones display abundant, weak to intense bioturbation throughout. The sand-prone intervals represent the products of barrier-beach systems, which are periodically cut-into by tidal inlet channels. Tidal inlet channels are represented by thickly bedded, erosively based, trough cross-bedded sandstones, which display irregular re-activation surfaces, typically with clay-drapes along foresets. In wells 202/04-1, 202/09-1 and 206/05-2, the barrier-beach are well established, with evidence for in-situ root development. The cyclic nature of the barrier-beach deposits (e.g. 202/04-1), is interpreted as a function of bar migration or abandonment during storm events and is marked by an argillaceous, carbonaceous sandstone present at the top of each bar. Above the abandonment facies lies thick units of bioturbated, homogenised, parallel laminated, occasionally pyritic mudstones. These represent deposition within a low-energy, back-barrier/lagoonal environment protected by the barrier-beach systems. Occasionally, very fine to fine-grained deposits are interbedded within the bioturbated mudstone successions which represents washover deposits. Organic material, in the form of carbonaceous/woody clasts and argillaceous, carbonaceous matrices within sandstone beds, is ubiquitous throughout (e.g. well 205/20-2), suggesting a restricted setting, with elevated terrigenous input from the hinterland. Moving towards the top of the core, coarser-grained successions document a progressively increasing energy (wave or tidal), evidenced by the occurrence of storm-generated, shell-rich beds, typically found near to the top of the barrier-beach (202/04-1). In addition, the interbedded mudstone intervals display an increasing pyritic content. Together, these observations suggest a progressive rise in relative sea level towards the top of the Rona R3 facies.

7.2.1.4 Rona Member R4 - Shoreface/Littoral

The Late Jurassic-aged Rona Member R4 sediments were encountered in 7 wells examined as part of this study (***Table 10***). These sediments were logged at a 10 cm-scale of resolution (Appendices 2, 4, 8, 9, 10, 12 and 13) and have been summarised (***Figure 12***).

Well Number	Top Depth (m)	Base Depth (m)	Underlain by in core	Overlain by in core	Comments
205/20-2	2933.00	2955.67	Rona Member R3	None	None

202/03-1A	1642.00	1673.15	None	None	Verstralen et al., 1995 showed a log of this and used it for the facies model
205/22-1A	3201.70	3208.59	Rona Member R2	Kimmeridge Clay Formation	Verstralen et al., 1995 showed a log of this and used it for the facies model.
205/26-1	2095.50	2103.15	Rona Member R2	None	None
204/28-1	UI - 1915.00 and LI - 1934.63	UI - 1928.21 and LI - 1938.11	None	None	Inter-digitated UI = Upper Interval LI = Lower Interval
204/27a-1	2095.15	2117.47	Rona Member R2	Rona Member R5	Verstralen et al., 1995 showed a log of this and used it for the facies model
202/04-1	1856.00	1862.07	Rona Member R3	None	None

Table 10 Depth of core data through the Rona Member R4 sub-division facies.

Description

In 205/20-2, the lowermost interval (below 2952.00 m in ***Figure 12***) comprises interbedded, dark grey to black-coloured, bioturbated mudstones, and coarsening upwards, very fine-grained to fine-grained, argillaceous sandstones. Alongside the coarsening upwards of the sediments, well-developed *cruziana* ichnofacies (*planolites* ichnogenera) pass up into *skolithos* ichnofacies (*skolithos* ichnogenera). The bivalve shell "*Pinna sp.*", along with 5-sided crinoid ossicles are also present within this succession. In addition, a 4 cm-thick bed composed of: densely-packed wood fragments; 1 cm wide rugose corals; oyster shells; and various diagenetic nodules is present. Above the interbedded succession at the base of the core, sediments comprise medium-grained, coarsening upwards to coarse-grained, moderate to well-sorted, quartz-rich, sub-angular to sub-rounded sandstones. The sandstones display sharp basal contacts, are massively bedded (structureless), with poorly developed planar cross bedding, highlighted by patches of clay material in the matrices. In at least one bed (at 2944.00 m in ***Figure 12***), tentative sigmoidal cross-bedding, depicted by thin, clay-grade laminae, is observed. Some beds show evidence for water-escape in the form of dish structures. A patchy calcite cement (pore-filling/secondary) is observed throughout.

In 202/03-1A, sediments comprise 20 cm to 2 meter-thick beds of fine to medium-grained, moderate and well-sorted, quartz-rich, sub-angular, structureless sandstone, with sharp basal contacts (***Figure 12***). Occasionally, beds contain 1-5 mm wide, sub-rounded to rounded, lithic clasts, concentrated in erosive, basal scour fills. In places, beds display poorly developed parallel lamination. Dish structures are occasionally present near to bed bases and bed tops occasionally contain concentrations of 1-2 cm wide, rounded mud clasts or broken shelly fragments. Broken shell-rich bed tops tend to occur within sandstones that display strong coarsening-upwards trends.

In 205/22-1A, sediments comprise a succession of very fine-grained to coarse-grained, coarsening upwards, well-sorted, quartz-rich sandstones (***Figure 12***). The sandstones display sharp basal contacts and are massively bedded (structureless), particularly near bed bases. In the middle part of the core, beds develop trough cross-bedding, occasionally containing concentrations of 1-2 cm wide, rounded lithic clasts. Parallel laminations are present at the top of the beds and are typically accompanied by small amounts (<2%) of clay within the matrices. Other beds include thin (10-36 cm), weakly bioturbated, parallel-laminated, moderate to well-sorted, quartz-rich sandstone.

In 205/26-1, the core comprises 10 cm to 2 m-thick beds of moderate to well-sorted, very fine-grained to coarse-grained, sub-rounded to rounded sandstone (***Figure 12***). The beds form a stacked succession of coarsening-upwards, very fine-grained to coarse-grained, massively bedded (structureless) sandstones with sharp basal contacts. Low-angle, planar cross-bedding develops in some of the bed tops, accompanied by a concentration of broken shelly material, <1 cm wide rounded quartz clasts and lithic clasts. The sandstones become progressively less mature towards the top of the succession. In addition, the concentration and size of broken shelly material within the bed tops increases upwards. A patchy calcite cement (secondary, pore-filling) occurs throughout. The top of the core is marked by a fine-grained, moderate to well-sorted, quartz-rich, parallel-laminated, sandstone. This is overlain by a very fine-grained, intensely bioturbated, argillaceous sandstone.

In 204/28-1, the succession comprises an “upper interval” and “lower interval” (***Figure 12***). These deposits interdigitate with those of the Rona R2 subdivision (***Figure 10***). The “lower interval” comprises fine to medium-grained, typically well-sorted, occasionally very well-sorted, sometimes poorly sorted, sub-angular to sub-rounded, coarsening upwards, massively bedded (structureless), becoming trough cross-bedded to parallel-laminated sandstone. Occasionally, beds display low-angle, inclined parallel lamination, along with 2-3 cm wide, sub-angular to sub-rounded lithic clasts. The “upper interval” comprises fine to medium-grained, well-sorted, becoming moderately sorted, sub-rounded, massively bedded (structureless), occasionally reversely graded sandstones. The lower part of the “upper interval” displays scattered, 1-2 cm wide, sub-rounded and rounded, lithic clasts, which are concentrated at bed tops, but can be found “floating” within structureless sandstones. These clasts are absent from the uppermost portion of the “upper interval”. A number of beds (at 1922.80 m and 1924.00 m in ***Figure 12***) contain concentrations of both intact and broken shelly material (bivalve shells), which are accompanied by 10-30 mm wide, rounded, granitic clasts. Shells are oriented in both life position and inverted.

In 204/27a-1, sediments comprise a lowermost c. 5 m-thick interval of reversely graded, fine- to medium-grained, sub-rounded, massively bedded (structureless), argillaceous sandstone (***Figure 12***). The sandstones display high concentrations of sub-rounded to rounded clasts composed of lithic material, granitic fragments and quartz. The beds progressively become “cleaner”, with an upwards reduction in the concentration of argillaceous material within the matrix. Above this lies a more thickly bedded interval composed of medium-grained to coarse-grained, reversely graded, both very poorly sorted and well-sorted, sub-angular, quartz-rich, massively bedded (structureless) sandstone. The beds display a concentration of both broken and intact shelly material, comprising brachiopod fragments, crinoid ossicles and calcified worm burrows, along with sub-rounded to rounded lithic clasts and rounded, intraformational mud clasts, that are particularly well-developed at bed tops. The top of the coarser-grained packages are marked by an erosive scour, commonly filled with a shell/clast-rich, very fine-grained, trough cross-bedded, parallel-laminated, ripple laminated (asymmetrical), argillaceous sandstone. The coarser-grained packages repeat two further times (2095 m – 2099 m and 2100 m – 2106 m). Interbedded with this are 1-2 m-thick, very fine-grained, well-sorted, sub-angular, quartz rich, occasionally shell-rich, argillaceous sandstones. These display pervasive, well-developed, ripple laminations (asymmetrical), along with weak to intense bioturbation. The asymmetrical ripples often display clay drapes, signifying flaser lamination.

In 202/04-1, sediments comprise a 6 m-thick succession of both fine and medium-grained, well-sorted and very well-sorted, coarsening-upwards, sharp-based, occasionally erosively based sandstone (***Figure 12***). These are interbedded with argillaceous sandstones, which contain moderate to intense bioturbation, along with 1-10 cm long, vertical burrows, representing the *skolithos* ichnofacies. “Cleaner”, typically coarse-grained sandstones display only weak bioturbation, are massively bedded, occasionally develop planar cross-bedding, along with elevated concentrations (c. 1-2%) of broken, shelly material.

Interpretation

In 205/20-2, deposition is interpreted to have occurred in a shoreface/littoral environment. The reversely graded, coarsening upwards successions, observed alongside *planolites* and *skolithos* trace fossils; along with broken shelly material, including: crinoid ossicles, solitary corals, belemnite shells and the bivalve Pinna sp.; together, provide evidence for a marine depositional setting. The transition from the *cruziana* ichnofacies into the *skolithos* ichnofacies, observed in these sediments, suggests a sub-littoral setting, shallowing upwards to a shallow marine, inter-tidal zone (Seilarcher, 2007). The 4 cm-thick bed, containing the densely packed macrofossil assemblage, represents a condensation horizon, formed during a period of negative sediment balance, likely during a transgressive event (Gomez and Fernández-López, 1994). The stacked succession of trough cross-bedded, moderate to well-sorted, sandstones represents deposition of an upper shoreface. In general, the sediments coarsen and thicken upwards, indicating a shallowing upwards succession. The observation of sigmoidal cross-bedding, with mud drapes on topsets and foresets, provides an indication of tidal processes (Kreisa and Moiola, 1986 and references therein), an interpretation supported by the presence of *skolithos* ichnogenera.

In 202/03-1A, sediments were deposited within a shoreface/littoral environment. The main evidence is provided by: coarsening-upwards and thickening of the beds moving up the succession; rounded lithic clasts; and broken shelly material concentrated along bed tops. When combined, these observations suggest wave working processes enacting on these sediments. Whilst a marine depositional environment cannot be determined from these sediments alone, analysis of the palynological samples recovered during this project suggests a marine setting for this cored interval (MPA 67623 – MPA 67618; Thomas, 2018a). The lack of preserved sedimentary structuring may suggest rapid deposition and suppression of primary structuring.

In 205/22-1A, sediments comprise fine to very coarse-grained, coarsening upwards, trough cross-bedded, parallel-laminated sandstones. They contain rounded lithic clasts, suggesting wave-working processes were responsible for deposition, permitting an interpretation of an upper shoreface to foreshore. These sediments are texturally similar to those seen in examples of wave-worked sediments within Rona R4. Palynological samples, processed as part of this study, do not provide any evidence to suggest a marine or lacustrine depositional environment, all being found to provide “indeterminate” paleo-environmental information (Thomas, 2018g). Consequently, their textural similarities to other shoreface deposits found in Rona R4 has been relied upon to group these sediments within Rona R4. Furthermore, the conformable relationship with the underlying Rona R2 sediments in 205/22-1A (Appendix 1) may provide additional evidence to support an assignation of Rona Member R4.

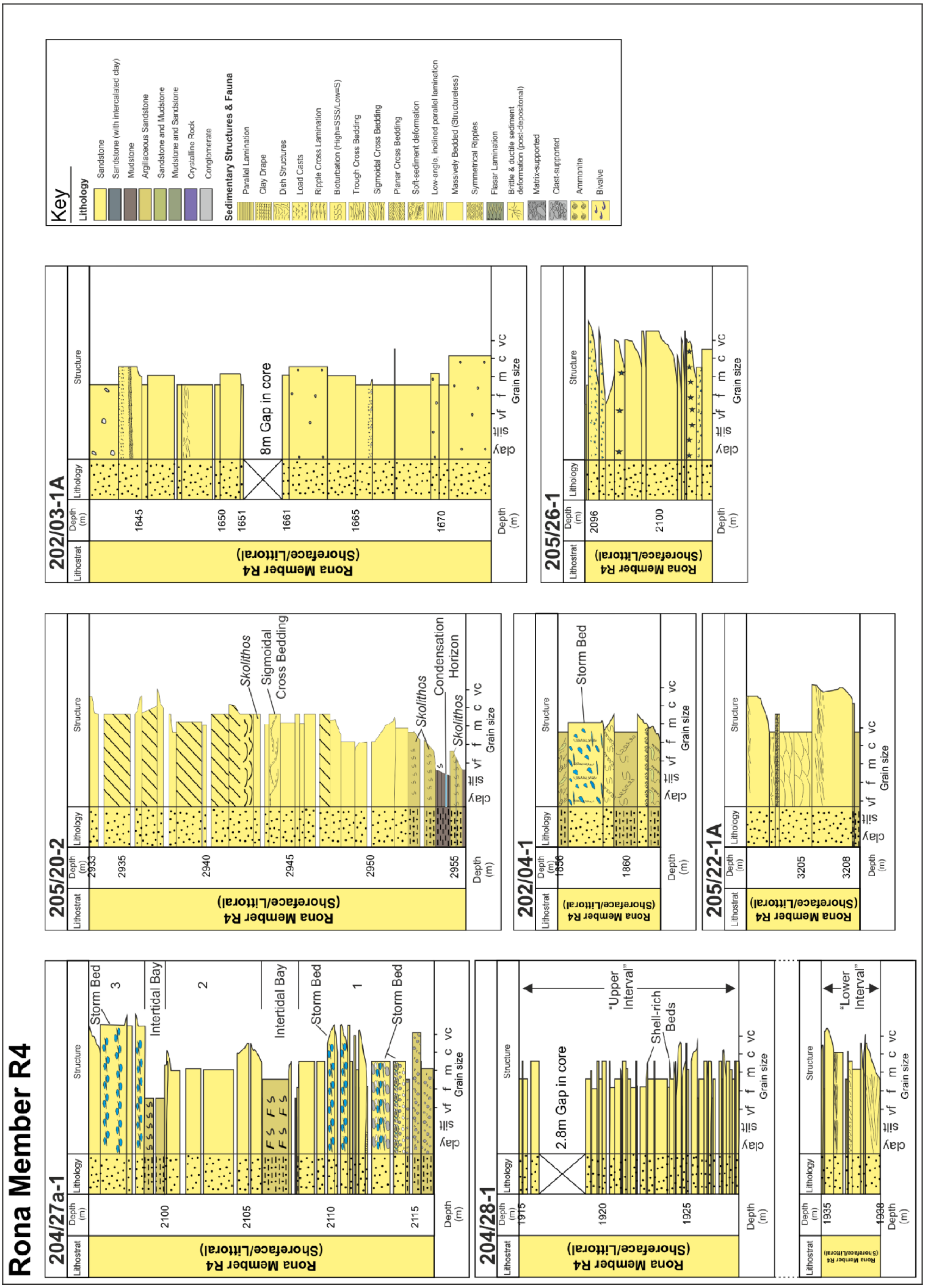

Figure 12 Sedimentary logs through the Rona R4 facies.

In 205/26-1, the stacked succession of reversely graded, broken shell-rich sandstones is interpreted as wave-worked, shoreface/littoral deposits. Palynological samples recovered from these sediments as part of this study, indicate an “open marine” depositional environment throughout (MPA 67648 to MPA 67644; Riding 2018d). The sedimentological evidence, coupled with the findings from the palynology studies, suggests deposition occurred in a marine, shoreface/littoral environment. The reversely graded beds represent upper shoreface deposits, with wave processes working broken shelly material in a nearshore environment. The top of the succession is marked by a parallel-laminated sandstone, representing deposition in a foreshore setting. This passes into bioturbated mudstones, possibly representing a flooding or transgression of the beach system.

In 204/28-1, both the “lower interval” and “upper interval” record deposition within a shoreface/littoral environment. This is evidenced by stacked, coarsening upwards packages of massively bedded (structureless), trough cross-bedded to parallel-laminated, occasionally shell-rich, well-sorted sandstones. In this well, Rona R4 deposits inter-digitate with Rona R2 (***Figure 10***). The succession records a complex interplay between the influx of both unconfined and confined fluidal flows (of Rona R2) from the hinterland and the establishment of the shoreface/littoral deposits (of Rona R4). A combination of wave and tidal process reworked the sediments delivered into the basin by the fan delta system. Within the “upper interval”, the broken and intact, shell-rich and granitic clast-rich sandstone beds represent storm-generated deposits”, evidencing perturbations in local climate. This fan delta may have drained into a ?marine or ?lacustrine body of water. Sedimentological evidence, alone, cannot determine if it was a marine or lacustrine (freshwater) body of water and the results from palynological sampling (Riding 2018i) provide “indeterminate” environmental information. As a result, the sediments have been placed within the Rona Member R4, based on comparative sedimentological textures/features observed in other examples of Rona R4, supported by stratal relationships with the Rona R2 deposits in other wells (Appendix 1).

In 204/27a-1, the sediments were deposited in a shoreface/littoral environment. The lowermost, coarse-grained succession, comprising, clast-rich, argillaceous sandstones, represents the transition from the underlying Rona R2 fan delta deposits into Rona R4 shoreface/littoral deposition (see 204/27a-1 on page 29). The transition is evidenced by lithic clasts, of comparative lithologies to the Rona R2 facies, becoming more mature, in terms of being sub-rounded to rounded and generally much smaller in size, signifying enhanced working of the sediments, likely by wave energy. In addition, the “cleaning” upward pattern suggests enhanced reworking of sediments. The three overlying coarsening upwards successions are well-sorted and relatively “clean”, with the sediments containing a concentration of both broken and intact shelly material, most likely reworked in a nearshore environment. Evidence for marine influences above 2113.21 m (***Figure 12***) is provided by marine palynomorphs present in palynological samples (Riding, 2018b). The top of the beach is marked by a slightly finer-grained, intensely bioturbated sandstone which is erosively scoured into and filled by coarse-grained sandstones and shelly debris.

The interbedded mudstones and very fine grained sandstones are bioturbated, indicating a well-oxygenated water column. Importantly, these display well-developed successions of ripple laminated (asymmetrical) and flaser laminated sandstones. The presence of flaser lamination indicates variable flow energies (and directions) and can be used to suggest the presence of sub-tidal or inter-tidal processes (Reineck and Wunderlich, 1968). The combination of observations suggests a low-energy, well-oxygenated, potentially tidally influenced depositional setting. An intertidal bay environment, formed in-between the shoreface/littoral deposits is appropriate.

In 202/04-1, sediments of the Rona R4 facies records deposition in a shoreface/littoral depositional environment. The transition from the underlying Rona R3 (marginal marine), into Rona R4 (shoreface/littoral), is marked by: an increase in bed thickness and overall grain size; the appearance of well-developed vertical burrows, representative of the *skolithos* ichnogenera; and a lack of internal sedimentary structuring. The sandstones display coarsening upwards, planar cross-bedding and broken shell material, indicating wave working processes. The intensity of bioturbation suggests a well-oxygenated water column, with the presence of *skolithos* (ichnofacies) suggesting a marine, nearshore environment (foreshore to lower shoreface; Seilarcher, 2007). The analysis of palynological samples confirms a marine depositional setting for these sediments (Thomas, 2018c).

Summary

The Rona Member (R4) can be characterised as a very fine to coarse grained, moderate to well-sorted, sub-angular to rounded, lithic clast rich (sub-rounded to rounded), relatively “clean”, coarsening upwards, massively bedded (structureless), becoming trough cross-bedded and parallel-laminated, sand-prone succession, deposited by both wave and tidal processes, in a shoreface/littoral environment. Evidence for an overall shallowing-upwards trend of the Rona R4 succession is provided in well 205/20-2. Coarse(r)-grained, shell-rich, storm deposits are present in 204/28-1. The upper-most deposits of Rona R4 record variable energies (storm-prone climatic conditions). The coarser-grained successions contain interbedded, very fine-grained, argillaceous sandstones and rare, thinly bedded mudstones. In well 204/27a-1, the very fine-grained, argillaceous sandstones display flaser lamination, suggesting the presence of tidal processes. In addition, tidal influences are present in the form of mud-draped, sigmoidal cross-bedding observed in well 205/20-2 and by *skolithos* burrows in 202/04-1 and 205/20-2. Evidence for a marine depositional environment is provided by analysis of palynological samples, with marine palynomorphs encountered in 202/03-1A, 205/26-1, 204/27a-1 and 202/04-1. This is supported through macrofossil identification, in the form of crinoid ossicles, solitary corals, belemnites, and the bivalve *Pinna* sp. encountered in 205/20-2. The presence of *skolithos* ichnogenera in 205/20-2, which is part of the *skolithos* ichnofacies, supports a marine, inter-tidal setting.

These deposits represent thickly bedded, relatively clean, well-sorted sandstones and lack interbedded successions of very fine-grained, argillaceous siltstones and mudstones. This makes for ideal hydrocarbon reservoir lithologies. Furthermore, the distribution of this facies may be linked to basin margin palaeogeographies of the Late Jurassic, with thick successions developing along the edges of the continental shelf and potentially along intra-basinal highs (i.e. the Rona High and the Judd High). The association between reservoir-quality sandstones of Rona R4, with the distribution of basin margin geometries, improves the predictability of this facies.

7.2.1.5 Rona Member R5 - Shallow Marine, Shelfal

The Late Jurassic-aged Rona R5 sediments were encountered in one well examined as part of this study (***Table 11***). These sediments were logged at a 10 cm-scale of resolution (Appendix 8) and have been summarised in representative logs (***Figure 13***).

Well Number	Top Depth (m)	Base Depth (m)	Underlain by in core	Overlain by in core	Comments
204/27a-1	2059.50	2095.15	Rona Member R4	Kimmeridge Clay Formation	Verstralen, et al., 1995 showed a log of this and used it for the facies model

Table 11 Depth of core data through the Rona Member R5 facies.

Description

In 204/27a-1, the uppermost c. 35 m of core represents the deposits of the Rona R5 facies (***Figure 13***). The lowermost c. 5 m comprises medium to very fine-grained, thinly bedded, well-sorted, occasionally moderately sorted, quartz-rich, sub-angular sandstone. Sedimentary structures include: trough cross-bedding near to the base; passing up into thinly interbedded, parallel-laminated, reversely graded sandstones; followed by thickly bedded, very fine-grained ripple laminated (asymmetrical), weakly bioturbated sandstones. In general, the level of bioturbation increases upwards, with weak bioturbation near to the bottom of the succession and intense bioturbation at the top. Above these deposits, (c. 2092 m in ***Figure 13***) sediments comprise 5-20 cm-thick, normally graded, well-sorted, quartz-rich, sub-angular structureless sandstones that develop parallel lamination in the middle of the beds and display ripple laminated bed tops. Above this, rests a c. 10 metre thick succession of thinly interbedded, fine-grained, well-sorted, normally graded, ripple laminated, weakly bioturbated sandstones and very fine-grained, argillaceous sandstones. Above this (c. 2077 m in ***Figure 13***) is a 20 m-thick succession of silt to very fine-grained, ripple laminated, parallel-laminated, moderately bioturbated, argillaceous sandstones. The succession gradually becomes finer-grained moving towards the top of the core with the uppermost 1 m comprising parallel-laminated, ripple laminated (asymmetrical) siltstones. These siltstones are dark grey to black-coloured and display evidence for weak bioturbation.

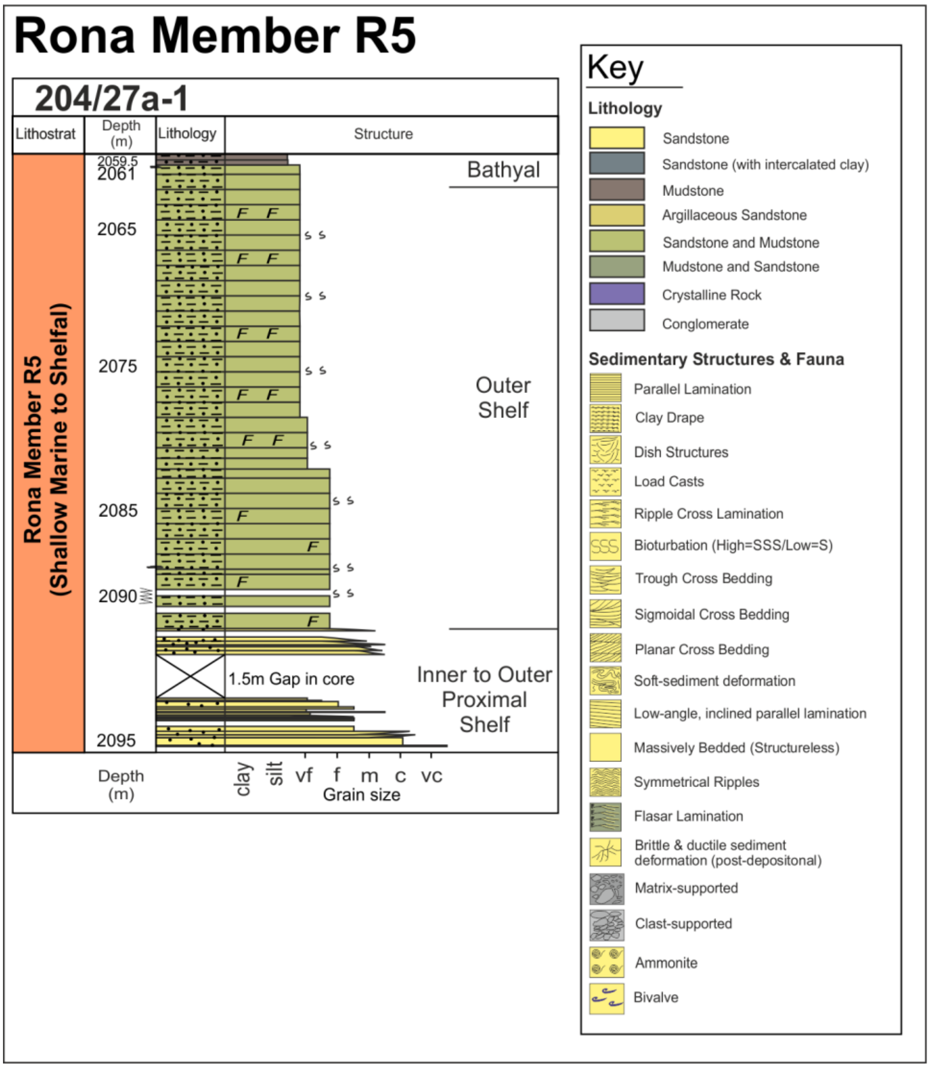

Figure 13 Sedimentary log through the Rona R5 facies.

Interpretation

In 204/27a-1, deposition occurred in a shallow marine, inner proximal shelf to outer shelf environment. The sediments document an upwards and progressive deepening of the marine basin. The marine depositional environment is confirmed by the presence of “marine” palynomorphs encountered throughout this interval (MPA 67841 - MPA 67468; Riding, 2018b). The c. 5 m of medium and fine-grained sediments, at the base of the succession, record deposition of the inner to outer proximal shelf, with reversely graded, trough cross-bedded sandstones at the base. These transition into thinly bedded, parallel-laminated, bioturbated, very fine-grained sandstones. Overlying this, a stacked, normally graded sandstone interval represents the deposits of low-density turbidity currents, which flowed out and onto the shelfal environment. This is followed by a thinly interbedded succession of bioturbated, shelfal sandstones and thinly bedded, low-density turbiditic sandstones. The turbiditic sandstones become less prevalent towards the top of the core. The uppermost 1 m, composed of dark grey to black-coloured, weakly bioturbated mudstones were deposited in a low energy setting. The dark colouration, along with the lack of bioturbation, indicates bottom water anoxia. These observations permit an interpretation of an outer shelf to bathyal environment, at the top of the Rona R5 facies. This is supported by palynological evidence, which indicates a switch from “marine” to “open marine” palynomorphs assemblages at c. 2060 m (Riding, 2018b). The progressive nature of this deepening event is an important observation as it indicates the transgression was not instantaneous and instead occurred gradually (a ?diachronous transgressive systems tract), whilst these shallow marine, shelfal sediments were being deposited.

Summary

The Rona R5 facies records deposition within a shallow marine setting, with a proximal shelf, to outer-shelf to bathyal transition evidenced in core from well 204/27a-1. The marine nature of the basin is confirmed by the presence of marine palynomorphs, encountered during the analysis of new palynological samples recovered from this well (Riding, 2018b). The lowermost deposits are represented by a coarsening-upwards, fine- to medium-grained, trough cross-bedded to parallel-laminated, well-sorted sandstone succession, deposited in an inner to outer proximal shelf environment. These are overlain by low-density turbidites, interbedded with ripple laminated sandstones, representing deposition of an inner to outer shelf. The sediments become finer-grained towards to the top of the core, with a gradual reduction in the thickness and regularity of the low-density turbiditic input. The uppermost deposits comprise dark grey to black-coloured, parallel-laminated, ripple laminated mudstones deposited in an outer shelf to bathyal environment. This is supported by palynological evidence, with a switch from “marine” to “open marine” palynomorphs assemblages at this point (Riding, 2018b). In addition, the dark grey colouration of the mudstones, along with a decrease in the amount of bioturbation in this interval, suggests the development of bottom water anoxia at the top of the cored section in 204/27a-1.

7.2.1.6 Rona Member – Environment of Deposition

The environment of deposition during the Late Jurassic is conceptualised in ***Figure 14***. Each of the Rona Member R1 to R5 facies can be accommodated in a simple palaeogeographical configuration, with the Rona R1 fluvial system potentially draining in from the south, feeding terrigenous clastic sediment into the Rona R3 marginal marine and Rona R5 shallow marine environments. The Rona R2 fan delta and Rona R4 shoreface/littoral facies formed at the edges of the basin, accumulating at sites of high sediment input. It is likely that the fan deltas fed sediment into the shoreface/littoral settings, where it was re-worked by wave working and longshore processes.

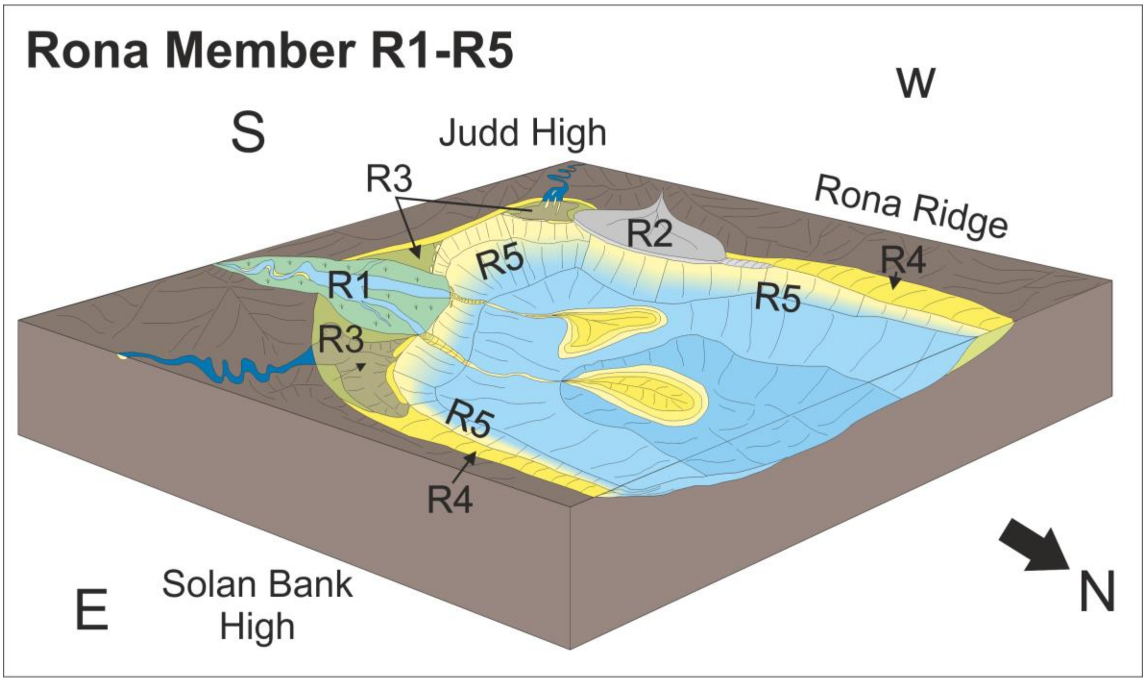

Figure 14 3D block diagram of the Rona Member R1-R5 facies in the Late Jurassic. R1 = Fluvial, R2 = Fan Delta, R3 = Marginal Marine, R4 = Shoreface/Littoral, R5 = Shallow Marine

7.2.2 Solan Sandstone Member

The Late Jurassic-aged Solan Sandstone Member sediments were encountered in two wells examined as part of this study (*Error! Reference source not found.*). These sediments have been logged at a 10 cm-scale of resolution (Appendix 15 and 16) and have been summarised in representative logs (***Figure 15***). The Solan Sandstone Member has been dated as Upper Jurassic in age (Herries et al., 1999; Riding, 2018f; Thomas, 2018h) and exists as a formal lithostratigraphical member within the Kimmeridge Clay Formation. In a conceptual model for the depositional environment of the Upper Jurassic (***Figure 14***) it is possible to interpret the Solan Sandstone Member and the Rona Member (section 7.2.1) as being contemporaneous. However, in Herries et al. (1999), the Solan Sandstone Member is interpreted as being slightly older than the Rona Member, with the KCF directly below the Solan Sandstone Member dated as slightly older than the KCF observed directly above the Rona Member.

Well Number	Top Depth (m)	Base Depth (m)	Underlain by in core	Overlain by in core	Comments
205/26a-4	2446.00	2454.85	Kimmeridge Clay Formation	None	None
205/26a-5Z	2932.78	2957.58	Kimmeridge Clay Formation	Kimmeridge Clay Formation	Encased within the KCF

Table 12 Depth of core data through the Solan Sandstone Member.

Description

In 205/26a-4, sediments comprise amalgamated, fine-grained and very fine-grained, very well-sorted, sub-rounded to rounded, quartz-rich, massively bedded (structureless) sandstones (***Figure 15***). Bed thicknesses range from 27 cm to 3.1 m. Load structures are evident at bed bases and there is one example of an erosive basal contact. Bed-tops typically display abrupt normal grading, accompanied by the development of parallel laminations and occasional ripple lamination (asymmetrical). An upwards increase in clay material in the matrix is present in some examples of sandstone beds. In general, there is a lack of interbedded mudstones. A patchy calcite cement (secondary/pore-filling) is present near to the top of the core.

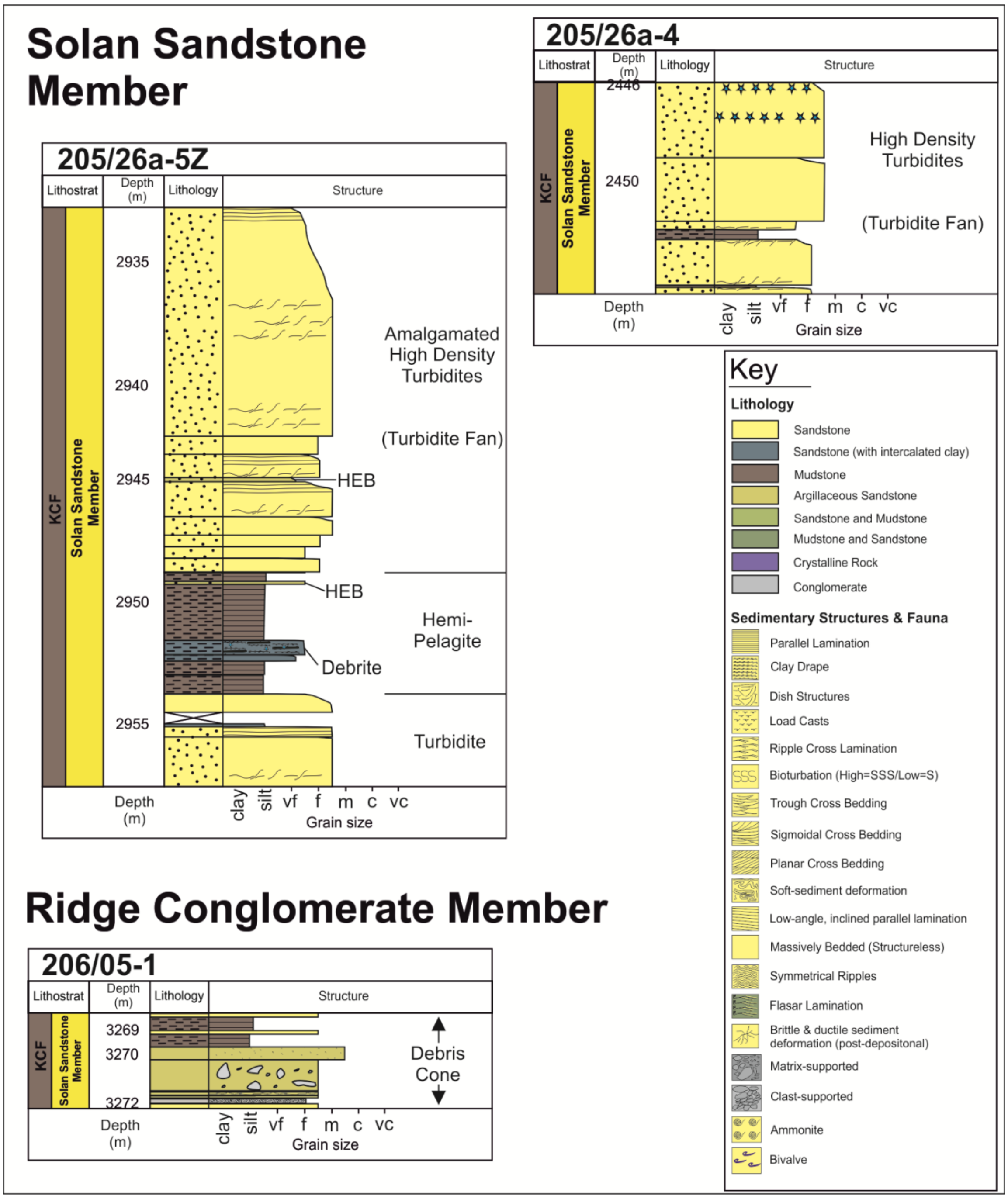

Figure 15 Sedimentary log through the Solan Sandstone Member and Ridge Conglomerate Member.

In 205/26a-5Z, sediments comprise fine-grained and very fine-grained, well and very well-sorted, sub-rounded, quartz-rich sandstones (***Figure 15***). The sandstones are typically massively bedded (structureless) and display dish structures, which tend to form near bed bases. The sandstones are amalgamated, which is particularly clear in the uppermost interval (above 2948 m in ***Figure 15***.), where a c. 5 m-thick, amalgamated package of eight separate "event beds" is present. Individual event beds commonly display an abrupt fining upwards (normal grading). Loaded basal contacts are common. Thinner beds tend to show well-developed parallel laminations in bed tops. In a few instances, the fine-grained sandstones display clay bed tops, comprising a mixture of material, including: shell material; clay-grade detritus; carbonaceous clasts and mud clasts. They tend to display sharp basal contacts with the underlying structureless sandstone and sometimes develop crude parallel laminations.

Interpretation

In 205/26a-4, the amalgamated packages of well-sorted sandstones (above 2454.00 m) represent the deposits of high density turbidite flows and hybrid event beds (Haughton et al., 2009). The presence of event bed amalgamation, along with a lack of interbedded, hemi-pelagic mudstones, suggests an axial setting, within a turbidite fan. The lack of structuring within each bed indicates rapid deposition below a traction carpet. Normal grading suggests the presence of decelerating flows.

In 205/26a-5Z, the stacked succession of massively bedded (structureless) sandstones, with dish structures and parallel-laminated bed-tops, suggests deposition under the traction carpet of high-density turbidity flows, in a turbidite fan setting. Within the sand-rich intervals, there is an absence of hemi-pelagic mudstones. This may suggests an axial setting. In addition, hybrid event beds are present, represented by a bed of structureless sandstone, overlain by an argillaceous/clay-rich sandstone, which contains an abundance of mudclasts and carbonaceous fragments (i.e. ***Figure 6***a). These are important to identify as they require significant run-out distances in order to achieve flow separation (Haughton et al., 2009). The presence of hybrid event beds, along with the thin nature of individual event beds, suggests deposition occurred within the distal part of a turbidite fan.

Summary

The Solan Sandstone Member of the Kimmeridge Clay Formation was deposited in a deep-marine turbidite fan environment (205/26a-4 and 205/26a-5Z). Deposition occurred through successive high-density turbidite flows and hybrid events beds, forming up to 16 m-thick, amalgamated packages of 0.2-3 meter-thick beds of very fine to medium-grained, well to very well sorted, sub-rounded to rounded, quartz-rich, structureless sandstone. Individual event beds display loaded bases, dish structures, normal grading, parallel and ripple laminated bed tops. Bed tops are occasionally clay-rich and contain concentrations of broken shelly material, carbonaceous fragments and mudclasts, interpreted as the product of hybrid event beds (Sensu. Haughton et al., 2009). The amalgamation of sandstone event beds, along with the lack of intervening hemi-pelagic mudstones, suggests an axial setting. It is likely that the turbidites encountered within 205/26a-4 and 205/26a-5Z are part of the same depositional system. The presence of hybrid event beds indicates significant transport distances and a non-channelized, setting within the turbidite fan.

7.2.3 The Ridge Conglomerate Member

These sandstones have been described as the "Ridge Conglomerate Member" in Haszeldine et al. (1987) and in Ritchie et al. (1996). These sediments have been logged at a 10 cm-scale of resolution (Appendix 18) and have been summarised in representative logs (***Figure 15***).

Description

In 206/05-1, sediments comprise a c. 4 m-thick interval of well-sorted, fine to medium-grained, sub-angular to sub-rounded, quartz-rich, sometimes massively bedded (structureless), argillaceous sandstones (***Figure 15***). Sandstone beds display loaded basal contacts, contain dish structures, have clay-rich matrices and are occasionally clast-rich. Interbedded with the sandstones are thin beds of both matrix and clast-supported conglomerates and thin (2-5 cm), parallel laminated mudstones. The clasts in the conglomerates comprise various lithic lithologies, range from sub-angular to sub-rounded and are scattered (floated) within the matrices.

Interpretation

In 206/05-1, sediments comprise of a mixture of the deposits of high-density turbidite flows (represented by the massive, structureless sandstones), along with more-cohesive flows such as debris flows (represented by the clast-rich conglomerates). These interbedded deposits likely formed in a subaqueous debris cone environment. The interbedded mudstones represent hemi-pelagic deposition, formed during periods of quiescence in debris cone activity. This suggests a fringing depositional setting. The relatively thin nature of the coarser-grained deposits (<4 m), along with the presence of interbedded, hemi-pelagic mudstones, provides the key evidence for a fringe location. The presence of coarser-grained lithologies, particularly the conglomerates, suggests a proximal slope depositional location. These sediments were transported by cohesive debris flows, which typically have limited transport distances. The debris cone may have been located (and sourced from) on the edge of a basin margin canyon system or immediately down-dip of an intra-basinal high.

Summary

The sediments in well 206/05-1 record a succession of well sorted, fine to medium grained, sub-angular to sub rounded structureless sandstones, interpreted as high-density turbidite deposits. These are interbedded with coarse-grained, clast-rich, argillaceous sandstones and matrix-supported conglomerates, interpreted as the products of debris flows. These deposits are interbedded with thin, parallel laminated, hemi-pelagic mudstones. This facies association is typical of deposition within a subaqueous debris cone. Coarse-grained, clast-rich debris flows typically have limited transport distances and, in general, remain close to the slope or canyon from where they are sourced. The sediment type and maturity, observed in 206/05-1, suggests a different depositional system to that observed in 205/26a-4 and 205/26a-5Z, in the Solan Sandstone Member. Both systems could easily co-exist within a complex palaeo-bathymetry, with subaqueous debris cone deposits of the Ridge Conglomerate Member sourced from an intra-basinal high and the high density turbidite fans, of the Solan Sandstone Member, being sourced from the shelf. This is in agreement with Haszeldine et al. (1987), in which they interpret the Ridge Conglomerate Member as a submarine scree deposit, derived from a nearby active fault scarp.

8 Sedimentology of the Cromer Knoll Group (Lower Cretaceous)

The sediments of the Early Cretaceous-aged Cromer Knoll Group sediments were encountered in three wells examined as part of this study (***Table 13***). These sediments were logged at a 10 cm-scale of resolution (Appendix 7, 11, 14) and have been summarised (***Figure 16***).

Well Number	Top Depth (m)	Base Depth (m)	Underlain by in core	Overlain by in core	Comments
204/19-1	4209.00	4223.00	none	none	None
205/21-1A	1338.00	1339.71	Kimmeridge Clay Formation	none	A palynological sample dated as being younger than the Cromer Knoll Group, was attributed to core jumbling.
205/26a-2	2093.37	2105.46	Rona Member R1	none	A 50 m gap in core between the Rona Member and Cromer Knoll Group.

Table 13 Depth of core data through the Cromer Knoll Group.

Description

In 204/19-1, the basal portion of the core comprises 30 cm of parallel-laminated, carbonaceous-clast-rich mudstones (***Figure 16***). Carbonaceous clasts are concentrated within fine-grained laminae within the mudstones. The overlying succession of coarser-grained deposits form an amalgamated package of 1-2 meter thick beds, comprising fine-grained and medium-grained, well to very well-sorted, quartz-rich, massively bedded (structureless), glauconitic sandstone. Bed-tops display normal grading, parallel lamination and an elevated clay content.

In 205/21-1A, sediments comprise medium to coarse grained, moderately-sorted, sub-angular to sub-rounded, quartz-rich, massively bedded (structureless), occasionally parallel laminated sandstones (***Figure 16***). They display a green-grey colouration and contain a pervasive calcite cement. The basal contact, with the underlying KCF deposits is sharp, displaying a number of 1-3 mm long, dark brown coloured flecks/fragments, concentrated at the bed base.

In 205/26a-2, sediments comprise intensely bioturbated mudstones and siltstones. Interbedded with very fine-grained to medium-grained sandstones. There is an example of an ammonite cast (***Figure 16***). Sandstones show coarsening-upwards, “cleaning-upwards” patterns and are pervasively bioturbated throughout. At the top of the core rests a stacked succession of fine- to medium-grained, “clean”, well-sorted, glauconitic, coarsening-upwards sandstones. These sandstones contain thin (<1 mm), dark grey-coloured, vertical lineations, interpreted as rootlets.

Interpretation

In 204/19-1, sediments represent the deposition of high-density turbidity currents. Typically, are massively bedded and contain detrital glauconite, likely reworked from a shallow water source. The homogenous, massively bedded (structureless) sandstones, along with the lack of interbedded, hemi-pelagic mudstones, suggests deposition occurred in a proximal, axial turbidite fan, likely in a deep marine setting. Carbonaceous clasts are present within these sediments, likely derived from a terrestrial-dominated hinterland, from which the turbidite fans were sourced.

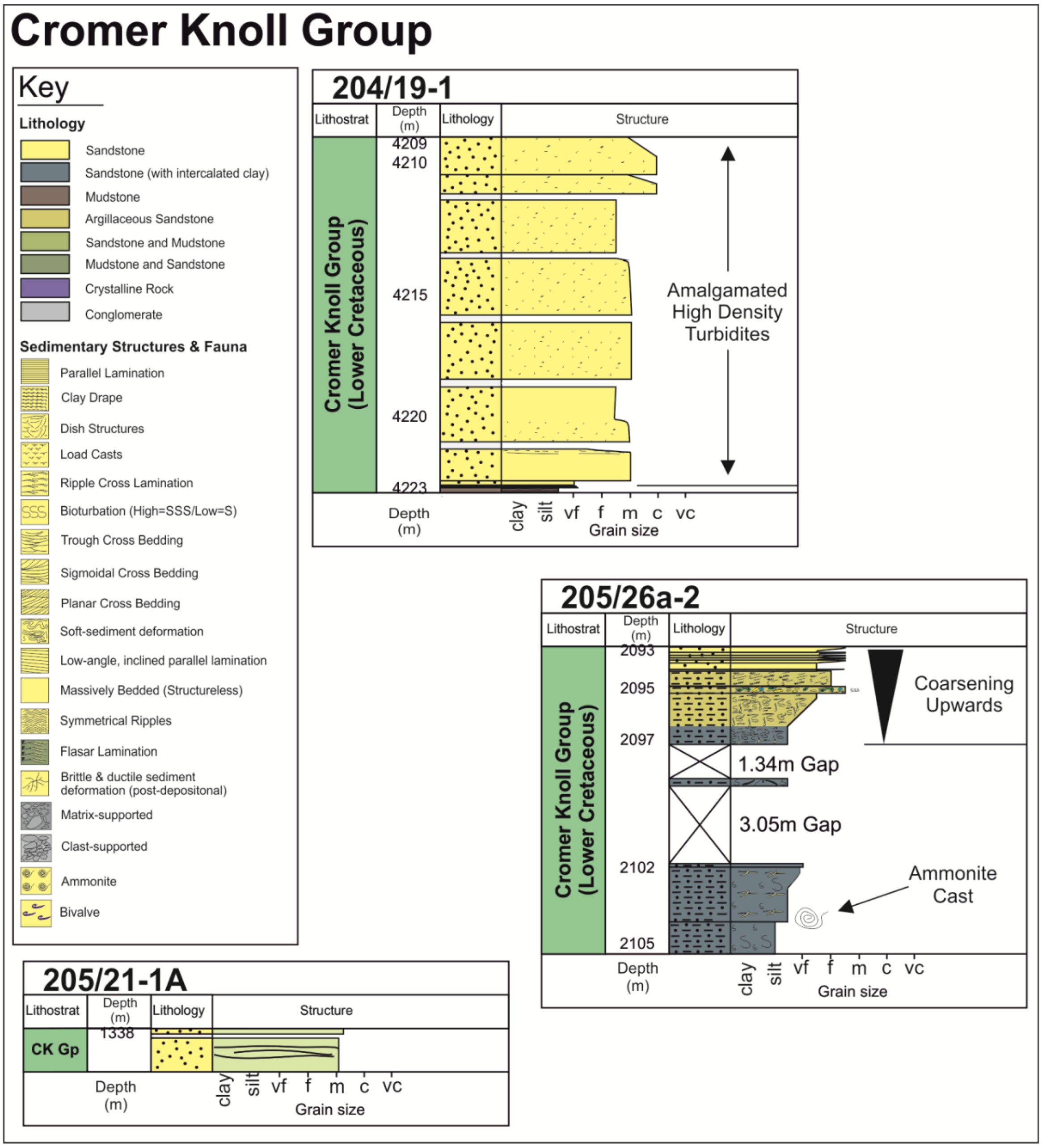

Figure 16 Sedimentary logs through the Cromer Knoll Group.

In 205/21-1A, the sediments are moderately sorted, thickly bedded and structureless. This permits the interpretation of deposition by high-density turbidity currents, within a turbidite fan, likely within a deep marine setting.

In 205/26a-2, sediments represent deposition in a shallow marine to littoral environment. The coarsening-upwards packages, along with glauconite, indicate that the sediments have been wave worked in shallow waters. In general, the coarsening-upwards of the succession suggests a shallowing-upwards pattern. The presence of root structures within wave-worked sediments, indicates stabilisation of shallow water sands and possibly periods of subaerial exposure. These deposits are comparable with the Rona Member, Rona R3 or Rona R4 facies. However, palynological sampling during this study (Riding, 2018e) suggests that these deposits were laid down in the Early Cretaceous, implying that they should be assigned to the Cromer Knoll Group and not the Rona Member of the Late Jurassic.

Summary

In 204/19-1, the c. 14 m of medium to coarse grained, moderately sorted, sub-angular to sub-rounded structureless sandstones represent deposition by high-density turbidity currents. In 205/21-1a, sediments are represented by medium to coarse-grained, moderately sorted, massively bedded sandstones also deposited by high-density turbidity currents, likely within a turbidite fan, in a deep-marine environment.

In contrast, sediments in well 205/26a-2 were deposited in a shallow marine to littoral setting. Deposits show evidence for shallow marine processes, including: wave working process; intense bioturbation; an ammonite cast; and a high concentration of glauconite on bed tops. Although these deposits would fit into the Rona Member, Rona R4 or Rona R5 facies, palynological dating suggests an Early Cretaceous age (Riding, 2018e), placing them within the Cromer Knoll Group.

9 Discussion

The below sections discuss the various broad subdivisions of sediments logged and interpreted as part of this study. They have been separated on the basis regional-scale packages of sediments, bound by major changes in basin configuration, depositional environment and/or unconformity surfaces. For this reason, each package must be discussed separately.

9.1 CRYSTALLINE BASEMENT ROCKS

The crystalline basement is observed within three wells examined as part of this study. In all three cases it is unconformably overlain by Upper Jurassic sediments of the Rona R2 facies. This relationship occurs on the south-eastern side of the Judd High, on the Judd Terrace, and the south-western corner of the Rona High (***Figure 2***). In 204/27a-1, which is located on the Judd Terrace, the crystalline basement displays a deep weathering profile, suggesting that the Judd Terrace was exposed, but potential formed a wet, palaeo-low area. In contrast, wells 205/22-1A and 205/21-1A, located on the Rona High, display a thin weathering profile, suggesting comparably less exposure. This may suggest that the Rona High was less exposed prior to the deposition of the Upper Jurassic Rona R2 sediments.

9.2 THE PAPA GROUP

The Triassic-aged sediments of the Papa Group were observed in two wells. They record deposition within a fluvial system with braided to meandering characteristics. The sediments are moderately mature and typically contains a high concentration of sub-rounded, granitic and lithic clasts, suggesting an actively eroding terrane/hinterland that was sourcing these sediments. Triassic deposits, observed at the top of 205/26a-4, record the effects of nearshore, wave-working of the sediments. This suggests the braided to meandering fluvial system was transgressed, at some point, within the Triassic (not necessarily at the top). Importantly, the uppermost relationship of the Triassic sediments is unconformable with the overlying deposits of the Upper Jurassic Kimmeridge Clay Formation; substantial thickness of Triassic-aged sediments may have been eroded.

9.3 THE SKERRY GROUP

During the Early Jurassic, sediments were deposited in a shallow marine, shelfal environment (Stack Skerry Formation) and a deep(er) marine setting (Sule Skerry Formation). The presence of a marine connection during this time is confirmed by ammonite macrofossils, identified as being of Late Sinemurian age, which would have lived within the water column on a marine shelf (Thomas, 2018b). Furthermore, the sediments record the deposition of a turbidite fan, in which high density turbidity currents and hybrid event beds brought in fine grained, well sorted sands into the shallow marine environment. The deep marine setting, interpreted within the Sule Skerry Formation, is based on: the lack clastic input into the system; the absence of bioturbation and the dark colouration. This permits the inference of a dysaerobic bottom water, most likely within a deep marine setting that was disconnected from the shelf. The difference in depositional setting between the Stack Skerry Formation and the Sule Skerry Formation (separated by 230 m in 202/03a-3, ***Figure 5***) suggests a deepening event, or a transgression of the shelf within the Early Jurassic, West of Shetland.

9.4 THE HUMBER GROUP – MIDDLE JURASSIC

In the dataset, deposition during the Mid Jurassic is represented by 3.86 m of poorly-preserved core (over-sampled). The core comprises heavily indurated, fine-grained, well sorted, ?structureless sandstone. This is interpreted as being deposited rapidly by a process that was effective in the sorting of the sediment. A high-density turbidite flow, within a deep-water setting, would be a reasonable mechanism for forming such deposits. However, caution is stressed as this is a "stretched" interpretation, with very little in the way of data to support this. The deposits are assigned to the Fair Sandstone Member of the Heather Formation (***Figure 1***.)

9.5 THE HUMBER GROUP – LATE JURASSIC TO EARLY CRETACEOUS

In the study area, the Kimmeridge Clay Formation is composed of the Solan Sandstone Member and Rona Member, along with the Ridge Conglomerate Member. The Rona Member has been sub-divided into five facies (Rona R1-R5), based on bulk depositional setting within the conceptual model for depositional environment of the Upper Jurassic (***Figure 14***.). Rona R1-R5 record the proximal to distal transition of facies along a Late Jurassic palaeo-shelf. The distribution of the various facies may be difficult to constrain, as there is uncertainty with regards to Early Jurassic basin configurations. In general, the Rona R1-R5 facies will form relatively linear facies belts, following the palaeo-coastline. The Rona R4 facies, which is sand-prone and would act as a good reservoir-lithology, may "line" the edge of the basin, making it more predictable than the other facies. In addition, the facies belts may develop along emergent, mid-basin high structures, permitting addition scope for reservoir development in the centre of the basin. Furthermore, the Rona 2 facies, is encountered in close proximity to emergent basin highs, which acted to source the fan delta systems. Where basement is present in the cored section, the Rona R2 facies always rests unconformably on top, suggesting a relationship between the basement rocks and the activation of fan delta systems.

The Solan Sandstone Member was deposited by high density turbidite flows and hybrid event beds, within a turbidite fan, in a deep marine environment. The intervening mudstones record hemi-pelagic deposition. In well 205/26a-5Z, the turbidites display bed amalgamation, but are quite thinly bedded. This suggests these sediments represent quite distal deposits within a fan. The presence of hybrid event beds supports this interpretation as they are typically encountered at the edge of fan systems (Haughton et al., 2003; 2009;Talling, 2013; Kane et al., 2017). On the basis of sedimentology alone, it is difficult to comment on the relationship between the Solan Sandstone Member and the Rona Member, based on sedimentology alone. However, it is conceivable that the Solan Sandstone Member could represent a notional "R6" facies" within the Rona Member, with the deep marine setting being the next, basinally-located facies belt.

In contrast, the Ridge Conglomerate Member was deposited by a mixture of debris flows and high-density turbidite currents in a subaqueous debris cone setting. The presence of clast-rich debris flow deposits, implies limited transport distances, suggesting deposition close to the break in slope and the source of the sediment.

9.6 THE CROMER KNOLL GROUP

Sediments of the Cromer Knoll Group, deposited during the Early Cretaceous, record a shallow marine to littoral setting; and a deep marine, high density turbidite fan setting. The littoral sediments, observed in well 205/26a-2, show evidence for wave working process, intense bioturbation, an ammonite cast and a high concentration of glauconite on bed tops. The deep marine, turbiditic sandstones observed in 205/21-1A and 204/19-1 are well sorted, thickly bedded and structureless. In 204-19-1, these deposits would be characteristic of a axial setting, within a turbidite fan.

10 Conclusions

The conclusions section has been subdivided into "Key Geological Conclusions" and "Hydrocarbon Exploration Conclusions".

10.1 KEY GEOLOGICAL CONCLUSIONS

- Basement rocks comprise crystalline basement, likely of Precambrian age (Lewisian) and display weathering profiles indicative of variable lengths and styles of exposure.
- Triassic-aged sediments record deposition within a braided-to-meandering fluvial system. In addition, the effects of nearshore processes enacting on these sediments is observed in well 205/26a-4.
- In well 202/03a-3, sediments of the Stack Skerry Formation record deposition within a marine, shelfal environment. These deposits contain abundant ammonite macrofossils, dated as late Sinemurian in age. Sediments of the Sule Skerry Formation record a deep(er) marine, anoxic setting, with little in the way of clastic input during this time.
- The Mid Jurassic-aged, Fair Sandstone Member of the Heather Formation is represented by a <4 m-thick, poorly preserved core sample. Consequently, the depositional environment is challenging to determine; however one possible interpretation would be deposition by high density turbidity currents, in a deep marine setting. This is based on the well sorted, structureless nature of the sandstones.
- The Late Jurassic-aged Rona Member is represented by a large proportion of core investigated for this study and has been separated into five different "facies". These are termed: Rona R1 (Fluvial); Rona R2 (Fan Delta); Rona R3 (Marginal Marine); Rona R4 (Shoreface/Littoral); and Rona R5 (Shallow Marine).
- During the Late Jurassic, the Solan Sandstone Member (and the Ridge Conglomerate Member) was deposited in a deep-marine, turbidite fan environment.
- In this conceptual model for the Late Jurassic, we suggest the turbidite fan, of the Solan Sandstone Member, may have been coeval with the deposition of the Rona Member.
- Unfortunately, new age determinations have failed to provide additional information concerning the relative ages of the Rona, Solan Sandstone and Ridge Conglomerate Members.
- Sediments of the Lower Cretaceous-aged Cromer Knoll Group record deposition in a shallow marine setting; and a deep marine, turbidite fan setting.

10.2 HYDROCARBON EXPORATION CONCLUSIONS

- Triassic-aged sandstones, logged as part of this study, form relatively thick, coarse-grained successions of sediment that could act as good hydrocarbon reservoirs. However, in the examples observed in this study, the Triassic sediments showed little in the way of visible porosity.
- This study has proven a fully-marine shelf, present during the Sinemurian of the Early Jurassic, West of Shetland. Well 202/03a-3 records deposition of thickly-bedded, clean well-sorted sandstones of the Stack Skerry Formation (reservoir lithologies); along with dark grey coloured, organic-rich, anoxic mudstones of the Sule Skerry Formation (source or sealing lithologies). Given this, there may be potential for an Early Jurassic hydrocarbon play West of Shetland.

- The Rona R3 facies (marginal marine) comprises a thickly interbedded succession of sandstone and mudstones. In particular, the mudstones are organic-rich, whilst there is a relatively high organic content within most of these sediments. Consequently, the Rona R3 facies could represent a potential source rock in areas where the KCF is not present, or is immature for oil generation.
- The Upper Jurassic, Rona R4 facies (shoreface/littoral) is composed of a relatively clean, fine to medium grained, thickly bedded, sand-prone succession, making it an ideal candidate for a reservoir lithology. Furthermore, the predictability of this facies is relatively good, with shoreface/littoral deposition likely to drape the basin margin and mid-basin highs.
- The deep marine, turbiditic sandstones, of the Cromer Knoll Group, are fine to medium grained, well sorted, thickly-bedded and would represent an excellent hydrocarbon reservoir lithology.

11 Recommendations for Future Work

1. Sedimentology of the Triassic, West of Shetland. Provenance of fluvial systems.
2. Transgressions in the Triassic: is there a transgression in the upper part of the Triassic-aged core? Is it marine or freshwater inundation?
3. Marine transgressions within the Late Jurassic: is it a single, diachronous transgression? Or a number of smaller-scale transgressions? Progressive vs. instantaneous flooding events.
4. Definition of basin morphologies and pre-Kimmeridgian structural configurations.

12 Appendices

Appendix 1 Representative Sedimentary Logs

Appendix 2 Sedimentary and Palynological Summary Log Well 202/03-1A

Appendix 3 Sedimentary and Palynological Summary Log Well 202/03a-3

Appendix 4 Sedimentary and Palynological Summary Log Well 202/04-1

Appendix 5 Sedimentary and Palynological Summary Log Well 202/09-1

Appendix 6 Sedimentary and Palynological Summary Log Well 202/12-1

Appendix 7 Sedimentary and Palynological Summary Log Well 204/19-1

Appendix 8 Sedimentary and Palynological Summary Log Well 204/27a-1

Appendix 9 Sedimentary and Palynological Summary Log Well 204/28-1

Appendix 10 Sedimentary and Palynological Summary Log Well 205/20-2

Appendix 11 Sedimentary and Palynological Summary Log Well 205/21-1A

Appendix 12 Sedimentary and Palynological Summary Log Well 205/22-1A

Appendix 13 Sedimentary and Palynological Summary Log Well 205/26-1

Appendix 14 Sedimentary and Palynological Summary Log Well 205/26a-2

Appendix 15 Sedimentary and Palynological Summary Log Well 205/26a-4

Appendix 16 Sedimentary and Palynological Summary Log Well 205/26a-5Z

Appendix 17 Sedimentary and Palynological Summary Log Well 205/26a-6

Appendix 18 Sedimentary and Palynological Summary Log Well 206/05-1

Appendix 19 Sedimentary and Palynological Summary Log Well 206/05-2

Appendix 20 Sedimentary and Palynological Summary Log Well 209/12-1

13 References

ANDREWS, I.J., DODD, T.J.H., QUINN, M.F., THOMAS, J.E., RIDING, J.B., STEWART, M.A. EIDESGAARD, Ó. and STARCHER, V.E, (2018). *Jurassic stratigraphy of the Faroe-Shetland region: implications for the evolution of the proto-NE. Atlantic margin* British Geological Survey Commissioned Report, CR/18/030

CATUNEANU, O. (2006). *Principles of Sequence Stratigraphy*. Elsevier, Oxford, United Kingdom.

GOMEZ, J.J. and FERNÁNDEZ-LÓPEZ. S. (1994). *Condensation processes in shallow platforms*. Sedimentary Geology, 92, 147-159.

HASZELDINE, R S, RITCHIE, J D AND HITCHEN, K. (1987). *Seismic and well evidence for the early development of the Faeroe-Shetland Basin*. Scottish Journal of Geology, VOL. 23 (3), 283–300.

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.

HAUGHTON, P.D.W., DAVIS, C., MCCAFFREY, W.D. and BARKER, S. (2009). *Hybrid sediment gravity flow deposits – Classification, origin and significance*. Marine and Petroleum Geology, 26, 1900-1918.

HERRIES, R, PODDUBIUK, R & WILCOCKSON, P. (1999). *Solan, Strathmore and the back basin play, West of Shetland*. 693–712 in Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference. FLEET, A J & BOLDY, S A R. (Editors). (London: The Geological Society).

KANE, I.A., PONTÉN, A.S.M. VANGDAL, B., EGGENHUISEN, J.T., HODGSON, D.M. & SPYCHALA, Y. (2017) *The stratigraphic record and processes of turbidity current transformation across deep-marine lobes*. Sedimentology, 64, 1236-1273.

KREISA, R.D. AND MOIOLA, R.J. (1986). *Sigmoidal tidal bundles and other tide-generated sedimentary structures of the Curtis Formation*, Utah. Geological Society of America Bulletin, Vol. 97, 381-387.

MCPHERSON, J.G., SHANMUGAM, G. and MOIOLA R.J. (1987). *Fan-deltas and braid deltas: Varieties of coarse-gained deltas.* GSA Bulletin. Vol. 99, pp. 331-340.

PEMBERTON, S. G., SPILA, M., PULHAM, A. J., SAUNDERS, T., MACEACHERN, J. A., ROBBINS, D., and SINCLAIR, I. K. (2001). *Ichnology and sedimentology of shallow to marginal marine systems: Ben Nevis and Avalon reservoirs, Jeanne d'Arc Basin*. Geological Association of Canada, Short Course Notes Volume 15, p. 343.

PEMBERTON, S.G., MACEACHERN, J.A., DASHTGARD, S.E., BANN, K.L., GINGRAS, M.K. and ZONNERVELD, J. (2012). *Shorefaces*, 863-603. Chapter 19 in: Developments in Sedimentology: Trace Fossils as Indicators of Sedimentary Environments. KNAUST, D. and BROMLEY, R.G. (Editors). Elsevier.

REINECK, H. and WUNDERLICH, F. (1968). *Classification and origin of flasar and lenticular bedding*. Sedimentology, 11, 99-104.

RIDING, J B. (2018a). *The palynology of Faroe-Shetland Basin well 204/19-1 (4222.8 to 4209.4 m),* version 2. British Geological Survey Commissioned Report, CR/17/019.

RIDING, J B. (2018b). *Palynology of Faroe-Shetland Basin well 204/27a-1 between 2137.00 and 2059.91 m*. British Geological Survey Commissioned Report, CR/17/070.

RIDING, J B. (2018c). *Palynology of Faroe-Shetland Basin well 205/20-2 between 2999.78 and 2958.81 m*. British Geological Survey Commissioned Report, CR/17/087.

RIDING, J B. (2018d). *Palynology of Faroe-Shetland Basin well 205/26-1 between 2103.91 and 2095.71 m*. British Geological Survey Commissioned Report, CR/17/083.

RIDING, J B. (2018e). *Palynology of Faroe-Shetland Basin well 205/26a-2 between 2158.00 and 2093.77 m*. British Geological Survey Commissioned Report, CR/17/124.

RIDING, J B. (2018f). *Palynology of Faroe-Shetland Basin well 205/26a-4 between 2498.91 and 2454.39 m*. British Geological Survey Commissioned Report, CR/17/125.

RIDING, J B. (2018g). *Palynology of Faroe-Shetland Basin well 206/05-1 between 3301.90 and 3155.08 m*. British Geological Survey Commissioned Report, CR/17/127.

RIDING, J B. (2018h). *Palynology of Faroe-Shetland Basin well 209/12-1 between 3469.85 and 3467.55 m*. British Geological Survey Commissioned Report, CR/17/082.

RIDING, J B. (2018i). *The palynology of Faroe-Shetland Basin well 204/28-1 between 1939.05 and 1916.00 m.* British Geological Survey Commissioned Report, CR/18/003.

RITCHIE, J D, GATLIFF, R W AND RIDING, J B. (1996). *Stratigraphic Nomenclature of the UK North West Margin. Volume 1: Pre-Tertiary Lithostratigraphy*. Keyworth, Nottingham: British Geological Survey

RITCHIE, J D & VARMING, T. (2011). *Jurassic*. 103–122 in Geology of the Faroe-Shetland basin and adjacent areas. RITCHIE, J D, ZISKA, H, JOHNSON, H AND EVANS, D. (Editors). (Keyworth, Nottingham: British Geological Survey & Tórshavn, Faroe Islands: Jarðfeingi.) ISBN 978 085272 643 3

RITCHIE, J D, ZISKA, H, JOHNSON, H & EVANS, D. (2011). *Geology of the Faroe-Shetland Basin and adjacent areas.* (Keyworth, Nottingham: British Geological Survey & Tórshavn, Faroe Islands: Jarðfeingi.) ISBN 978 085272 643 3

SEILACHER, A. (2007). *Trace Fossil Analysis*. Springer Science. ISBN 9783540472254

STOKER, M.S., STEWART, M.A., SHANNON, P.M., BJERAGER, M., NIELSEN, T., BLISCHKE, A., HJELSTUEN, B.O., GAINA, C., MCDERMOTT, K. AND ÓLAVSDÓTTIR, J. (2017). *An overview of the Upper Palaeozoic-mesozoic stratigraphy of the NE Atlantic region*. From: PÉRON-PINVIDIC, G., HOPPER, J. R., STOKER, M. S., GAINA, C., DOORNENBAL, J. C., FUNCK, T. & ÁRTING, U. E. (Editors) 2017. The NE Atlantic Region: A Reappraisal of Crustal Structure, Tectonostratigraphy and Magmatic Evolution. Geological Society, London, Special Publications, 447, 11–68.

TALLING, P.J. (2013) *Hybrid submarine flows comprising turbidity current and cohesive debris flow: Deposits, theoretical and experimental analyses, and general models*. Geosphere, 9, 3, 460-488.

THOMAS, J E. (2018a). *Palynology of the interval 1671.21 to 1643.75 m of well 202/03-1a, Faroe-Shetland Basin*. British Geological Survey Commissioned Report, CR/17/132.

THOMAS, J E. (2018b). *Palynology of the interval 1796.78 to 2066.83 m of well 202/03a-3, Faroe-Shetland Basin*. British Geological Survey Commissioned Report, CR/16/213.

THOMAS, J E. (2018c). *Palynology of the interval 1856.4 to 1896.9 m of well 202/04-1, Faroe-Shetland Basin.* British Geological Survey Commissioned Report, CR/16/174.

THOMAS, J E. (2018d). *Palynology of the interval 840.55 to 860.21 m of well 202/09-1, Faroe-Shetland Basin*. British Geological Survey Commissioned Report, CR/17/134.

THOMAS, J E. (2018e). *Palynology of the interval 1358.12 to1446.0 m of well 202/12-1, Faroe-Shetland Basin*. British Geological Survey Commissioned Report, CR/17/135.

THOMAS, J E. (2018f). *Palynology of the interval 1335.47 to 1353.04 m of well 205/21-1A, Faroe-Shetland Basin*. British Geological Survey Commissioned Report, CR/17/136.

THOMAS, J E. (2018g). *Palynology of the interval 3222.35 to 3177.46 m of well 205/22-1A, Faroe-Shetland Basin*. British Geological Survey Commissioned Report, CR/17/138.

THOMAS, J E. (2018h). *Palynology of the interval 2960.84 to 2929.24 m of well 205/26a-5Z, Faroe-Shetland Basin*. British Geological Survey Commissioned Report, CR/17/133.

THOMAS, J E. (2018i). *Palynology of the interval 2575.47 to 2610.15 m of well 205/26a-6, Faroe-Shetland Basin.* British Geological Survey Commissioned Report, CR/16/214.

THOMAS, J E. (2018j). *Palynology of the interval 3173.41 to 3169.84 m of well 206/05-2, Faroe-Shetland Basin*. British Geological Survey Commissioned Report, CR/16/137.

QUINN, M F. (2018). *Seismic interpretation and mapping of the Jurassic succession in the SW part of the Faroe-Shetland Basin as part of Jurassic stratigraphy of the Faroe-Shetland region project*. British Geological Survey Commissioned Report, CR/18/036

VERSTRALEN, I. (1996). *Sedimentology and reservoir characteristics of the Upper Jurassic, West of Shetlands*. Unpublished PhD thesis, University of Aberdeen.

VERSTRALEN, I, HARTLEY, A J and HURST, A. 1995. *The sedimentology of the Rona Sandstone (Upper Jurassic), West of Shetlands, UK.* 155–176 in Characterisation of Deep-Marine Clastic Systems. HARTLEY, A J and PROSSER, D J (Editors). Geological Society, London, Special Publications, No. 94. London: Geological Society.

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