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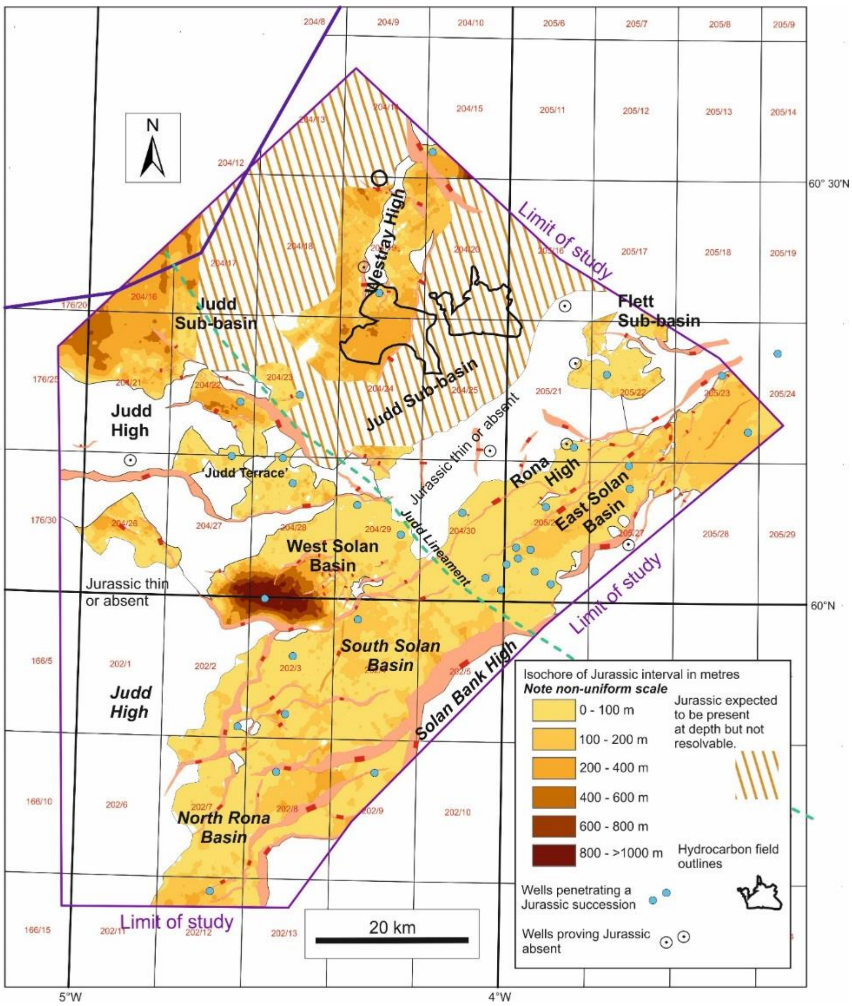
Jurassic stratigraphy of the Faroe-Shetland region: implications for the evolution of the proto-NE Atlantic margin

Energy Systems & Basin Analysis Programme

Commissioned Report CR/18/030



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Jurassic stratigraphy of the Faroe-Shetland region: implications for the evolution of the proto-NE Atlantic margin

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Foreword

This report is the result of a joint study by the British Geological Survey (BGS) and Jarðfeingi (the Faroese Earth and Energy Directorate) on behalf of the Faroe-Shetland Consortium (FSC) and presents a regional analysis of Jurassic stratigraphy of the Faroe-Shetland region and the implications for the evolution of the proto-NE Atlantic margin.

This report integrates the main conclusions of the various component studies that comprise the 'Jurassic Project'. Readers are directed to the individual, detailed reports for further background information, a discussion of methodology and a fuller discussion of the conclusions. The detailed reports cover the following subjects: seismic interpretation, structure and thickness (Quinn 2018), sedimentology (Dodd, 2018) and palynology (Riding, 2018a-i and Thomas, 2018a-j).

Acknowledgements

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I J Andrews	Reporting, task and project management
T J H Dodd	Core logging and depositional environment analysis
M F Quinn	Seismic interpretation
J E Thomas	Biostratigraphic analysis (lead)
J B Riding	Biostratigraphic analysis
M A Stewart	Tectonic overview, databases & GIS
Ó Eidesgaard	Organic geochemistry of oil and gas shows in Faroese sector
V Starcher	Final compilation

Dr Kevin Page of Plymouth University identified the Early Jurassic ammonites from well 202/03a-3 (included in Thomas, 2018b).

In compiling this report, the authors readily acknowledge the assistance of several BGS colleagues, including M Kassyk and A F Henderson for cartography and Robert Gatliff for his review of this report. We thank Faroe-Shetland Consortium oil company sponsors for allowing us to access their proprietary seismic data for the purpose of this report. BP and Hess are acknowledged for the data illustrated in *Figure 7* and *Figure 8*. Common Data Access (CDA) Limited is acknowledged for allowing access to released well data for the purpose of this report.

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Summary

This report summarises the results of the “Jurassic stratigraphy of the Faroe-Shetland region” project which was conducted as part of the Phase 3 of the Faroe-Shetland Consortium. The work was carried out on the Jurassic strata within a defined area of study located in the Faroe-Shetland Basin and adjacent areas. It is an amalgamation of three specialised reports of which two cover new, independent sedimentological and biostratigraphical analyses of selected Jurassic cores (Dodd., 2018; Riding, 2018a-i and Thomas, 2018a-j) and the third focusses on the seismic interpretation of the Solan basin region to define the geometry and structural location of preserved Jurassic strata (Quinn, 2018).

The dataset for this task comprised of all released commercial wells that penetrated Jurassic strata in and adjacent to the study area. The sedimentological and biostratigraphical work focussed on the wells which had Jurassic core material. For the seismic interpretation task, four 3D and five 2D seismic surveys were available.

The main focus for the project was the generation of new sedimentological and depositional environmental interpretations of the Jurassic cores. Concurrently, independent work was undertaken to age date and identify the environmental conditions from the observed micro and macro fossil assemblages. The sedimentological and biostratigraphical interpretations tended to support each other in their observations and conclusions.

The seismic interpretation was carried out in a defined area located at the south-western end of the Faroe-Shetland Basin and adjacent North Rona and Solan basins. Two-Way Travel Time maps to Top and Base Jurassic and an isochore map of the Jurassic succession in metres were generated. The seismic interpretation also generated a fault map that showed a range of fault trends.

Results of all three studies were integrated into a revised set of range charts, well correlation diagrams, distribution maps, fault maps and an updated stratigraphic framework for the Jurassic of the Faroe-Shetland region.

There were serval key observations that could be made from both the individual research areas and also from the integrated models.

The seismic interpretation clearly indicated that compared to overlying and underlying successions, the Jurassic is relatively thin and there is little evidence of thickening of the Jurassic succession against faults. The Lower Jurassic is overlain by relatively thin Upper Jurassic Kimmeridge Clay Formation, suggesting that widespread erosion must have occurred prior to Late Jurassic deposition. This erosive episode removed much of the Lower, and most of the Middle Jurassic strata.

The isochore maps also showed that a thick Lower Jurassic succession of more than 1000 m was present in the NE-SW trending West Solan Basin and this has been interpreted as a remnant of widespread deposition during Early Jurassic (and possibly Mid Jurassic) times. It is preserved in a downthrown E-W trending basin which is located at the juxtaposition of two major fault trends The identification of this possible transtensional basin should shed light on the structural evolution of the area. The Top and Base Jurassic TWTT maps and seismic data in the West Solan Basin provide evidence of compression between the post-Lower Jurassic to end-Lower Cretaceous.

From the sedimentological and biostratigraphical research of the Early Jurassic, there is new evidence to confirm the presence of relatively deep marine conditions in the West Solan Basin, with sediments containing the most northerly occurrence of a specific genera of an ammonite providing a tightly constrained age within the Late Sinemurian. These analyses indicate an open marine connection between Western Europe and the Faroe-Shetland Basin. Sediments from the same basin record deposition within a marine shelfal environment grading to a deeper marine, anoxic setting, with little in the way of clastic input in the basin during this time.

The study confirmed that there is limited Middle Jurassic preserved in the area. Sediments observed within the well 206/05-1 on the Rona High have been classified as Middle Jurassic but the only available palynological sample in this section was barren so an uncertainty relating to the dating exists. The sediments were construed to be deposited in a submarine fan setting, potentially in a deep marine environment but due to a paucity in hard evidence other interpretations may be possible.

Upper Jurassic sediments are observed to be more widespread and, have been interpreted to show a variety of depositional environments through time, with an overall deepening trend. Palynological analyses have provided age determinations for the Kimmeridge Clay Formation including the Rona, Solan and Ridge Conglomerate members and have strengthened the view that the Rona and Solan members are of equivalent age.

The Late Jurassic can be subdivided into several depositional environments: meandering fluvial (Rona R1); debris cone or fan delta (Rona R2); marginal marine (Rona R3); shoreface/littoral (Rona R4) and shallow marine (Rona R5). Mudstones of the Kimmeridge Clay Formation were deposited in deep marine, sometimes anoxic conditions, while Solan Sandstone members are considered to be deep marine turbidites or debris flow deposits. From these varied environmental observations, it is most likely that this area underwent periods of localised uplift, erosion and deposition forming a series of emergent highs across the study area. Paleogeography maps were not produced due to the lack of data points in the study.

In conclusion, the study confirmed that a variety of depositional environments were present in the Faroe-Shetland region during the Jurassic. The evidence suggests a complex geological history with significant periods of uplift, erosion, and deposition which varies across individual basins and sub-basins in relatively close proximity.

1 Introduction

One of the aims of Phase 3 of the Faroe-Shetland Consortium (FSC) was to investigate Jurassic stratigraphy within the Faroe-Shetland region through a re-evaluation of sedimentology and biostratigraphic age dating, with the aim of further elucidating basin history and the likely distribution of Jurassic source rocks.

Work began in mid-2015 and was completed in April 2018, on schedule at the end of the agreed three-year time frame.

The geographical focus of the project was initially the entire Faroe-Shetland area; however, subsequent discussion agreed a more focussed area of interest (particularly for the structural interpretation) centred on the south-western part of the basin where Jurassic strata could be best imaged on the available seismic data (*Figure 1*).

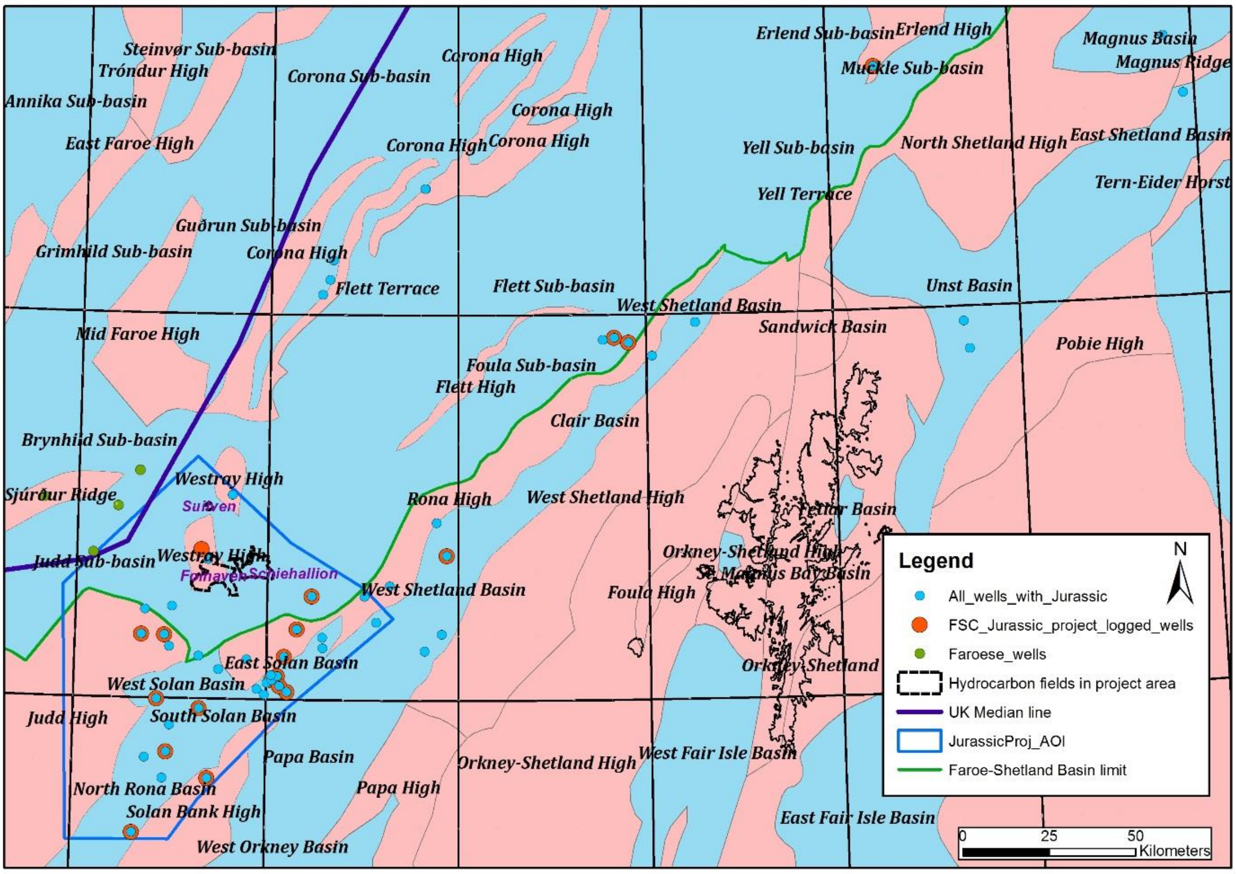


Figure 1 Location of project area. Well locations with red rims are those where core was interpreted. The blue polygon defines the area covered by seismic interpretation and where majority of sedimentological and palynological analyses were carried out.

The overall objective of the project was to arrive at a better understanding of the distribution of Jurassic strata in the Faroe-Shetland region, and to further understand the stratigraphic evolution of the wider region during the Jurassic. In particular, the study was designed to revisit the debate about the proto-rift system by providing further evidence about whether there is a relatively restricted extension (Doré et al. (1999)) or an established connection within the Faroe-Shetland region by the mid-Jurassic. (Ziegler, 1988).

The detailed project methodology was grounded in an integrated study of well and seismic data with three main components:

(1) a rigorous examination of the sedimentology of the cored Jurassic successions in 19 key wells, with the view to ascertain depositional environment [Section 4],

(2) an updated assessment of the age and depositional environment of Jurassic rocks in 19 key wells using biostratigraphic analyses [Section 4],
(3) a review of the distribution and geometry of the Jurassic strata using selected seismic reflection data available to the FSC [Section 5].

Further work included an objective review of the organic geochemistry of oil and gas shows in the Faroese sector (Section 9).

The results of these three component studies (Quinn, 2018; Dodd, 2018; Riding, 2018a-i and Thomas, 2018a-j) are integrated here into a summary document augmented by revised range charts and well corrections (Section 6), a database and associated GIS project. A revised stratigraphic framework for the Jurassic in the Faroe-Shetland area is proposed and implications for our understanding of the evolution of the Faroe-Shetland region during the Jurassic are discussed (Section 8).

The original study proposed an investigation into the Jurassic tectonostratigraphy within the Faroe-Shetland region through a re-evaluation of sedimentology and chronology, with the aim of further elucidating basin history and the likely distribution of Jurassic source rocks. The final results concentrated on the depositional environments and Jurassic sediment distribution but did not focus on the tectonostratigraphy of the region in detail due to time constraints. The title of the study has been changed to match the final outcomes.

Note should also be made of the fact that only data and conclusions relating to the Jurassic are summarised here. Some new information on Triassic and Lower Cretaceous strata gained during the course of this project are contained in the separate reports.

2 Rifting in the Faroe-Shetland Basin

The supercontinent Pangea, formed by the suturing of the Gondwanan and Laurentian landmasses in the late Carboniferous, was inherently unstable and subjected to numerous rifting events until the formation of the Atlantic Ocean in the Palaeogene. The general pre-Atlantic breakup and tectonic evolution of this part of Pangea (later to become the NE Atlantic margin) from the Carboniferous onwards is usually described in terms of the development of a southwards-propagating ‘Arctic’ rift system, and a northwards propagating ‘proto-Atlantic’ rift system, both strongly influenced by the pre-existing NE-SW trending Caledonian structural grain (Doré et al., 1999; Roberts et al., 1999; Stoker et al., 2016 and references therein). The Arctic rift system is considered to trend approximately NE-SW from Norway/Greenland south through the West of Shetland and, eventually, into the North Sea, while the more complex ‘proto-Atlantic’ or ‘Atlantic’ rift system encompasses parts of southeast Greenland, the Hebrides, Rockall, Porcupine and the western Celtic Sea (Roberts et al., 1999; Coward et al., 2003). More recently, Stoker et al. (2016) prefer to describe the whole system (excluding the North Sea) as a ‘NE Atlantic’ rift. Roberts et al. (1999) and Doré et al. (1999) suggest that the Arctic and proto-Atlantic rift systems remained separate until the Late Jurassic or even Mid-Cretaceous, with only fragmented, discontinuous connections prior. A number of authors (Ziegler, 1988; Coward et al., 2003; Pharaoh et al., 2010) consider a fully connected NE Atlantic rift system developing much earlier, from the Permian onwards. The Doré et al. (1999) and the Ziegler (1988) models can be considered as the two end members of the rift debate.

In order to further the understanding of the proto-NE Atlantic rift system, it is imperative to gain knowledge about the sedimentology of the Jurassic succession in the Faroe–Shetland area. For example, if deep marine conditions were established in parts of the region from the Early Jurassic onwards, this may strengthen the argument for a well-established rift system with continual rifting and subsidence throughout the Jurassic. Several key publications linking sedimentology to rifting have already been written but the paucity of data has resulted in a high degree of uncertainty and there are still opposing views about the basin model.

Lower, Middle and Upper Jurassic sediments in the Faroe-Shetland Basin are described by Haszeldine et al. (1987) as being deposited in or proximal to relatively deep marine environments, but this interpretation is based largely on evidence from a single well (206/05-1). In contrast, Verstralen et al. (1995b) describe Upper Jurassic turbidite sandstones in the Faroe-Shetland Basin as being deposited in a variety of environments that transition from sub-aerial fan delta into shoreface / shallow marine, and finally deeper-marine, in response to Late Jurassic regional transgression. According to Vestralen et al. (1995), deposition of the shallower coarse clastic facies was mainly controlled by marine transgression of residual islands, probably elevated by footwall uplift along fault bounding highs such as the West Shetland, Rona and Judd highs.

3 Stratigraphic framework

Largely building upon the work of Haszeldine et al. (1987), Verstralen and Hurst (1994), Verstralen et al. (1995a and b) and the results of well correlation and limited biostratigraphical information, the first published lithostratigraphical review of the Upper Jurassic was completed by Ritchie et al. (1996). However, further insights by Verstralen (1996) and Herries et al. (1999), particularly with regard to Upper Jurassic strata in the East Solan Basin and adjacent areas led to a revised scheme presented in Ritchie and Varming (2011) (*Figure 2*).

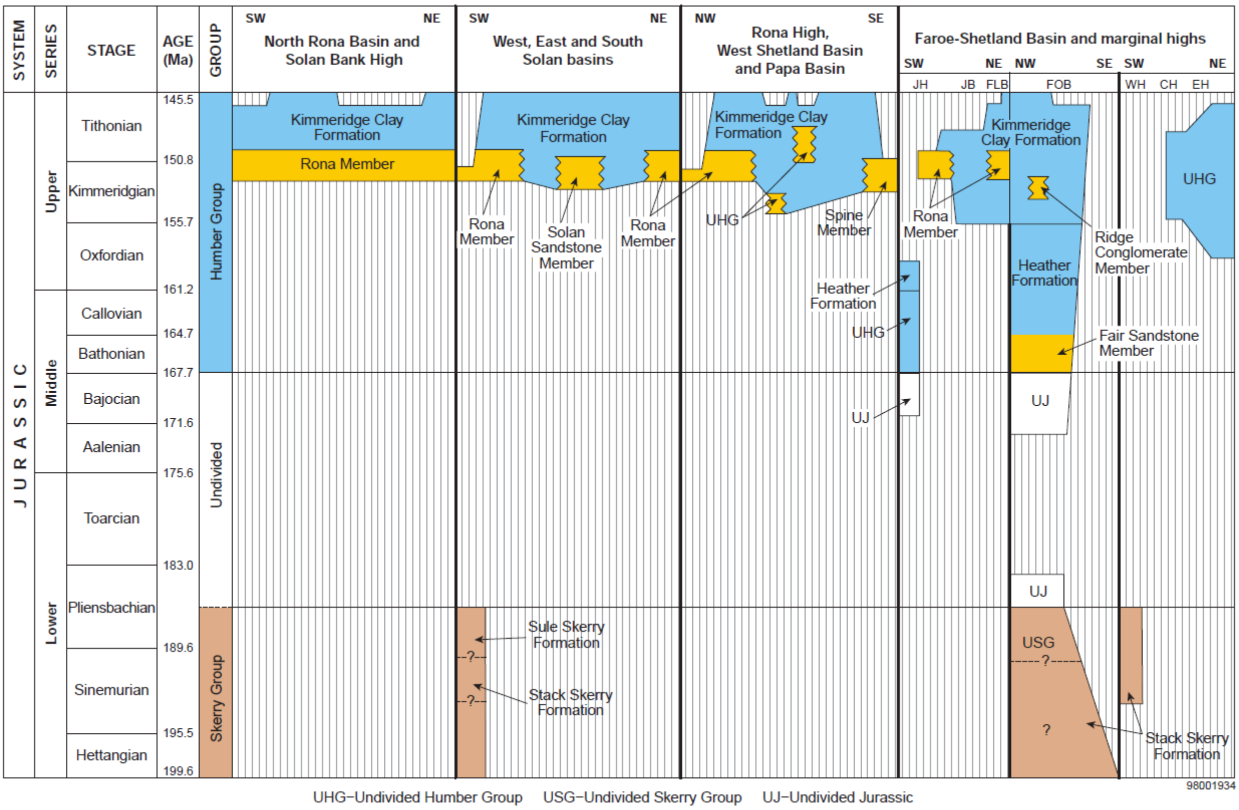


Figure 2 Generalised Jurassic lithostratigraphical nomenclature for the Faroe–Shetland area (from Ritchie and Varming 2011).

Early Jurassic strata in the West of Shetland area are assigned to the Skerry Group (Ritchie et al. 1996) with the Sule Skerry Formation overlying the Stack Skerry Formation. In type well 202/03a-3, the Skerry Group is subdivided into the shale-dominated Sule Skerry Formation and the sandstone-shale succession in the Stack Skerry Formation. The former is of early Pliensbachian age and the latter is assigned a late Sinemurian to early Pliensbachian age (GeoStrat 1988, Ritchie et al 1996).

The few occurrences of rocks of Mid-Jurassic age in the study area are rarely assigned to any formal scheme due to uncertainty in the age dating process. Exceptions include the rocks of Pliensbachian-Bajocian to Callovian (and Oxfordian-Portlandian) age in well 206/05-1 described by Haszeldine et al. (1987) and a unit of (?Bajocian) Bathonian to Oxfordian age which occurs in well 204/22-1 (GeoStrat 1990, Ichron 1996, Ritchie and Varming 2011). Bajocian-Callovian-aged rocks are also reported in well 205/20-2 (Arco 1984, Ritchie and Varming 2011).

Late Jurassic strata is more extensive in the region but there are still lithostratigraphical nomenclature uncertainties particularly surrounding the Solan and Rona Members. In 1996 Ritchie et al. (1996) defined a 'Rona Sandstone Formation' beneath the Kimmeridge Clay Formation, whereas Verstralen et al. (1995a) used the term 'Rona Member'. Herries et al. (1999) refer to the 'Solan Sandstone' and 'Rona Member'. Verstralen (1996) uses a 'Rona Member' and 'Solan Member' of the Kimmeridge Clay Formation and this classification was formally adopted by Ritchie and Varming (2011) and has been used throughout this study.

As well as debate about the nomenclature of the two sandstones there is also uncertainty in their age relationship. Verstralen (1996) concluded that the Solan Sandstone was considerably younger than the Rona Sandstone (with a questionable hiatus between them). Herries et al. (1999) discussed the significant difference in age of the Kimmeridge Clay Formation immediately above the two sandstones, concluding that the Rona sandstones were, for the most part, younger than the Solan Sandstone. An alternative and widely held view that the two sandstones are approximately coeval was adopted by Ritchie et al. (2011). This study presents an independent view of this debate which will be discussed in the section 4.

The youngest formation of the Jurassic succession is the extensive Kimmeridge Clay Formation which is renowned for its source rock properties in the region.

4 Sedimentology and biostratigraphy of key Jurassic wells

This study concentrated on new palynological and sedimentological analysis of nineteen wells selected from the BGS Keyworth Core Store as having Jurassic-aged cored sections. The majority of these wells lie within the defined focus study area (*Figure 1*) but descriptions for wells outside of this region (205/05- 1 and 2 (Rona High), 205/20- 2 (West Shetland Basin) and 209/12- 1 (Erlend High)) were also produced in order to better understand the regional sediment distribution. The amount of core sampled from each well and their position in the stratigraphic framework is shown in *Table 1*.Stratigraphic interpretation of wells 214/09-1, 213/25- 1, 213/27- 1, 2, 3 (Corona High) to the north of the focus area are given in Ritchie and Varming (2011). .

The cores were logged at a 10 cm scale and interpreted in terms of sedimentary processes, facies and depositional environments. As part of the core logging, samples were collected in order to undertake a detailed palynological assessment to provide further information regarding depositional environment and age. The samples were all prepared using standard acid-based techniques. The samples, aqueous residues and microscope slides are held in the BGS collections at Keyworth, Nottingham.

Both studies were carried out independently and were initiated without any reference to previous models or publications. The integration of the results occurred at a later stage.

In the following subsections, each stratigraphic unit or facies is described in terms of its sedimentology and biostratigraphy. A more comprehensive report of the sedimentology (Dodd 2018) and individual detailed palynological well summaries (Riding, 2018a-i; Thomas, 2018a-j) are provided as separate reference documents. A summary table indicating the depostional environment based solely on the biostratigraphy is shown in *Table 9*.

Please note that at the Jurassic-Cretaceous transition, this report uses Boreal stage nomenclature (i.e. Volgian and Ryazanian) rather than Tethyan (i.e. Portlandian and Purbeckian). All depths quoted are measured depth below Kelly Bushing in metres. No core shifts have been made.

Well	Core logged (measured depths, m)	Stratigraphy (and core number) of logged core	Number of biostratigraphic samples (see Section 4)
202/03-1A	1642-1673.15	Rona (#1-2)	6
202/03a-3	1784-1822	Sule Skerry Fm (Lower Jurassic) (#1-2)	8
	2050-2066.93	Stack Skerry Formation (Lower Jurassic) (#3)	11
202/04-1	1855.95-1898	Rona Member (#1-3)	18
202/09-1	840.34-843.26, 848.87-860.21	Rona Member (#1-3)	9
202/12-1	1356-1361.54	Kimmeridge Clay Formation (#1)	3
	1418.23-1447.5	Rona Member (#2)	8
204/19-1	4209-4223	Cromer Knoll Group (#2, was 'Jurassic' on original composite log)	5
204/27a-1	2043-2043.7	Kimmeridge Clay Formation (#1-2)	0
	2059.5-2138	Basement (#8-9), Rona Member (#3-7)	44
204/28-1	1915-1939.6	Rona Member (#1-3)	10
***205/20-2**	2934.9-3001.31	Papa Group (Triassic) (#2), Rona Member (#1-2)	13
205/21-1A	1338-1365.5	Basement (#7-9), Rona Member (#5-6), Kimmeridge Clay Formation & Cromer Knoll Group	10
205/22-1A	3176-3179	Kimmeridge Clay Formation (#1)	1
	3201.7-3226	Basement (#4) & Rona Member (#2-4)	9
205/26-1	2095.5-2104.64	Rona Member (#1)	6
205/26a-2	2093.37-2105.46	Cromer Knoll Group (#4-8)	5
	2157.37-2158.29	Rona Member (#9)	2
205/26a- 4	2446-2501.25	Papa Group (Triassic) (#1-2), Kimmeridge Clay Formation & Solan Member (#1)	20
205/26a- 5Z	2928-2961.26	Solan Member & Kimmeridge Clay Formation (#1-2)	10
205/26a- 6	2574-2578	Rona Member (#1) & Kimmeridge Clay Formation (#1)	11
***206/05-1**	3148-3178.36	Kimmeridge Clay Formation (#1-2)	5
	3267.46-3276.6	Kimmeridge Clay Formation & Ridge Conglomerate Member (#3)	4
	3901.14-3904	Fair Sandstone Member of Heather Formation (#4)	0
***206/05-2**	3169.31-3174.18	Rona Member (#1)	6
***209/12-1**	3467.41-3469.54	Rona Member (#1)	4

*Table 1 List of 19 wells sampled for sedimentological and biostratigraphical analysis in this study. * = outside the detailed seismic focus area.*

4.1 STACK SKERRY FORMATION

4.1.1 Sedimentology

Early Jurassic strata in the West of Shetland area are assigned to the Skerry Group (Ritchie et al. 1996) with the Sule Skerry Formation overlying the Stack Skerry Formation. This formation was only present in one core in the study (202/03a-3) and subsequently the description is based upon this type well.

The lower section of the Stack Skerry Formation comprises two hemi-pelagic, dark-grey, moderate to intensely bioturbated mudstones, thinly interbedded with fine to very fine-grained, parallel to ripple laminated sandstones, interpreted as the produce of low-density turbidity currents. The low-density turbidite flows were likely sourced from an in-draining river system. Unfortunately there is no evidence as to the direction from which the turbidites were flowing as the core was not orientated. The key finding is that the observed deposits are interpreted to be in close proximity to a source and are typical of deposition on a shelfal setting.

The upper half of the 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. The significance of these observations is that there was a marine shelf, located to the west of Shetland, during the Early Jurassic.

4.1.2 Biostratigraphy

202/03a-3

<u>Samples 9 to 19</u>. The palynological assemblages from this interval (2051.69 to 2066.83) are dominated by long-ranging pollen and spores of a generally Mesozoic (Jurassic) aspect. Rare specimens of the dinoflagellate cyst *Liasidium variable* indicate the Late Sinemurian (Early Jurassic) at 2062.83 and 2066.83 m (samples 16 and 19) (Riding and Thomas, 1992). These palynological age determinations are compatible with ammonite specimens indicating the Late Sinemurian Raricostatum Zone (Raricostatoides Subzone). Marine influence is shown in all samples by the presence of acritarchs, foraminiferal test linings and rare dinoflagellate cysts. There is a trend to higher levels of brown woody /plant material in the lower core run.

In addition, 14 core samples that contained ammonite specimens were extracted from this interval. These ammonites were identified by Dr Kevin Page, lecturer in Earth Sciences, Plymouth University. Numerous well-preserved specimens of *Echioceras* sp. and *Crucilobiceras* sp. were identified and all are assigned to the *Echioceras raricostatum* ammonite zone (latest Sinemurian). This zone can be subdivided into four subzones including the *raricostatoides* Subzone to which all the specimens from 202/03a-3 are allocated.

Not only do these ammonites provide a high-resolution biostratigraphic pick for the Stack Skerry Formation, but this is by far the most northerly occurrence of this genus, indicating that there was a marine connection between Western Europe and the Faroe-Shetland Basin at this time (K Page pers. comm.).

Full details can be found in Thomas (2018b).

4.1.3 Integration Sedimentology and Biostratigraphy

By integrating the sedimentological observations with the biostratigraphical results it can be stated that Stack Skerry Formation was deposited in marine shelfal setting.

The presence of *Teichicnus* ichnogenera, of the *Cruziana* ichnofacies observed in the lower section of the core suggests a sub-littoral, shelfal setting. The interbedded nature of the sandstones and mudstones, low density turbidites, along with the intensity of bioturbation all suggest a well oxygenated water column which is indicative of a shallower marine setting instead of a deeper more bathyal environment. The marine influence observed in the sedimentology results is clearly supported by the biostratigraphy. The occurrence of ammonite fossils strengthens the argument that this formation was deposited in a marine shelfal environment and has shown strong new evidence for a marine connection between the south (Western Europe) and the study area (Faroe-Shetland Basin).

4.2 SULE SKERRY FORMATION

4.2.1 Sedimentology

The Sule Skerry Formation was observed only in one well. In 202/03a-3, sediments comprise a c. 36 m thick succession homogeneous, dark grey to brown coloured, parallel laminated mudstones. The parallel laminated mudstone are interpreted as the product of suspension fall-out within the water column. There is a lack of bioturbation or shell material throughout, suggesting the bottom waters were anoxic. In addition, the complete 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.

4.2.2 Biostratigraphy

202/03a-3

Samples 1 to 8. The palynological samples from 1796.78 to 1820.14 m are dominated by long-ranging pollen and spores of a generally Mesozoic (Jurassic) aspect. The absence of striate bisaccate pollen suggests an age younger than the Early/Mid Triassic. The absence of heavily ornamented spores such as *Cicatricosisporites* spp. suggests an age no younger than Kimmeridgian (Dörhöfer, 1979). The absence of *Callialasporites* spp. may be regarded as negative evidence for an Early Jurassic age because the range base of this genus is at the Early to Mid-Jurassic boundary (Riding et al., 1991). Marine influence is shown in all samples by the presence of acritarchs (mostly *Micrhystridium* spp.), occasional foraminiferal test linings and rare dinoflagellate cysts. The kerogen assemblage is dominated by amorphous organic material.

Full details can be found in Thomas (2018b).

4.2.3 Integration Sedimentology and Biostratigraphy

The sedimentology and biostratigraphy both suggest that the Sule Skerry Formation was deposited in a deep marine setting. Evidence for this interpretation includes: total lack of bioturbation or shell fragments - indicative of potentially anoxic bottom waters; a lack of clastic input indicative of deep water; and the presence of a *Raricostatum* ammonite fauna, which confirm a Late Sinemurian age and which are found in fully marine basins.

4.3 FAIR SANDSTONE MEMBER OF HEATHER FORMATION

The Fair Sandstone Member of the Heather Formation was identified in only one well (206/05-1) with a 3m cored interval. The sediments comprise relatively mature, well-sorted, sub-rounded, quartz-rich sandstone. This provides an indication for enhanced working of the sediment, which can occur in a range of depositional settings, but is commonly found in deep-water turbidite fan environments. A sample taken for palynology at 3901.90 m proved entirely barren and cannot be dated. Previous work by Ritchie et al. (2011) assigned this core to the Fair Sandstone Member of the Heather Formation and through lack of new age dating, this study has adopted the same classification. The sediments have been assigned to high density turbidite deposition as a possible environment. Indicators of deep water conditions include: a high degree of maturity and working of the sediment, often found in deep marine settings; and a lack of structure within the bed suggesting rapid deposition in deeper water (although this may be a result of later induration).

However it is acknowledged that other settings could also be inferred as there is a paucity of data for this formation.

4.4 RONA MEMBER R1

4.4.1 Sedimentology

The Rona R1 sediments were interpreted to occur in three wells. In general, Rona R1 sediments comprise thickly bedded (0.5-1.5 m), fine- to coarse-grained, moderately sorted, trough cross bedded, normally-graded, 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 development of thin point bars, 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, coarse-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 general, 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 within the core (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 that 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. In general, sediment maturity is low, suggesting the fluvial system was being sourced from an actively eroding hinterland, composed of granitic/igneous terranes.

4.4.2 Biostratigraphy

Rona R1	**202/12-1**	Volgian (4); indeterminate (4)
Rona R1	**205/26a-2**	Indeterminate (2)
Rona R1?	**205/26a-6**	Late Jurassic to Early Cretaceous (5); indeterminate

Table 2 Wells in which Rona R1 has been identified with proposed ages.

202/12-1

Samples 4 to 11. Palynological residues from these samples are generally very poor, in some cases so sparse that a meaningful count of the kerogen or palynomorph assemblages is impossible. Samples 5 and 7 are both dominated by black wood with lesser amounts of brown wood and plant material. The assemblages yield non-age-diagnostic pollen with rare, poorly preserved dinoflagellate cysts. The presence of the spore genus *Cicatricosisporites* at 1361.41 and 1427.28 m (samples 3 and 7) indicates Volgian or younger strata at this level and above. Moderate to weak marine influence is indicated periodically through the interval studied although the very sparse samples cannot be given a robust classification. The sample at 1432.48 m (sample 10) is made up entirely of amorphous organic material.

Full details can be found in Thomas (2018e).

205/26a-2

Samples 6 and 7. The samples at 2157.58 and 2158.00 m proved to be palynologically barren. Sample 7 is rich in amorphous organic material, by contrast the kerogen in sample 6 was too sparse to meaningfully count.

Full details can be found in Riding (2018e).

205/26a-6

Samples 2 to 7. The organic residues from samples 2 and 3 (2578.7 and 2580.53 m) are too sparse to perform a count of the kerogen and palynomorphs are absent. Sample 4 (2584.11 m) yielded a sparse kerogen assemblage made up of equal proportions of wood, plant material and amorphous organic material. The assemblage from sample 5 (2592.93 m) includes the spore *Cyathidites* and a fragment of a chorate dinoflagellate cyst, possibly an opercular plate from the Late Jurassic/ Early Cretaceous genus *Systematophora*. Sample 6 (2593.97 m) yields undifferentiated bisaccate pollen, *Exesipollentites scabratus* and a fragment of a chorate dinoflagellate cyst, possibly an opercular plate. The dinoflagellate cyst fragments indicate a very tentative Late Jurassic to Early Cretaceous age and some marine influence.

Full details can be found in Thomas (2018i).

4.4.3 Integration Sedimentology and Biostratigraphy

The biostratigraphy confirmed the presence of the Rona R1 sediments and also was responsible for reassigning the samples in well 205/26a-6 as Jurassic compared to the earlier interpretation of Triassic age. These additional Jurassic samples and the other previously identified Rona R1 sediments are rich in organic material which would be expected in a meandering fluvial environment. Further sedimentological evidence suggests that this formation represents a laterally avulsing fluvial system. Evidence of crevasse splays formed on overbank areas during periods of high river discharge (flood conditions) may suggest a fluvial system that documents variable discharge (“a flashy regime”).

4.5 RONA MEMBER R2

4.5.1 Sedimentology

The deposits of the Rona R2 facies, identified in five wells, 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 sub-aerial deposition within that part of the fan.

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 sandstone.

4.5.2 Biostratigraphy

Rona R2	**204/27a-1**	Early to Mid Volgian (8); indeterminate (2)
Rona R2	**204/28-1**	Indeterminate (4)
Rona R2	**205/21-1A**	Indeterminate (6)
Rona R2	**205/22-1A**	Volgian or younger (3); Jurassic/Cretaceous; indeterminate
Rona R2	**205/26-1**	Indeterminate

Table 3 Wells in which Rona R2 has been identified with proposed ages.

204/27a-1

Samples 30 to 39. The succession between 2118.37 and 2122.77 m (samples 30 to 37) is interpreted as being no older than Volgian, and hence Early to Mid Volgian, on the basis of the sporadic presence of the highly ornamented spore genus *Cicatricosisporites.* The lower two samples (38 and 39) at 2123.6 and 2126.08 m proved barren of palynomorphs, and cannot be dated. Only terrestrial palynomorphs are present.

Full details can be found in Riding (2018b).

205/28-1

Four samples between 1928.73 and 1939.05 m proved to be entirely barren of palynomorphs. The organic residues are extremely sparse. Furthermore, the kerogen associations obtained are not countable. All the horizons studied yield small, black globular bodies which probably represent liquid hydrocarbons. As a consequence, no biostratigraphical or palaeoecological conclusions can be drawn.

Full details can be found in Riding (2018i).

205/21-1A

Samples 5 to 10 (1344.17 to 1353.04 m) yielded very poor organic residues dominated by amorphous organic material or black woody material. Palynomorphs are largely absent, and where present, are not age-diagnostic apart from having a general Mesozoic aspect.

Full details can be found in Thomas (2018f).

205/22-1A

Samples 6 to 10. Samples from this interval have similarly sparse palynomorph assemblages. Brown woody and plant material dominates at 3209.07 m (sample 6); black wood dominates at 3210.33 m (sample 7). Sample 8 (3219.75 m) yields abundant black wood and rare spores and pollen including specimens of *Cicatricosisporites* and *Tuberositriletes*. These highly ornamented spores indicate Late Jurassic (Volgian) or Cretaceous strata (Dörhöfer, 1979) thus allowing a Volgian or younger age to be assigned to samples 8 and above. Sample 9 yields abundant plant material and brown wood and a typically Jurassic/Cretaceous spore and pollen assemblage. Sample 10 at (3222.35 m) is dominated by amorphous organic material but is devoid of palynomorphs.

Full details can be found in Thomas (2018g).

205/26-1

Sample 6, at 2103.91 m**,** proved entirely barren.

Full details can be found in Riding (2018d).

4.5.3 Integration Sedimentology and Biostratigraphy

Based primarily on sedimentologial information, the sediments within the Rona R2 member can been defined as fan delta or debris flow deposits draining into a marine basin. In general, these coarse sands are indicative of subaerial to shallow water/shoreface environments, with the debris flows overlain by the fan delta deposits. There is limited biostratigraphic information with most of the samples dominated by amorphous organic material or black woody material. There is a notable absence of marine taxa suggesting localised emergent highs were present in the area.

4.6 RONA MEMBER R3

4.6.1 Sedimentology

Rona R3 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 and interbedded, parallel-laminated. Both the sandstones and mudstones display abundant, weak to intense bioturbation throughout. The sand-prone beds 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. In these deposits, the foreset angles and bounding/re-activation surfaces are irregular and tend to display clay-drapes along foresets. In wells 202/04-1, 202/09-1 and 206/05-2, the beach barriers are well established, with evidence for in-situ root development. The cyclic nature of the barrier-beach deposits (202/04-1), is interpreted as a function of bar migration during storm events, marked by the argillaceous, carbonaceous sandstone 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, located immediately behind, and protected by, the barrier-beach systems. Occasionally, very fine to fine-grained deposits are interbedded within the bioturbated mudstone successions, representing washover deposits. Moving towards the top of the core, coarser-grained successions document a progressively increasing energy (wave/tidal), evidenced by the occurrence of storm-generated, shell-rich beds, typically found near to the top of the barrier bars (202/04-1). In addition, the interbedded mudstone successions show an increasing pyritic content. Together, these observations suggest a progressive rise in relative sea level towards the top of Rona R3.

4.6.2 Biostratigraphy

Rona R3	**202/04-1**	Early to Mid Volgian (15); Early to Mid Volgian (no younger than Albani Zone)
Rona R3	**202/09-1**	Early Volgian (7); Early Volgian (no younger than Pectinatus Zone); indeterminate
Rona R3	**205/20-2**	Indeterminate (6); Kimmeridgian to Mid Volgian (3); Late Kimmeridgian to Mid Volgian (Anguiformis Zone)
Rona R3	**206/05-2**	Volgian or younger (5); indeterminate
Rona R3	**209/12-1**	Indeterminate (4)

Table 4 Wells in which Rona R3 has been identified with proposed ages.

202/04-1

Samples 3 to 18. The presence of *Gocheodinia mutabilis* at 1863.88 m (sample 3) gives an age of no younger than the Mid Volgian Okusensis Zone. The other dinoflagellate cysts sporadically present in this interval include the *Cribroperidinium globatum* Group, *Cyclonephelium hystrix* and

Systematophora spp. They have longer Late Jurassic ranges but are not incompatible with an Early to Mid Volgian age (Riding and Thomas, 1992). The presence of *Leptodinium subtile* at 1871.26 (sample 8) brackets the sample between the Oxfordian and Mid Volgian Albani Zone. Marine indicators are present except in samples 4 and 5.

At this stratigraphical level spores and pollen are generally long ranging and thus of little help in age determination. However, the presence in almost every sample of the very distinctive spore genus, *Cicatricosisporites*, indicates strata of Volgian or younger age (Dörhöfer, 1979).

Full details can be found in Thomas (2018c).

202/09-1

Nine samples from core from the interval 840.55 to 860.21 m well 202/09-1 yielded kerogen assemblages dominated by black and brown woody and plant material with amorphous organic material (AOM) very uncommon throughout. Spores and pollen dominate the palynological assemblages with spores particularly important indicating a well-oxygenated environment with significant terrestrial input. Useful dinoflagellate cyst assemblages are present only in the uppermost sample (1; 840.55 m) where *Oligosphaeridium patulum* and *Perisseiasphaeridium pannosum* indicate a Kimmeridgian to Early Volgian (Mutabilis to Pectinatus zones) age (Riding and Thomas, 1992).

The presence of the spore genus *Cicatricosisporites* in samples including sample 8 (856.54 m) near the base, indicates a Volgian or younger age and hence an Early Volgian age for the whole sample run.

Full details can be found in Thomas (2018d).

205/20-2

The dinoflagellate cysts in samples 1, 2 and 4 (2958.81, 2960.77 and 2968.08 m) include *Cribroperidinium* spp.?Dichadogonyaulax? *pannea*, indeterminate forms, *Systematophora areolata* and *Systematophora* spp. This assemblage is typical of the Late Jurassic (Oxfordian to Volgian). A questionable specimen of *Dichadogonyaulax*? *pannea* was encountered in sample 2 (2960.77 m). This species is confined to the Kimmeridgian to Middle Volgian interval (Eudoxus to Anguiformis zones) (Riding and Thomas, 1992). The occurrence of the spore genus *Cicatricosisporites* in samples 1 and 3 is entirely consistent with this assessment.

Samples 5 to 10 (2970.35 to 2982.94 m) all proved barren or very sparse in terms of identifiable palynomorphs so no age assessments are possible in this succession.

Full details can be found in Riding (2018c).

206/05-2

Samples 1 to 6. Analysis of palynological assemblages revealed a generally poor run of samples lacking good age-diagnostic palynomorphs. Sample 1 (3169.84 m) is very sparse and dominated by amorphous organic material. Samples 2 and 3 (3170.97 and 3171.16 m) yield long-ranging spores and pollen indicating the Jurassic or Cretaceous such as the spores *Baculatisporites commaumensis, Cyathidites minor, Gleicheniidites* sp. and *Retitriletes austroclavatidites,* and pollen including undifferentiated bisaccates, *Araucariacites australis, Cerebropollenites macroverrucosus, Classopollis classoides, Exesipollenites scabratus* and *Perinopollenites elatoides*. Marine taxa are absent. The kerogen assemblage is dominated by woody and plant material. A Volgian or younger age is tentatively assigned in sample 5 at 3172.49 m by the presence of the spore genus *Cicatricosisporites.* This maximum age can be applied to the succeeding samples (1 to 4).

Full details can be found in Thomas (2018j).

209/12-1

Samples 1 to 4. The four samples all proved entirely barren of palynomorphs, hence no age assessment is possible. Only one possible fragment of an indeterminate dinoflagellate cyst was observed at 3469.84 m (sample 3) suggesting probable marine deposition. The organic residues all comprise black macerals indicating high levels of thermal alteration.

Full details can be found in Riding (2018h).

3.1.3 Integration Sedimentology and Biostratigraphy

Spores and pollen dominate the palynological assemblages indicating significant terrestrial input. Organic material, in the form of carbonaceous/woody clasts and argillaceous, carbonaceous matrices within sandstone beds, is ubiquitous throughout (i.e. well 205/20-2), suggesting a restricted setting. These findings are in agreement with the sedimentology which clearly indicates that the Rona R3 represents deposition in a marginal-marine barrier-beach and back barrier/lagoon depositional environment. The coarser grained successions at the top of the core suggest a progressive rise in relative sea level and supports the belief that there was a gradual inundation of the Solan/North Rona Basin area in the Late Jurassic.

4.7 RONA MEMBER R4

4.7.1 Sedimentology

The Rona 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 through 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 flasar 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.

4.7.2 Biostratigraphy

Rona R4	**202/03-1A**	Mid Volgian (5); Kimmeridgian to Mid Volgian
Rona R4	**202/04-1**	Early to Mid Volgian; Early to Mid Volgian (Okusensis Zone)
Rona R4	**204/27a-1**	Mid Volgian (10); Early to Mid Volgian (4)
Rona R4	**204/28-1**	Indeterminate (7)
Rona R4	**205/22-1A**	Volgian or younger (4)
Rona R4	**205/26-1**	?Ryazanian-Valanginian transition (5)

Table 5 Wells in which Rona R4 has been identified with proposed ages.

202/03-1A

Samples 1 to 6. Six samples produced residues dominated by abundant brown woody and plant material with much smaller amounts of amorphous organic material, black wood and palynomorphs. The terrestrially derived palynomorph assemblages of this interval are dominated by long-ranging taxa typical of the Late Jurassic but of little help in subdividing the interval. Marine palynomorphs are present throughout indicating a marine environment.

The dinoflagellate cyst assemblages contain a number of taxa with ranges that bracket samples 1 to 5 within the Mid Volgian. At 1643.75 m (sample 1) the dinoflagellate cysts *Cribroperidinium globatum, Prolixosphaeridium anasillum* and *Tubotuberella apatela* indicate a Late Jurassic age no younger than Mid Volgian (Riding and Thomas, 1992). At 1666.99 m (sample 5) a dinoflagellate cyst assemblage including *Cyclonephelium hystrix, Gonyaulacysta* sp. A, *Kallosphaeridium* sp. *Prolixosphaeridium anasillum, Perisseiasphaeridium insolitum* and *Systematophora areolata* together indicate an early Mid Volgian age. The dinoflagellate cyst assemblage in sample 6 indicates Late Jurassic (Kimmeridgian to Mid Volgian) strata.)

Full details can be found in Thomas (2018a).

202/04-1

Samples 1 and 2. At 1856.4 m (sample 1), questionable specimens of the dinoflagellate cysts *Pareodinia halosa* and *Cyclonephelium* sp. are present but not particularly age diagnostic, being only generally characteristic of the Late Jurassic. The presence of the dinoflagellate cysts *Gocheodinia mutabilis* and *Kleithriasphaeridiun porosispinum* at 1860.01 m (sample 2) gives an age of no younger than the Mid Volgian Okusensis Zone and no older than the Early Volgian Hudlestoni Zone (Riding and Thomas, 1992). The presence of dinoflagellate cysts indicates marine conditions.

Full details can be found in Thomas (2018c).

204/27a-1

The interval between 2098.99 and 2113.21 m (samples 16 to 25) is assigned to the Mid Volgian on dinoflagellate cyst evidence. The range bases of dinocysts *Cribroperidinium gigas* and *Cribroperidinium hansenii* occur at 2113.21 m. Only long-ranging pollen and spores, which provide little evidence of age, occur between 2113.9 and 2117.35 m (samples 26 to 29). The palynomorphs indicate marine conditions in the upper part of the interval. From the lower part of Rona 4, only terrestrial palynomorphs are present.

Full details can be found in Riding (2018b).

204/28-1

Seven samples between 1916.00 and 1937.80 m proved to be entirely barren of palynomorphs. The organic residues are extremely sparse. Furthermore, the kerogen associations obtained are not countable. All the horizons studied yield small, black globular bodies which probably represent liquid hydrocarbons. As a consequence, no biostratigraphical or palaeoecological conclusions can be drawn.

Full details can be found in Riding (2018i).

205/22-1A

Samples 2 to 5. Samples from this interval yield very sparse palynomorph assemblages. Kerogen analysis shows that amorphous organic material dominates samples 2, 3 and 4 (3203.7 m to 3205.18 m); brown woody and plant material dominates sample 5 (3207.71 m).

Full details can be found in Thomas (2018g).

205/26-1

Samples 1 to 5. The five productive samples from between 2095.71 and 2103.09 m yielded rare, poorly-preserved dinoflagellate cysts. These include thick-walled forms of *Cribroperidinium, Cyclonephelium* spp.?Systematophora *palmula* and *Systematophora* spp. This association is indicative of the Jurassic–Cretaceous transition. The interval is tentatively assigned to the Late Ryazanian to the earliest Valanginian due to the presence of questionable specimens of the dinoflagellate cyst *Systematophora palmula* (Davey, 1982; Heilmann-Clausen, 1987; Costa and Davey, 1992) in samples 1 and 5 (2095.71 and 2103.09 m). The rest of the palynoflora is consistent with this assessment and represents marine deposition.

Full details can be found in Riding (2018d)

4.7.3 Integration Sedimentology and Biostratigraphy

A marine depositional environment is provided by palynological evidence, 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. *Skolithos* trace fossils, which are part of the *Skolithos* ichnogenera in 205/20-2 also suggests a marine depositional setting. The sedimentology has evidence of both wave and tidal processes and shows an overall shallowing upwards trend. The Rona R4 Member can be classified as being deposited in a shoreface/littoral environment.

The fan delta deposits of Rona R2 are typically overlain by deposits of the Rona R4 facies (section 8.1.1.4) and, in 204/28-1, are observed to interdigitate suggesting a vertical, and therefore spatial link between the shoreface/littoral setting and the in-draining fan delta.

4.8 RONA MEMBER R5

4.8.1 Sedimentology

The Rona R5 facies records deposition within a shallow-marine, proximal shelf, to outer-shelf to bathyal depositional environment. In core from well 204/27a-1, the basal 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 asymmetrically ripple laminated sandstones, representing deposition of an offshore/inner shelf. The sediments become finer-grained towards to the top, 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 cross laminated, silt-grade mudstones deposited in an offshore, outer shelf to bathyal environment. 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 Rona R5.

4.8.2 Biostratigraphy

Rona R5	**204/27a-1**	Mid Volgian to Ryazanian (6); Mid Volgian (8); Ryazanian-Valanginian transition

Table 6 Wells in which Rona R5 has been identified with proposed ages.

204/27a-1

Samples 1 to 15. The uppermost sample (1) at 2059.91 m is assigned to the Ryazanian–Valanginian transition due to the occurrence of the chorate dinoflagellate cyst *Systematophora palmula* (Davey, 1982; Heilmann-Clausen, 1987; Costa and Davey, 1992). The succession from 2061.95 to 2078.05 m (samples 2 to7) is deemed to be Mid Volgian to Ryazanian in age largely on the basis of the occurrence of *Cribroperidinium hansenii* (Davey, 1982; Heilmann-Clausen, 1987; Poulsen, 1996). The range tops of *Muderongia simplex* (‘sp. A’) and *Senoniasphaera jurassica* at 2081.47 m indicate the Mid Volgian Kerberus Zone (Poulsen and Riding, 1992; Riding et al., 2000). The interval between 2084.32 and 2094.42 (samples 9 to 15) is assigned to the Mid Volgian on dinoflagellate cyst evidence. The key taxa are *Cribroperidinium gigas, Cribroperidinium hansenii, Muderongia simplex* (‘sp. A’) and *Senoniasphaera jurassica*. Amorphous organic material is common or abundant in the Rona 5 section and the palynomorphs indicate marine conditions.

Full details can be found in Riding (2018b).

4.8.3 Integration Sedimentology and Biostratigraphy

The palymorphs encountered within the Rona R5 Member confirm that marine conditions were present during the deposition of this formation. The sedimentology and amorphous organic material suggest deposition occurred as shallow marine to shelfal deposits. There is also evidence of a progressive deepening of the depositional environment. The uppermost deposits are indicative of deposition within an offshore, outer shelf to bathyal environment.

4.9 KIMMERIDGE CLAY FORMATION

4.9.1 Sedimentology

The Kimmeridge Clay Formation is widespread in this region and cores from eight wells were examined in this study. 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 hemi-pelagic fall-out within the water column, forming vertically-aggrading laminations. Occasionally, 1-2 cm-thick, turbiditic or debritic sandstones interrupt the otherwise low energy deposition. Bioturbation is largely absent within the mudstones suggesting anoxic bottom waters. 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, during the Late Jurassic.

In general, there is lack of clast input into the deepwater environment, signified by an absence of thin interbeds of sandstone within the thicker deposits of hemi-pelagic mudstone. When significant clastic input into the basin does occur, it forms abrupt, c. 20 m-thick packages of turbiditic sandstones 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 process that tend to be more active during basinal lowstands.

4.9.2 Biostratigraphy

Kimmeridge Clay Fm	**202/12-1**	Early to Late Volgian; Mid to Late Volgian; Mid to Late Volgian (Oppressus-Primitivus zones)
Kimmeridge Clay Fm	**204/27a-1**	No samples
Kimmeridge Clay Fm	**205/21-1A**	Late Jurassic/Cretaceous; [Mid to Late Cretaceous (Albian to Cenomanian) - probable 'core jumbling' invoked]
Kimmeridge Clay Fm	**205/22-1A**	Volgian or younger
Kimmeridge Clay Fm	**205/26a-4**	Mid Volgian to Early Ryazanian (9)
Kimmeridge Clay Fm	**205/26a-5Z**	Kimmeridgian or younger (4); Kimmeridgian to Early Volgian (Pectinatus Zone)
Kimmeridge Clay Fm	**205/26a-6**	Kimmeridgian to Early Cretaceous
Kimmeridge Clay Fm	**206/05-1**	Late Jurassic (5); indeterminate (2)

Table 7 Wells in which the Kimmeridge Clay Formation has been identified with proposed ages.

202/12-1

Samples 1 to 3. Samples 1 to 3 (1358.12 to 1361.41 m) yield age-diagnostic palynomorphs indicating Early to Late Volgian ages. Sample 2 at 1359.8 m contains *Dingodinium tuberosum* and *Gochteodinia villosa* which bracket the age of the sample around the late Mid Volgian and the early Late Volgian (Oppressus–Primitivus zones) (Riding and Thomas, 1992) and hence gives a Mid to Late Volgian age for the upper two samples. Amorphous organic material dominates the samples from this interval.

Full details can be found in Thomas (2018e).

205/21-1A

Samples 3 and 4. Sample 3 (1339.9 m) includes *Cribroperidinium* sp., *Endoscrinium* sp. *Oligosphaeridium* sp. and *Sirmiodinium grossii.* These long-ranging taxa indicate a Late Jurassic to Cretaceous age (Costa and Davey, 1992; Riding and Thomas, 1992).

A very rich and diverse dinoflagellate cyst assemblage is present at 1343.56 m (sample 4) including *Epelidosphaeridia spinosum, Isabellidinium gallium, Palaeoperidinium cretaceum, Palaeoperidinium pyrophorum* and *Xenascus ceratiodes* together indicate a Late Albian to Cenomanian age (mid to Late Cretaceous) (Costa and Davey, 1992, Williams et al., 2017). The age determination indicated by this palynological assemblage is anomalous when viewed in the context of the overlying and underlying samples and the wireline logs. The sample was obtained from bagged rubbly core so 'core jumbling' on the rig or during curation is a likely source of the anomaly.

Full details can be found in Thomas (2018f).

205/22-1A

Sample 1. Abundant amorphous organic material is present with rare pollen grains and a foraminiferal test lining. This is the only marine indicator encountered in the section studied. Age-diagnostic palynomorphs are absent but the pollen assemblage has a generally Jurassic/Cretaceous aspect.

Full details can be found in Thomas (2018g).

205/26a-4

Samples 3 to 11. The dinoflagellate cyst assemblages include *Cribroperidinium* spp., *Cyclonephelium* spp., *Endoscrinium* sp., ?*Muderongia* sp., *Oligosphaeridium* spp., *Perisseiasphaeridium insolitum* and *Systematophora daveyi,* which are indicative of a Late Jurassic to earliest Cretaceous (Mid Volgian to Early Ryazanian) age (Heilman-Clausen, 1987; Riding and Thomas, 1992). The principal marker here is *Perisseiasphaeridium insolitum* in sample 10 (2468.65 m), which ranges from the Mid Volgian to Early Ryazanian (Davey, 1982). All the other forms in samples 3 to 11 are entirely consistent with this age assessment. The samples stratigraphically above sample 10 are also deemed to be of Volgian to Early Ryazanian age; no key markers are present here. Due to the sparsity of the palynofloras, biostratigraphical interpretations cannot be resolved to the level of ammonite zones.

The pollen, spores and miscellaneous palynomorphs are not biostratigraphically significant but are consistent with the Late Jurassic to earliest Cretaceous age determination. The kerogen assemblage is dominated by amorphous organic material from sample 3 to sample 8.

Full details can be found in Riding (2018f).

205/26a-5Z

Samples 1 to 3. The kerogen assemblages from this interval are dominated by abundant amorphous organic material. In sample 2, poorly preserved dinoflagellate cysts include specimens tentatively assigned to *Cribroperidinium globatum* and *Oligosphaeridium* sp. If confirmed, this would suggest a Late Jurassic age (Riding and Thomas, 1992)

Samples 9 and 10. Amorphous organic material dominates the kerogen in this interval. Sample 9 (2958 m) yields the dinoflagellate cyst *Cribroperidinium globatum* indicating a Late Jurassic age (Riding and Thomas, 1992) along with specimens tentatively attributed to *Cyclonephelium hystrix* and *Prolixosphaeridium* sp. Sample 10 (2960.84 m) is the most diverse dinoflagellate cyst assemblage from the section studied and it includes *Cribroperidinium globatum*, *Cyclonephelium hystrix*, *Oligosphaeridium patulum* and *Prolixosphaeridium anasillum*. Together they indicate a Kimmeridgian to Early Volgian (no younger than Pectinatus Zone) age.

Full details can be found in Thomas (2018h).

205/26a-6

Sample 1 (2575.47 m) is dominated by abundant amorphous organic material which partially obscures the palynomorphs even in the oxidised residue. The long-ranging dinoflagellate cysts *Cribroperidinium globatum* and *Cyclonephelium hystrix* are present indicating a Late Jurassic (Kimmeridgian) to Early Cretaceous age (Riding and Thomas, 1992). The presence of dinoflagellate cysts indicates a marine environment. Spores and pollen taxa are all long-ranging and typically Mesozoic but with no good age indicators.

Full details can be found in Thomas (2018i).

206/05-1

Samples 1 to 5 (3155.08 to 3183.79 m) yielded sparse palynomorph floras. The only forms with biostratigraphical significance are *Cribroperidinium* sp. in sample 2 (3159.89 m) and *Systematophora* sp. in sample 3 (3168.88 m). These two genera are typically (but not exclusively) Late Jurassic to Early Cretaceous (Riding and Thomas, 1992). The low diversity pollen, spores and miscellaneous palynomorphs are not biostratigraphically significant. They are, however, consistent with this age determination. The palynologically productive interval represents marine deposition. The kerogen is dominated by amorphous organic material.

Sample 8 at 3274.92 proved entirely barren and cannot be dated.

Full details can be found in Riding (2018g).

4.9.3 Integration Sedimentology and Biostratigraphy

The sedimentology indicates deposition in an anoxic/dysaerobic, deepwater environment. This interpretation is in agreement with the biostratigraphy where the lack of bioturbation within the mudstones suggests anoxic bottom waters. The presence of dinoflagellate cysts in at least two of the samples is representative of marine deposition.

4.10 SOLAN SANDSTONE MEMBER

4.10.1 Sedimentology

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, normal grading, parallel and asymmetrical ripple laminated bed tops and dish structures. Bed tops are commonly clay-rich and contain concentrations of broken shelly material and carbonaceous fragments and mudclasts, interpreted as the product of hybrid event beds (Haughton et al., 2009). The amalgamated sandstones, and lack of intervening hemi-pelagic mudstones, suggests a lobe axis 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.

4.10.2 Biostratigraphy

Solan	**205/26a-4**	Mid Volgian to Early Ryazanian (2)
Solan	**205/26a-5Z**	Kimmeridgian or younger (5)

Table 8 Wells in which the Solan sandstone has been identified with proposed ages.

205/26a-4

Samples 1 and 2. The dinoflagellate cysts assemblage is very sparse: *Muderongia* sp. and *Tubotuberella apatela* are present in sample 1 (2452.25 m); *Systematophora daveyi* is present in sample 2 (2454.39 m). They are indicative of a Late Jurassic to earliest Cretaceous (Mid Volgian to Early Ryazanian) age (Heilman-Clausen, 1987; Riding and Thomas, 1992). The kerogen assemblage is dominated by amorphous organic material.

Full details can be found in Riding (2018f).

205/26a-5Z

In samples 4 to 8, the kerogen assemblages are dominated by abundant amorphous organic material. The presence of the dinoflagellate cyst *Cribroperidinium globatum* in sample 4 (2944.9 m) again indicates a Late Jurassic age. The dinoflagellate cyst *Cyclonephelium hystrix* is present in sample 6 (2950.91 m) indicating a Kimmeridgian or younger age (Riding and Thomas, 1992). In sample 8, the AOM is markedly clumped. On removal by a second oxidation treatment only sparse plant tissue remains. This interval is characterised by a variable proportion of marine taxa.

Full details can be found in Thomas (2018h).

4.10.3 Integration Sedimentology and Biostratigraphy

The Solan Sandstone Member of the Kimmeridge Clay Formation was deposited in a deep-marine turbidite fan environment based on the sedimentological interpretation. The depositional environment was confirmed by the presence of various marine taxa.

Based on the revised age dating, this study suggests that the Solan Sandstone and the Rona Sandstone are approximately coeval. This is in agreement with the work by Ritchie et al. (2011).

4.11 RIDGE CONGLOMERATE MEMBER

4.11.1 Sedimentology

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 with 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.

4.11.2 Biostratigraphy

206/05- 1

Samples 6 and 7. The occurrence of the dinoflagellate cyst *Ambonosphaera staffinensis* in sample 6 (3269.07 m) indicates a Late Jurassic, probably Mid Oxfordian to Mid Volgian, age. Sample 7 at 3272.08 m proved entirely barren, and cannot be dated. The kerogen is dominated by amorphous organic material.

Full details can be found in Riding (2018g).

4.11.3 Integration Sedimentology and Biostratigraphy

The biostratigraphy indicates the age of the sample but provides limited evidence relating to the depositional environment. The sedimentology suggests that the Ridge Conglomerate Member consists 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. The interpretation suggests that the debris flow originates from a local source.

	Marine	?Marine	Indeterminate	Marine taxa absent	Total of samples in unit/facies
Cromer Knoll Group	10		1	1	12
Kimmeridge Clay Formation	25	1	3		29
Solan Member	6		1		7
Ridge Conglomerate Member	1		1		2
Rona R5 (shallow marine to shelfal)	15				15
Rona R4 (shoreface/ littoral)	23		11	4	38
Rona R3 (marginal marine)	20	3	5	17	45
Rona R2 (fan delta)		1	11	13	25
Rona R1? §		2	4		6
Rona R1 (fluvial)	2		4	4	10
Sule Skerry Formation	8				8
Stack Skerry Formation	25*				25
Triassic			12		12
Triassic? §			4		4
Weathered basement			5		5

Table 9 Summary of environmental conclusions for each unit/facies based on palynological analysis. See Riding (2018a-i) and Thomas (2018a-j) for details.

§ = the classification as Rona R1 and Triassic is conjectural as the samples were taken below the core interval in well 205/26a-6 that was logged. The unit/facies suggested here is based on the correlation with well 205/26a-2 (see Appendix A).

* = the presence of ammonites in 14 samples also indicates a marine environment.

- Marine – marine palynomorps present
- ?Marine – marine palynomorphs questionably present, e.g. poor preservation
- Indeterminate – insufficient palynomorphs present to determine the environment
- Marine taxa absent – only terrestrial palynomorphs present

5 Seismic interpretation of the Solan basins and adjacent areas

The third study incorporated into the overall project was a seismic mapping task. The extents and thickness of the Jurassic succession have been mapped using a combination of 2D and 3D seismic data tied with a well dataset that has logged the presence or absence at more than 30 locations over a defined area of study 100 km west of Shetland (Quinn, 2018). The area of study includes the southern Westray High and Judd Sub-basin and basins and highs to the east of the Judd High, including the north-eastern part of the latter, parts of the Rona High, Solan Bank High, North Rona Basin and Solan Basins *(Figure 1* and *Figure 3*) and was selected to coincide with the cored wells studied in the sedimentology and biostratigraphy tasks.

Figure 3 Location of area of study (blue polygon) defining limit of the Jurassic mapped using seismic interpretation. Field and well locations from the OGA website, http://data-ogauthority.opendata.arcgic.com/. Background structure from Stoker et al., 2015.

The majority of wells, proving a Jurassic succession in the study area, show the Jurassic overlain by Lower Cretaceous rocks, often with a limestone lithology near the base of the Lower Cretaceous (*Figure 4*). A small number of wells record Upper Cretaceous or Cenozoic sediments resting on Jurassic (*Figure 4*).

Seven wells prove Jurassic absent (four with Lower Cretaceous resting on Crystalline Basement; two with Upper Cretaceous resting on Basement; one with Quaternary resting on Triassic) (*Figure 4*).

The key maps produced were TWTT to Top and Base Jurassic and an isochore map of the Jurassic succession in metres (e.g *Figure 5* and *Figure 6*).

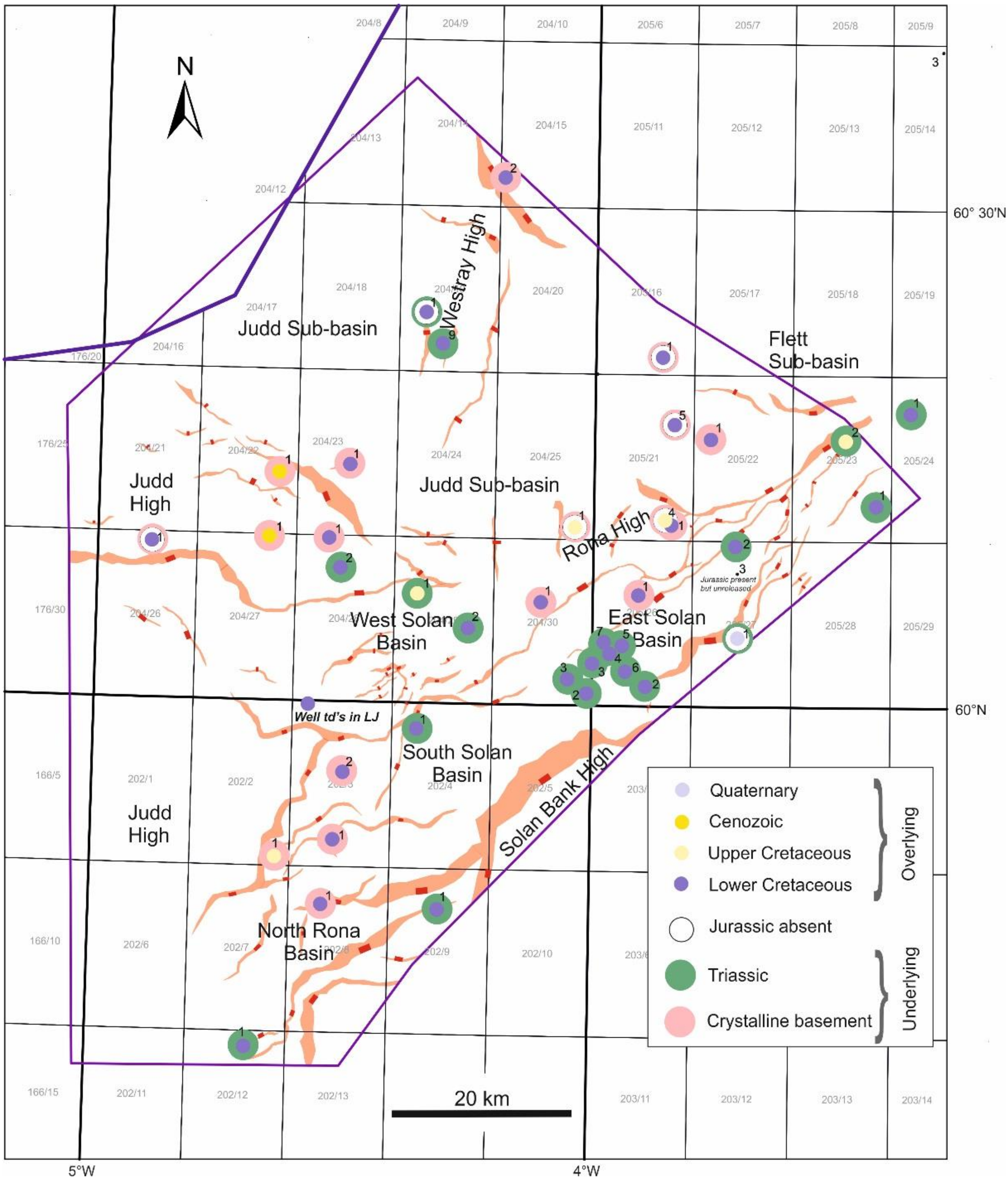


Figure 4 Wells proving a Jurassic succession and Jurassic absent within the area of seismic interpretation. Successions immediately underlying or overlying the Jurassic are shown.

5.1 DISTRIBUTION OF JURASSIC MAPPED BY SEISMIC INTERPRETATION

The Top Jurassic surface (*Figure 5*) varies in TWTT from approximately 800 ms to over 5200 ms. The shallowest areas occur on parts of the Rona and Solan Bank highs while interpreted Top Jurassic is deepest to the north of the Judd High, in the western part of the Judd Sub-basin. The Base Jurassic surface varies in TWTT from approximately 900 ms to >5400 ms in the western part of the Judd Sub-basin.

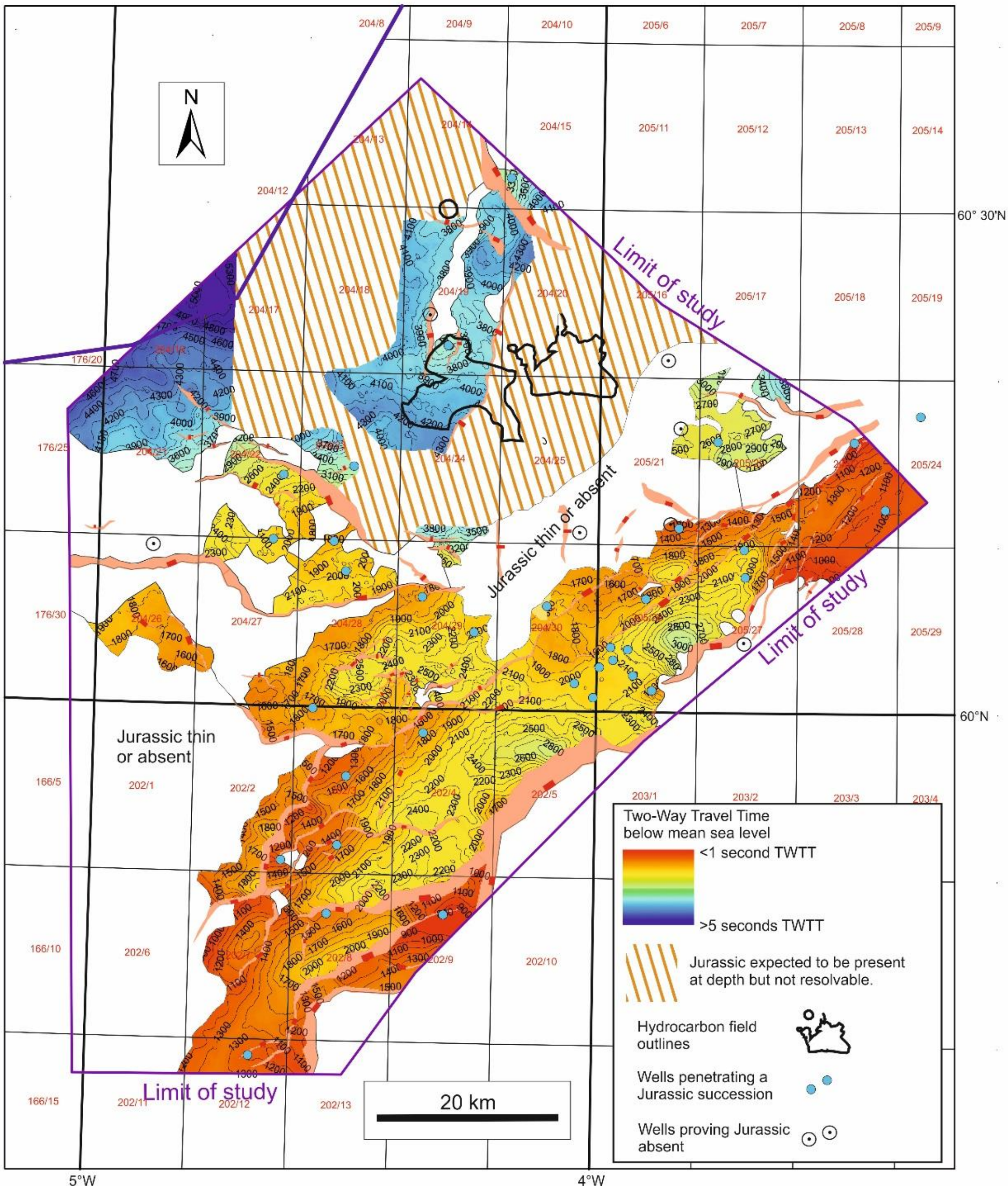


Figure 5 TWTT to Top Jurassic in the study area. The Jurassic is expected to be present over the area defined by diagonal lines but lack of data and greater depth prevented its seismic interpretation.

Jurassic thickness (*Figure 6*) varies from more than 1400 m in the West Solan Basin to less than 200 m in some of the south-westerly marginal basins such as the North Rona Basin.

The Jurassic is thin or absent over much of the Judd High, with a more patchy distribution on the Judd High adjacent to the Judd Sub-basin. Seismic mapping suggests >1400 m total Jurassic thickness in the West Solan Basin. Seismic mapping indicates Jurassic thicknesses of up to 200 m in marginal basins.

NE-trending faults delineate the North Rona and Solan basins while faults with a more ENE-trend are located within the North Rona Basin. NW-trending faults mark the boundary between the Judd High and Judd Sub-basin. The Judd High itself is divided into faulted terraces, the major faults having a general E-W trend. The West Solan Basin is located at the juxtaposition of the dominantly NE-trend characterising the 'back basins' and E-W trend seen on the Judd High. There is a suggestion of a N-S trend over the Westray High and within the Judd Sub-basin (*Figure 6*).

The NE- and NW-trending faults tend to have the greater throws. For instance, the NE-trending Otter Bank Fault has throws of 1.5 to 2 seconds TWTT and the NW-trending Judd Fault more than 1 sec TWTT throw. The ENE-trending faults in the North Rona Basin have throws of 100s of ms.

The following sections describe the distribution of Jurassic sediments within the individual sub-basins and basins.

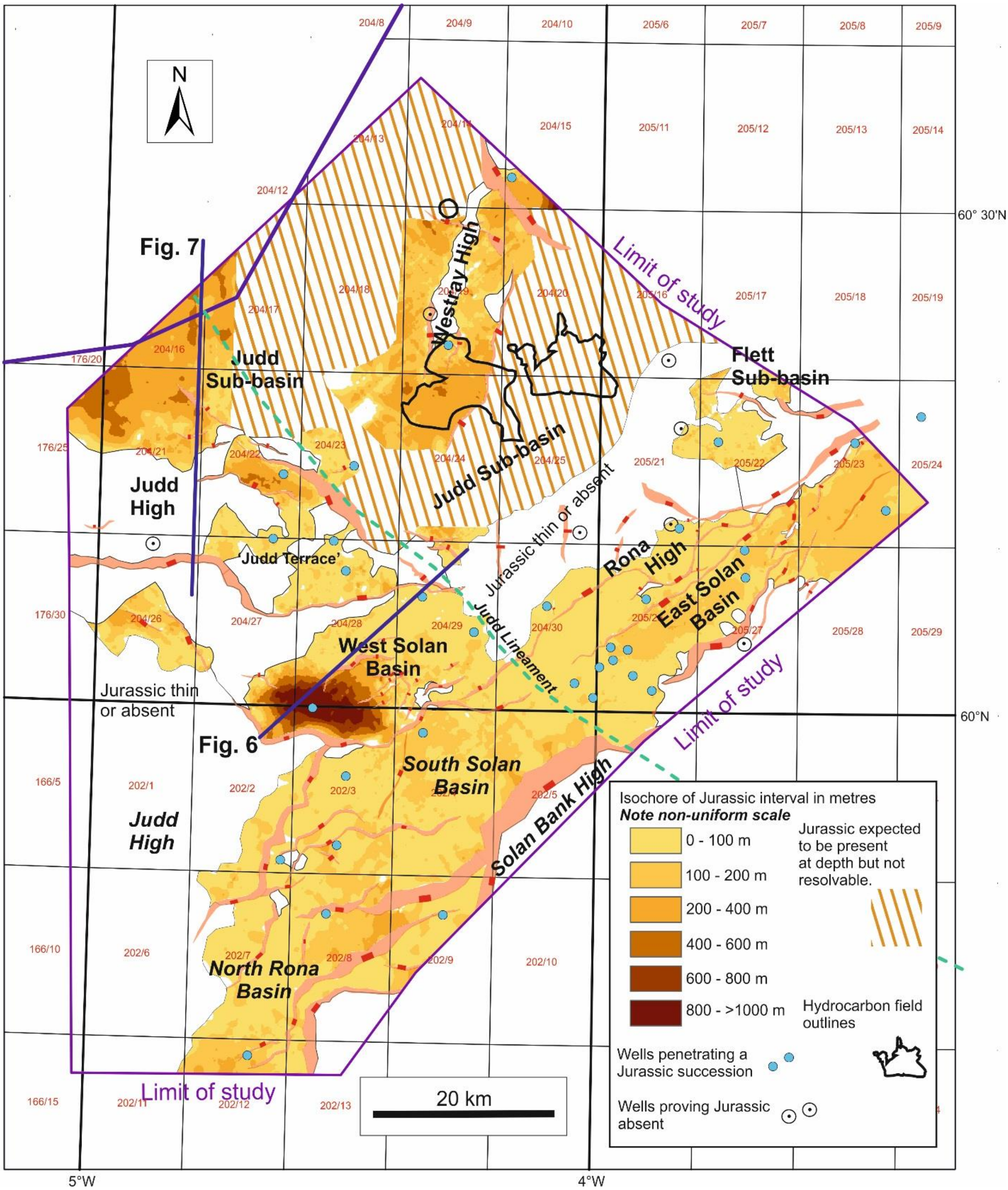


Figure 6 *Isochore of the Jurassic interval in the study area. The Jurassic is expected to be present over the area shown by diagonal lines but lack of data and/ or its greater depth prevented interpretation. Locations of seismic lines are shown.*

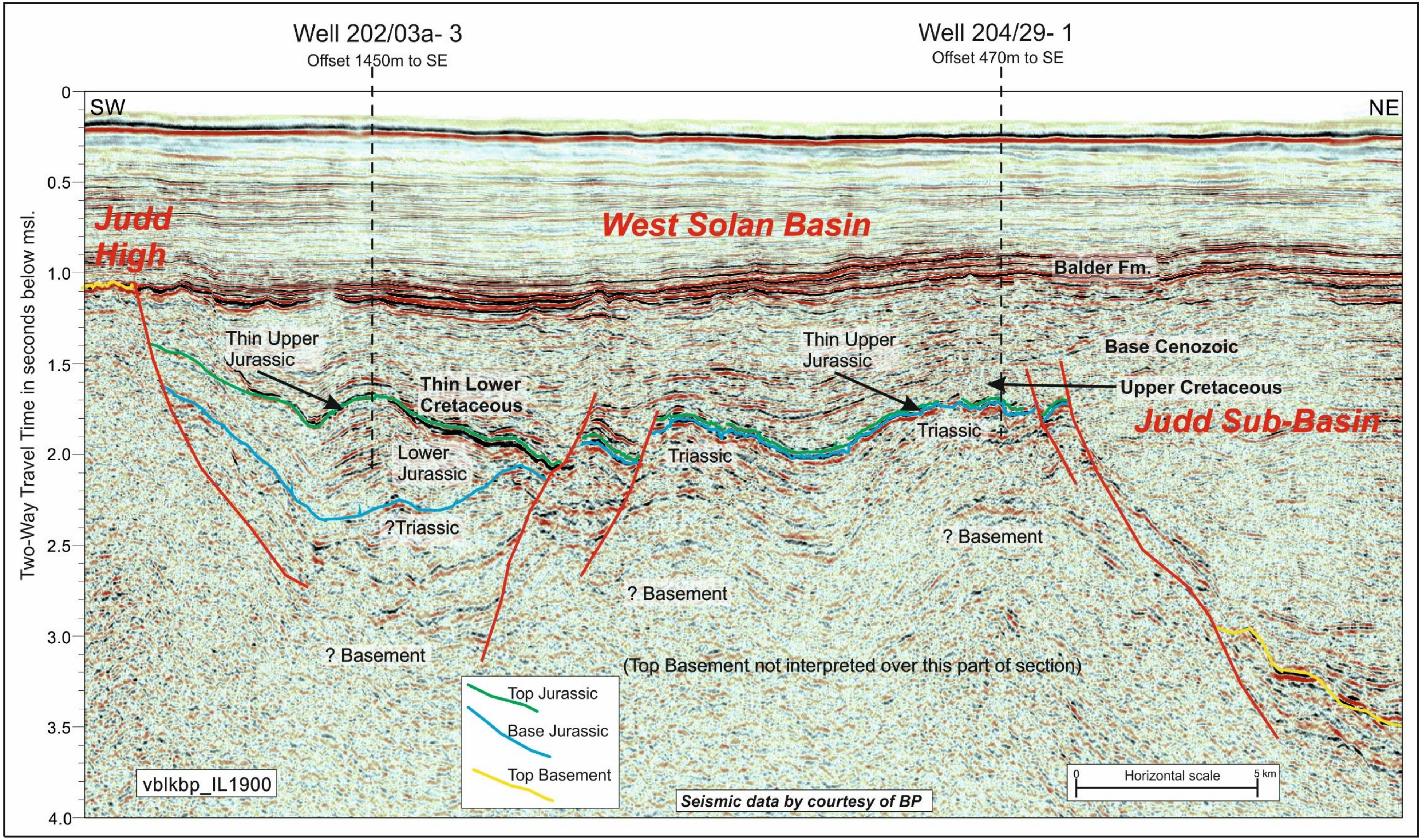


Figure 7 *West Solan Basin: SW-NE trending interpreted 3D seismic section showing thick Lower Jurassic sediments resting on a possible thick Triassic succession in the SW with a thin Upper Jurassic succession to the NE. Line location shown on Figure 6.*

5.1.1 The North Rona, South Solan and East Solan basins

These basins are located along the south-eastern part of the study area and have a mapped thickness of Jurassic of generally less than 200 m. However, locally thicknesses may increase to more than 300 m. All well penetrations in these basins proved an Upper Jurassic succession only, except for 202/04-1 (South Solan Basin), that proved 135 m of Lower Jurassic sediments beneath 28 m of Upper Jurassic.

5.1.2 The West Solan Basin

The basin is located inboard to the north-west of the basins noted above, with an overall NE trend. The south-western part, that has a predominantly Lower Jurassic succession of >500 m and thickens to a maximum interpreted thickness of 1426 m, forms an E-W trending depocentre, Well 202/03a-3 proved 25.9 m of Upper Jurassic sediments resting on 769.7 m of Lower Jurassic. In comparison, the north-eastern part of the West Solan Basin comprises only Upper Jurassic sediments mainly <100 m (*Figure 5* and *Figure 6*). The rapid Lower Jurassic thickness changes seen in *Figure 7* can be explained by erosion prior to KCF deposition.

The E-W trending Jurassic depocentre of the West Solan Basin is located at the intersection of the NW-fault trend seen on the Judd High and the NE-trend that is dominant in the Solan Basins. It is possible that the depocentre was initiated and developed in a transtensional regime during deposition of the Lower Jurassic (Quinn 2018). In addition, the NE-trending seismic section (*Figure 7*) shows evidence of compression along its length and particularly at location of well 202/03a- 3. Compression must have occurred after deposition of the Lower Jurassic (as this is deformed) but no probably no later than end Lower Cretaceous as Upper Cretaceous and Cenozoic sediments appear to onlap the Base Cretaceous unconformity (*Figure 7*).

5.1.3 The Judd High

The north-eastern part of the Judd High is present within the study area. A NW-trending fault defines its boundary with the Judd Sub-basin. Another, E-W trending fault, with a NNW-trending 'dog-leg' transects the high forming a terrace, referred to as the 'Judd Terrace' (Quinn 2018), on which five wells have been drilled to date. Distribution of the Jurassic is patchy and is generally between 0 and 200 m thick but on part of the 'Judd Terrace', Jurassic thicknesses have been interpreted to be >400 m thick (*Figure 6*). Well 204/26- 1 records Lower Cretaceous resting on crystalline basement.

Four wells prove a Jurassic succession, three prove <100 m but the fourth, well 204/22-1 records 246 m Upper (thin Oxfordian, 14 m) and Middle Jurassic Heather Formation resting on an undivided Middle Jurassic succession on the original BP composite log. Ritchie and Varming (2011) restrict the extent of Heather Formation to a late Callovian age with the latter resting on an undivided Middle Jurassic succession; Well 204/22-1 is located on the 'Judd Terrace', closest to the Judd Sub-basin, and is the only well in the study area with a possible Middle Jurassic succession.

5.1.4 The Westray High

The Westray High comprises two small north to NNW-trending intra-basinal highs (*Figure 6*). The southerly high and the southern part of the northern high lie within the study area. The highs are deeply buried, for instance Well 204/19-1 drilled just off the crest of the south Westray High, penetrated the base Lower Cretaceous/ Top Triassic boundary at 4263 m TVDSS. The south Westray High is located beneath the Palaeocene Foinaven Oil Field and immediately west of the Schiehallion Oil Field. The Jurassic is interpreted to be absent along the crest of the south Westray High (*Figure 5*) and to thicken eastwards down-dip into the Judd Sub-basin (*Figure 6*).

One well on the south Westray High, well 204/19-9, and well 204/15-2 located on the north Westray High within the study area proved Jurassic successions. Well 204/19- 9 drilled on the eastern flank of the south Westray High, 1.5 km off the crest, proved 185 m of Lower Jurassic sediments overlain by Lower Cretaceous sediments and resting on Triassic. However, it is expected that Upper Jurassic sediments will be present down-dip where the total Jurassic interval is interpreted to be 200-300 m thick but in some areas may exceed 400 m. Well 204/15-2, located on the footwall of a major fault bounding the northern Westray High (*Figure 4* and *Figure 5*), penetrated 233 m of Upper Jurassic siltstone, sandstone and occasional limestone.

5.1.5 The Judd Sub-basin

Although there is a lack of well evidence and limited seismic coverage over the Judd Sub-basin, the expectation is that a Jurassic succession will be present at depth within the Judd Sub-basin (Ritchie and Varming, 2011); limited seismic interpretation in this study supports this view. A tentative seismic interpretation within part of the Judd Sub-basin, north of the Judd High and west of the Westray High maps a possible Jurassic succession (*Figure 6*). *Figure 8* shows a Cenozoic seismic package, the base tied to nearby wells 204/21-1 and 204/16-1 (that both reach total depth close to the top of the Upper Cretaceous), and a Cretaceous succession characterised by abundant sill intrusions. The Cretaceous appears to onlap a deeper seismic package (*Figure 8*) suggesting the presence of an older succession, possibly Jurassic, resting on Triassic or basement forming the Judd High. A series of faults cut the Jurassic succession with relatively small displacements throwing into the sub-basin (*Figure 8*); the Jurassic succession thins and eventually terminates on the flanks of the Judd High. The Jurassic shows a gradual increase in thickness downdip into the Judd Sub-basin; the Jurassic isochore shows interpreted thickness of >500 m (*Figure 6*).

The style of the faulting is reminiscent of the Jurassic succession that thins onto the NW flank of the Rona High (see Figures 22 and 24 in Quinn et al., 2014 and Haszeldine et al., 1987). The Jurassic succession on the Rona High includes Upper Jurassic sandstone, and in the project area, Upper Jurassic sands have been proved in many wells. For instance, well 204/27a-1, 15 km to the SE, proved more than 70 m of Upper Jurassic Rona Sandstone. Dodd (2018) predicts the presence of a clean well sorted marine sandstone, the Rona Sandstone Member (R4) and Solan Sandstone Member (R6) on the northern flank of the Judd High. The Solan Sandstone Member is a proven hydrocarbon reservoir in the East Solan Basin.

The interpretation of the Jurassic on the northern flank of the Judd High forms an untested hydrocarbon play where Jurassic reservoir sands pinchout up-dip, are faulted and rotated, and are sourced down-dip by a thickening Upper Jurassic succession.

5.1.6 South-West Flett Sub-basin

Well 205/22- 1A proved 50.5 m of Upper Jurassic mudstone, limestone, sandstone and conglomerate at a location immediately NW the Rona High (*Figure 6*). Seismic interpretation and adjacent well penetrations show a restricted area of Upper Jurassic sediments generally less than 100 m and patches around 200 m in thickness.

The restricted nature of the deposit must be due in part to erosion prior to deposition of the Lower Cretaceous, as deep marine mudstones (presumably deposited widely) have been described from a core at the top of the Jurassic succession in well 205/22- 1A (Dodd, 2018). The interpretation of the older palaeo-environment from the core as a proximal fan delta/ alluvial cone resting on crystalline basement (Dodd, 2018) suggests a local source area and its location immediately NW the Rona High, points to the latter as the likely source for the clastic material.

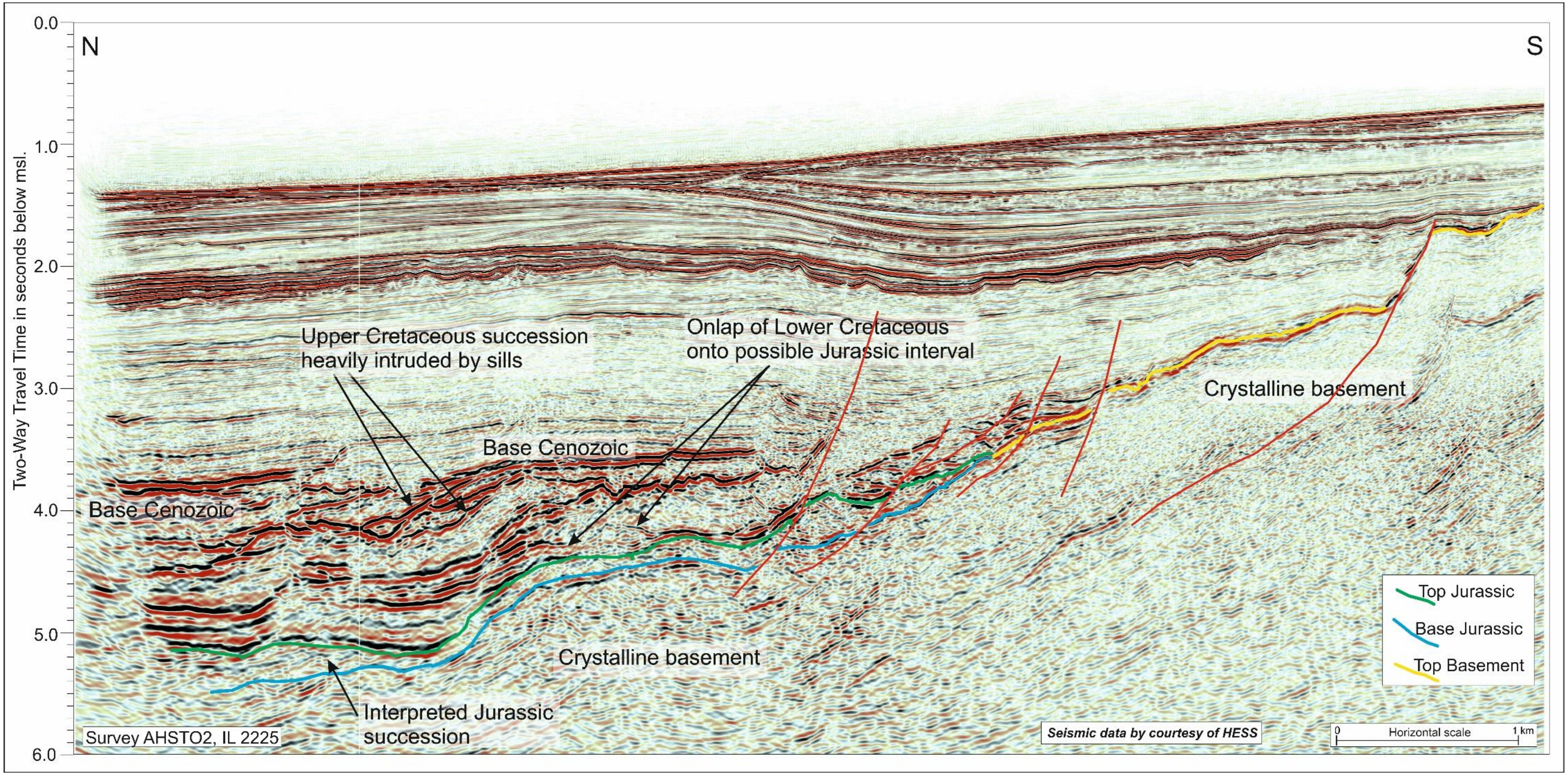


Figure 8 *Judd Sub-basin: 3D seismic section showing interpretation of the Jurassic succession on the northern flank of the Judd High. Note numerous sill intrusions predominantly within the Cretaceous interval. Line location shown on Figure 6.*

6 Revised Jurassic range charts and well correlations

The stratigraphic database of Jurassic well penetrations in the Faroe-Shetland region has been updated based on the new assessments of the depositional environments and the ages. Revised range charts (*Figure 9* and *Figure 10*) and three well correlations (Appendix 2) have been created based on the new interpretations.

Prior to creating the revised Jurassic range charts, a review of the wireline logs (specifically the gamma ray and the sonic log) of the cored wells was undertaken. Packages were identified that could be cross-correlated between the wells. Through integration with the biostratigraphy and the sedimentology results, it was possible to assign the packages to the core stratigraphical units or facies. The correlation led to revised tops of the formations in a few of the wells and these variations are shown in *Table 10.*

The study did not attempt to extend the correlation beyond the study area or cored wells but there is scope to move into other basins if required.

The range charts were modified from work produced by Ritchie and Varming, 2011. The new analysis based on the revised results from the sedimentology, biostratigraphy and well correlations has been incorporated into the charts. Cores that had not been reviewed in this study were kept in the chart for completeness but are showed in a greyed-out colour. *Table 10* highlights where the new work has replaced the original interpretations and notes the changes.

Based on *Table 10*, there are several minor adjustments to lithostratigraphic tops but there are also three key differences between the current work and the previous publications:

- Palynological analysis provides age determinations for the Kimmeridge Clay Formation including the Rona, Solan and Ridge Conglomerate members. However, there is no new evidence to distinguish Rona Sandstone and Solan Sandstone on age and the study concludes that these two members are co-eval in age.
- On palynological evidence, a tentative new age determination is assigned to sandstones at 2578.7m to 2596.75m in well 205/26a-6. This interval is now regarded as Late Jurassic or Early Cretaceous Rona R1 but was previously assigned to the Triassic. Similarly sandstones at 3169.84 to 3172.49 m in well 206/05-2 are now regarded as Volgian or younger Rona R3, but were previously assigned to the Lower Jurassic.
- In well 205/26a-2, the section of Rona R1 Sandstone (12.2 m) had been previously assigned to the Triassic. The new assignment to the Rona Member was based on the well correlation as it showed similar log responses to a comparable unit in well 205/26a-6 which was been re-dated as 'Late Jurassic or younger' (Thomas 2018i). The palynology did not provide any evidence to support or disprove this change as the section in question was not cored and therefore no samples were available for dating.
- In the well 206/05-2, in the Faroe Shetland Basin, Dodd (2018) and Thomas (2018j) re-date 4.8 m of sandstones as Volgian or younger in age, and assign the section to the Rona R3 facies (see below). Three metres of sandstone in well 206/05-1 are described by Dodd (2018) as Middle Jurassic age.

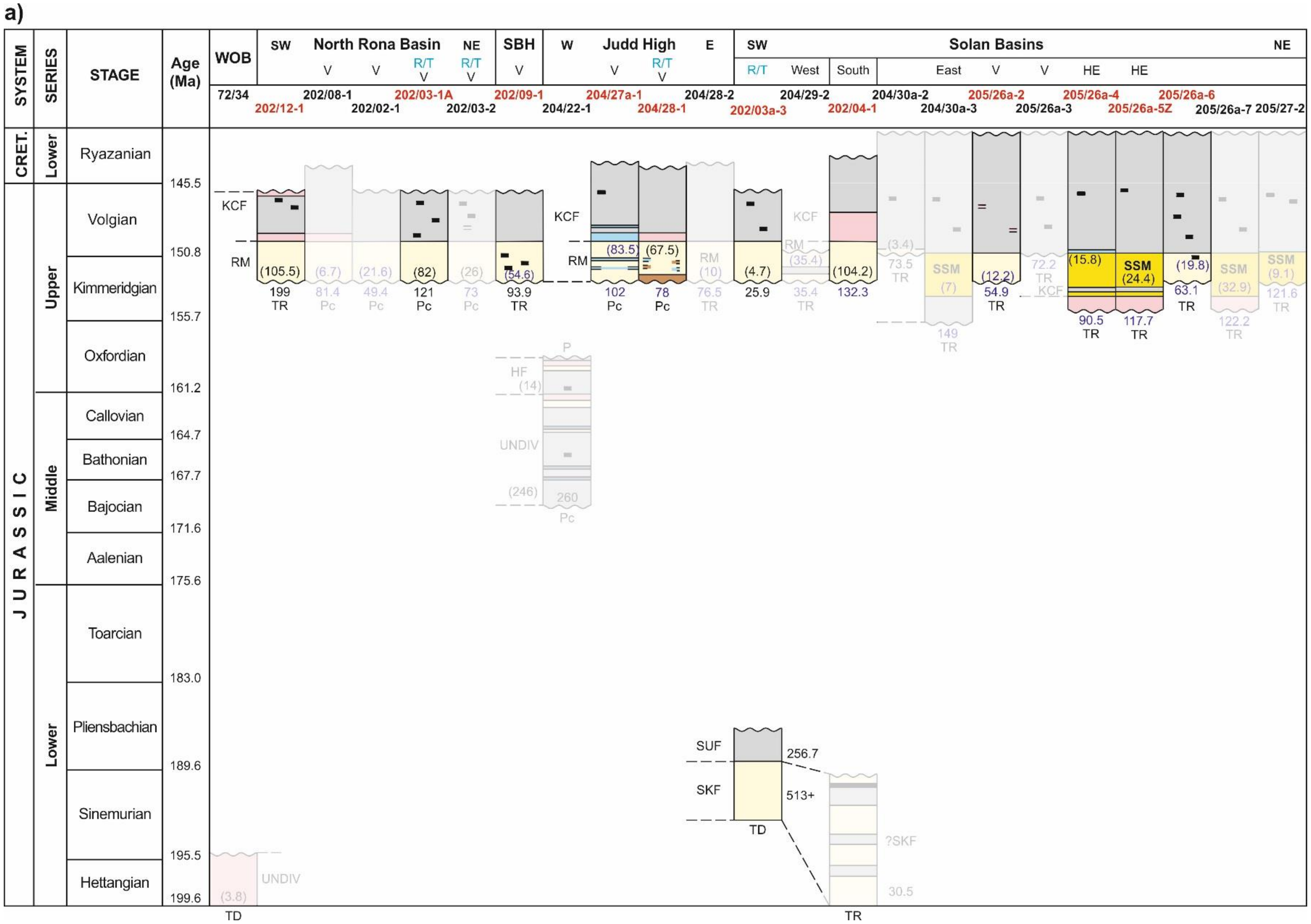
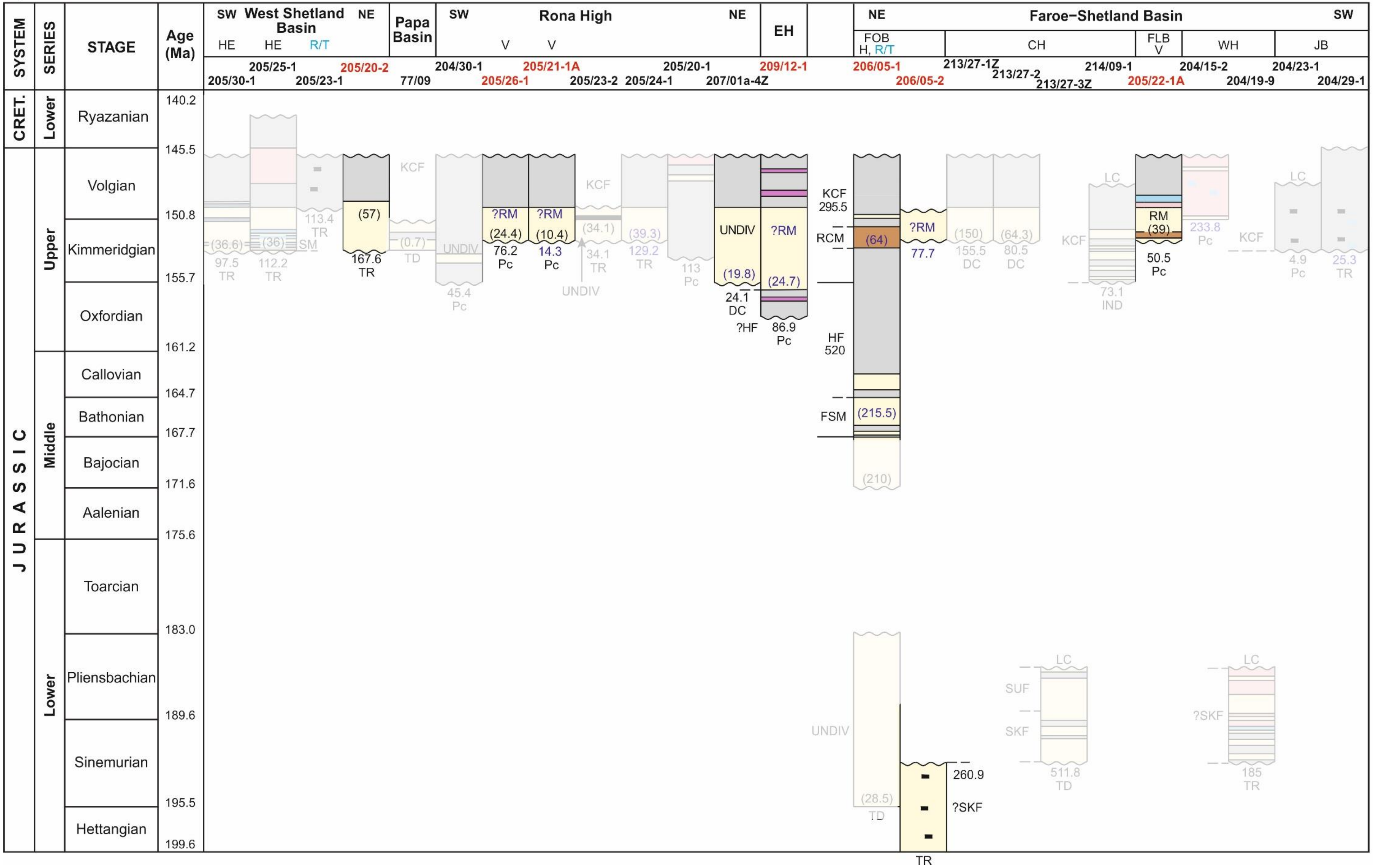


Figure 9 Stratigraphical range chart showing generalised lithology and thickness (m) of Jurassic and earliest Cretaceous rocks within the North Rona Basin, Solan Bank High, Judd High and Solan basins (modified from Ritchie and Varming, 2011). Greyed-out sections were not part of the current core sedimentology/biostratigraphy study.

b)


SYSTEM
SERIES
STAGE
Age (Ma)
SW West Shetland Basin NE
Papa Basin
SW Rona High NE
EH
NE Faroe−Shetland Basin SW
CRET.
JURASSIC
Lower
Upper
Middle
Ryazanian
Volgian
Kimmeridgian
Oxfordian
Callovian
Bathonian
Bajocian
Aalenian
Toarcian
Pliensbachian
Sinemurian
Hettangian
140.2
145.5
150.8
155.7
161.2
164.7
167.7
171.6
175.6
183.0
189.6
195.5
199.6
205/30-1
205/25-1
205/23-1
205/20-2
77/09
204/30-1
205/26-1
205/21-1A
205/23-2
205/24-1
205/20-1
207/01a-4Z
209/12-1
206/05-1
206/05-2
213/27-1Z
213/27-2
213/27-3Z
214/09-1
205/22-1A
204/15-2
204/19-9
204/23-1
204/29-1
KCF
?RM
RM
UNDIV
RCM
HF
FSM
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SKF
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TR
Pc
DC
TD
IND

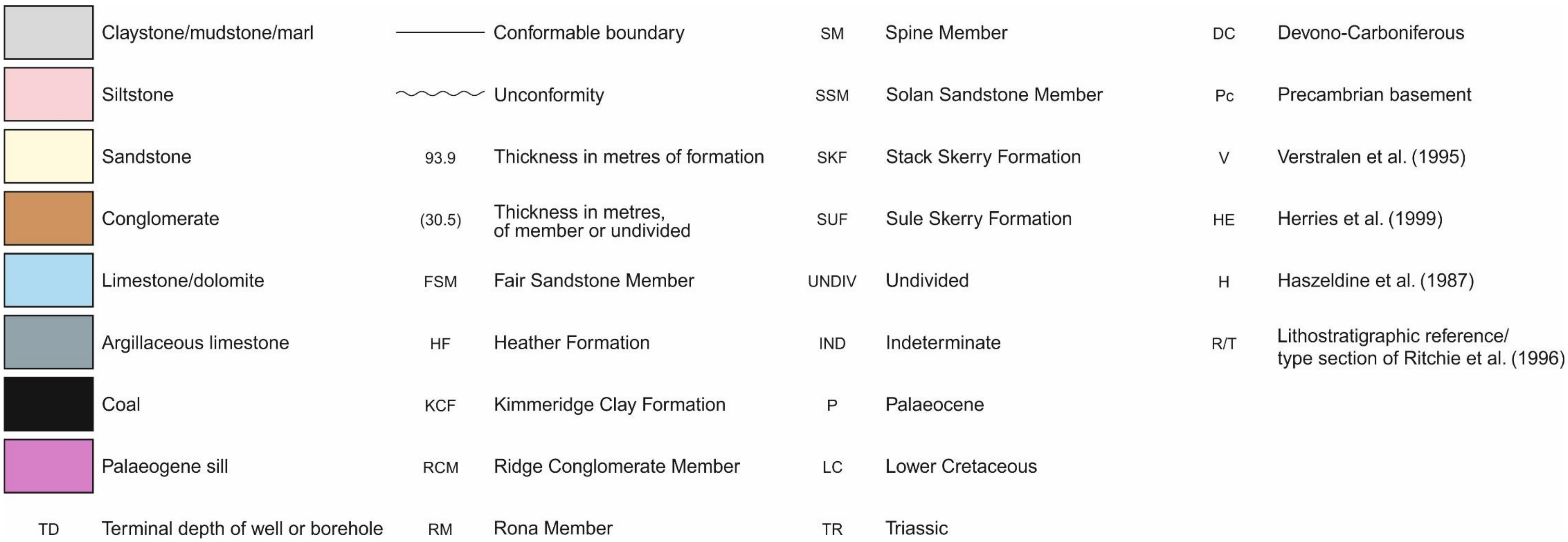

Figure 10 Stratigraphical range chart showing generalised lithology and thickness (m) of Jurassic and earliest Cretaceous rocks within the West Shetland Basin, Papa Basin, Rona High, Erlend High and Faroe–Shetland Basin (modified from Ritchie and Varming, 2011). Greyed-out sections were not part of the current core sedimentology/biostratigraphy study.

Timescale is based on ‘A Geologic Time Scale 2004’ by F M Gradstein, J G Ogg, A G Smith, et al. (2004) and the International Stratigraphical Chart, 2006 (ICS) with additions. Note: all thicknesses are for the Humber Group and include strata of early Ryazanian (earliest Cretaceous) age. Thicknesses quoted in Figure 60 of Ritchie and Varming (2011) are restricted to the Jurassic. All thicknesses are drilled thicknesses based on measured depths in wells.

Well	Comment
202/12-1	
202/08-1	The top of the Kimmeridge Clay Formation is interpreted slightly higher at 1568.2 m (5145 ft) rather than 1569.1 m (5148 ft) (on composite log) based on the log response.
202/02-1	
202/03-1A	Type section for the Rona Formation [now Rona Sandstone Member] and reference section for the Kimmeridge Clay Formation (Ritchie et al. 1996).
202/03-2	The Rona thickness now excludes ‘weathered granite’.
202/09-1	Change from Ritchie and Varming (2011): Rona thickness = 54.6 m (rather than 56.5 m).
204/22-1	This interpretation follows Ritchie and Varming (2011) with 14 m of Oxfordian Heather Formation overlying an undifferentiated Middle Jurassic unit. Alternatively, the entire Jurassic section (260 m) could be included in the Heather Formation. Company age dating of the unit is Bajocian-early Oxfordian and Bathonian-early-mid-Oxfordian.
204/27a-1	Changes from Ritchie and Varming (2011): top Rona = 2047.5 m (rather than 2053 m) and top Kimmeridge Clay = 2029 m (rather than 2027 m). Both are based on the log response
204/28-1	Reference section for the Rona Formation [now Member] (Ritchie et al. 1996).
204/28-2	
202/03a-3	Type well for the Skerry Group, Sule Skerry Formation and Stack Skerry Formation (Ritchie et al. 1996).
204/29-2	
202/04-1	The "undifferentiated" unit (26.2m) of the composite log is tentatively assigned to the Triassic by Ritchie et al. (2011). Change from Ritchie and Varming (2011): top Kimmeridge Clay = 5980 ft (1822.7 m) (rather than 5966 ft, 1818.4 m) based on log response.
204/30a-2	The Top of the Kimmeridge Clay Formation is reinterpreted at 2359.8 m (7742 ft). The Rona Member (3.4 m) is restricted to between 2438.7 m (8001 ft) and 2442.1 m (8012 ft).
204/30a-3	The Solan Member (7 m) is restricted to between 3119.6 m (10,235 ft) and 3126.6 m (10,258 ft).
205/26a-2	The composite log has Top Triassic at 2151.9 m (7060 ft). Dodd (2018) interprets core #9 is Rona Member R1. Hence, the Top Triassic is moved down to below a shale at 2163.8 m (7099 ft). The ?Rona Sandstone (12.2 m) is reinterpreted from Triassic of the composite log based on early Kimmeridge age determinations at 2148.8 m (7050 ft) and 2158.0 m (7080 ft) (BGS 1983). It is also influenced by a correlation with a comparable unit in well 205/26a-6 which has been re-dated as ‘Late Jurassic or younger’ (Thomas 2018i) – see below.
205/26a-3	
205/26a-4	There is no type well for the Solan Sandstone Member, but this is one of the best preserved sections (along with 5Z). Top Triassic in the core (Dodd 2018) is 2469.2 m (8101 ft) – close to the 2470.1 m (8104 ft) on the composite log.
205/26a-5Z	

Well	Comment
205/26a-6	The composite log has Top Triassic at 2577.1 m (8455 ft), but new age dating assigns a 'Late Jurassic or younger' age to samples below this at 2592.93 and 2593.97 m (but 'Indeterminate' ages below that) (Thomas 2018i). The base of a shale (correlated with a similar one in 205/26a-2) is taken as the base of the Jurassic. As a result, Top Triassic is revised at 2596.9 m (8520 ft). Note – this core was not logged below 2578 m as it was considered to be of Triassic age at the time.
205/26a-7	
205/27-2	The basal Jurassic sandstone is assigned to the Solan Sandstone on the composite log. The criteria for this assignment are not known. It could alternatively be assigned to the Rona Sandstone. Other Solan occurrences have Kimmeridge Clay above and below.
205/30-1	
205/25-1	The Top Kimmeridge Clay could be 2304.3 m (7560 ft) (as here) or possibly 2286 m (7500 ft) (to include the early Ryazanian unit).
205/23-1	Reference section for the Kimmeridge Clay Formation. Thickness revised form 112.5 m in (Ritchie et al. 1996) to 113.4 m (Ritchie and Varming 2011).
205/20-2	The 23.8 m-thick unit described on the composite log and by Ritchie and Varming (2011) as 'undifferentiated Middle Jurassic' was dated by ARCO as 'Callovian-Bajocian' on the 1994 composite log (no biostratigraphical report is available). The re-dating of the 'Middle Jurassic' sequence is based on (a) the recognition of facies as Rona R3 by Dodd (2108) and (b) a Kimmeridgian to Mid Volgian age at 2968.08 m (9737.8 feet) and 2964.97 m (Riding 2018c). The top of the Triassic in the core is 2983.9 m (Dodd 2018) – close to the 2984.9 on the composite log.
204/30-1	
205/26-1	There is 1.5 m (5 ft) of conglomerate at the base of core #1 (2103.1-2104.6 m). The composite log incorporates this as 'weathered granite' within their 'Basement'. Dodd (2018) includes these beach conglomerates in the Rona Member (R4 facies) which will take the Top Basement pick down slightly (to c.2104.6 m, 6905 ft) from that on the composite log (2103.1 m, 6900 ft).
205/21-1A	A 'Bajocian/Bathonian' unit on the composite log was reassigned to the Rona Member by Ritchie and Varming (2011). Dodd. (2108) confirms this as Rona Member R2 in cores. The 3.96 m of overlying shale ('?JU') on the composite log (4392-4405 ft) was interpreted as Lower Cretaceous by Ritchie and Varming (2011). In this report, this shale is assigned to the Kimmeridge Clay Formation and is overlain by glauconitic sands interpreted as the lowest unit of the Cromer Knoll Group. However, a sample at 1343.56 m within this putative Kimmeridge Clay Formation yielded an anomalous 'Mid to Late Cretaceous (Albian to Cenomanian)' age (Thomas 2018f). This age appears unlikely given the Aptian (and Albian) dates well above this depth (Bigg 1975). Probable 'core jumbling' is invoked. The thickness (76.2 m) in Hopper et al. (2014) is thought to have been transposed from well 205/26-1.
205/23-2	
205/24-1	
205/20-1	
207/01a-4Z	

Well	Comment
209/12-1	Core from the sandstone unit is interpreted as Rona R3 facies (Dodd 2018). This was previously an undivided Upper Jurassic unit in Ritchie & Varming (2011).
206/05-1	Reference section for the Heather Formation, Fair Sandstone Unit [now Member], Kimmeridge Clay Formation and Ridge Conglomerate Unit [now Member] (Ritchie et al. 1996). [The Bajocian (210 m) and Pliensbachian-Sinemurian (28.5 m) strata were originally assigned to the Clair Group by Ritchie et al. (1996).]
206/05-2	Dating from core samples indicates that at least part of this 'Lower Jurassic' unit is of 'Volgian or younger' age (Thomas 2018j) and has a facies interpreted as Rona R3 (Dodd 2018). A new Top Lower Jurassic is placed at c. 3200.4 m (10,500 ft) giving a Rona thickness of 77.7 m and a thinning of the ?Stack Skerry Formation from 338.6 m to 260.9 m.
213/27-1Z	
213/27-2	
213/27-3Z	
214/09-1	
205/22-1A	A '?Jurassic' unit on the composite log was assigned to the Rona Member by Ritchie and Varming. (2011). This was confirmed as Rona Member facies R2 and R4 in the cores (Dodd 2018).
204/15-2	
204/19-9	The lower 128 m of the undifferentiated Skerry Group of the composite log was reinterpreted as 'Westray High Limestone Formation' of the Papa Group by Quinn and Ziska (2011). The boundary is placed where late Sinemurian strata overly late Rhaetian-Sinemurian strata (there is no lithological break). Limestones are present in the lowest 30 m.
204/23-1	
204/29-1	
204/19-1 (not included on Fig. XX)	The unit assigned to the 'Late Jurassic' on the original composite log was reassigned to the Lower Cretaceous by Ritchie and Varming (2011).

Table 10 Key points and changes made to the stratigraphic tops database during this study

7 Updated stratigraphic framework for the Jurassic of the Faroe-Shetland region

The integration of the new data collected during this study with the established framework of Ritchie et al. (2011) allows for the publication of a suite of distribution and thickness maps for the main stratigraphic units *(Figure 11, Figure 12, Figure 13, Figure 14 and Figure 15*). Key to this analysis is the isopach map derived from seismic interpretation by Quinn (2018), and superimposed on this is an updated knowledge of the age of cored samples (see Section 3).

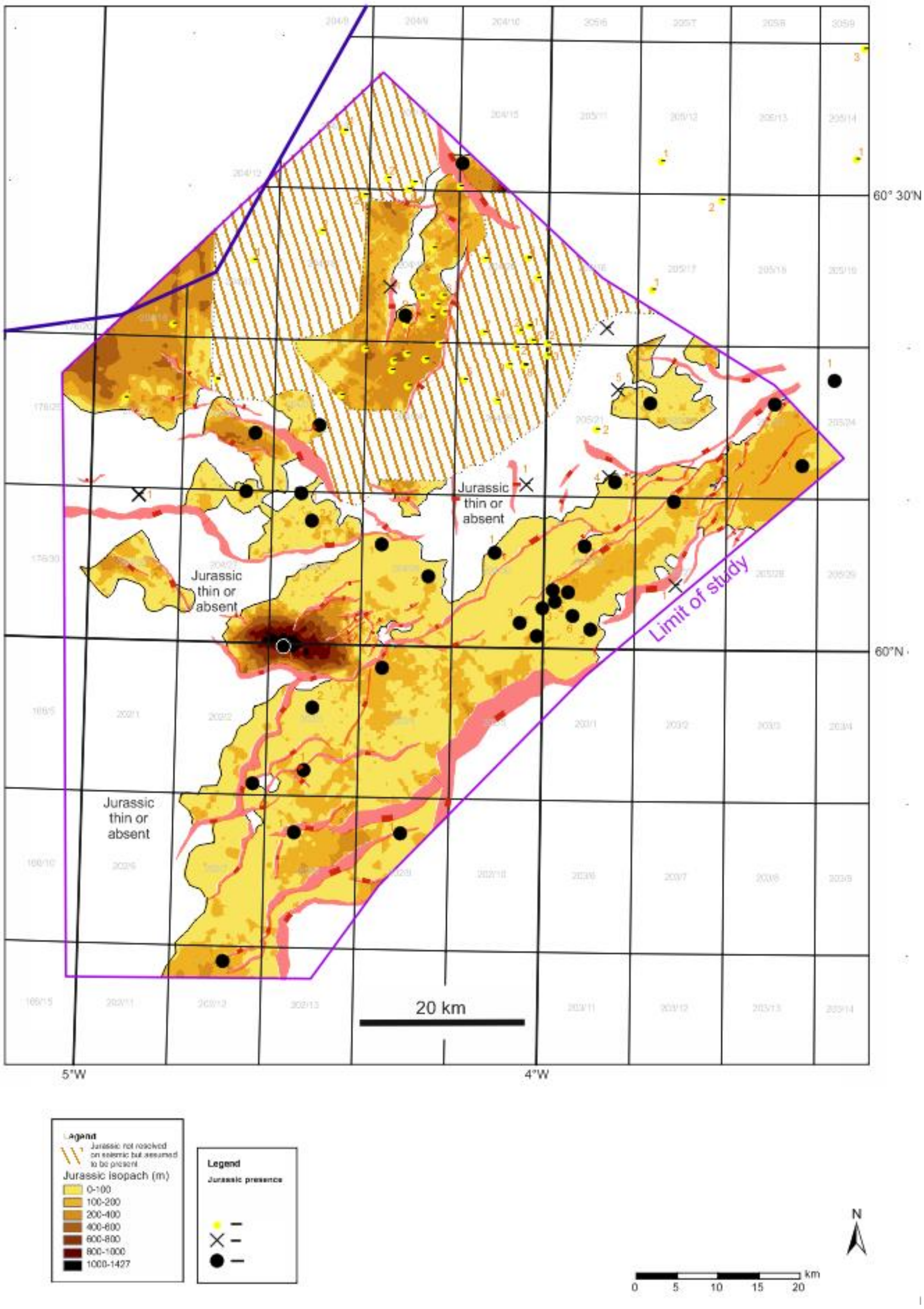

Figure 11 Distribution of the Jurassic in the study area. The thickness grid is derived from seismic interpretation (Quinn 2018) and is constrained by where the Jurassic can be resolved at TWTT less than c.4.5 seconds (deep areas are hashed).

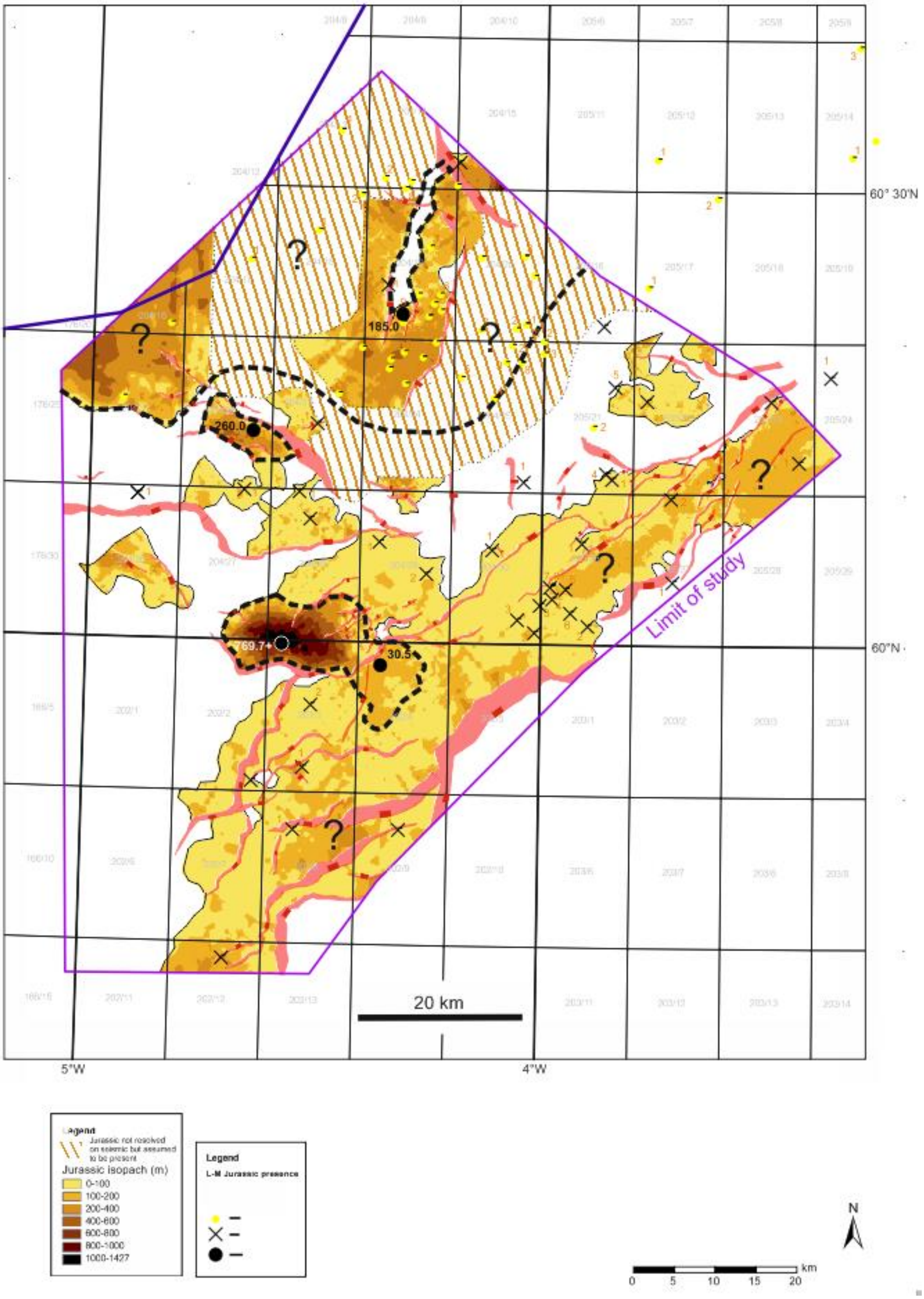

Figure 12 Distribution and thickness (m) of the Lower-Middle Jurassic in the study area. The presence of Lower-?Middle Jurassic strata in the deeper parts of the Judd Sub-basin, North Rona Basin and East Solan Basin is speculative (indicated by "?").

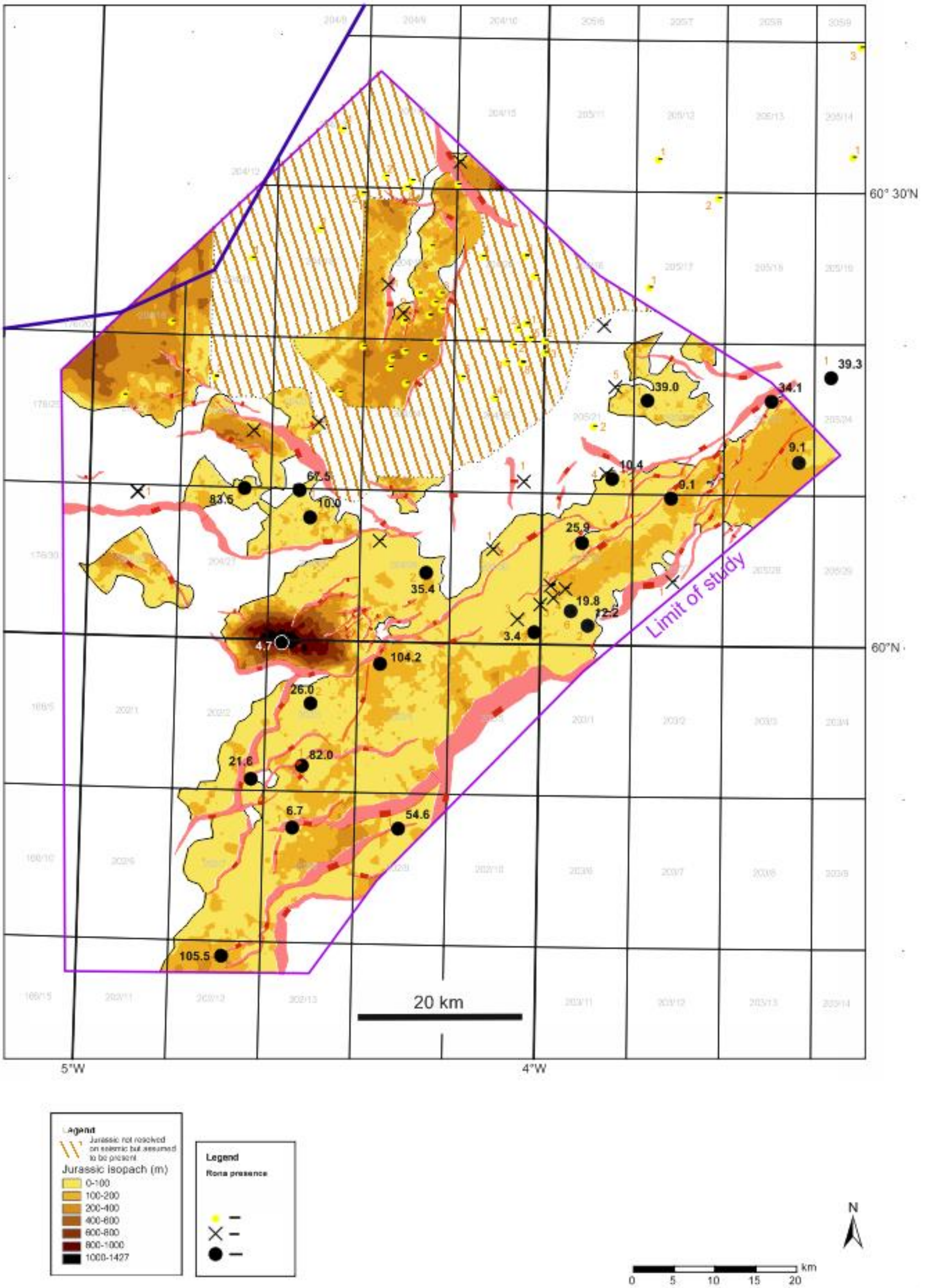

Figure 13 Distribution and thickness (m) of the Rona Member in the study area.

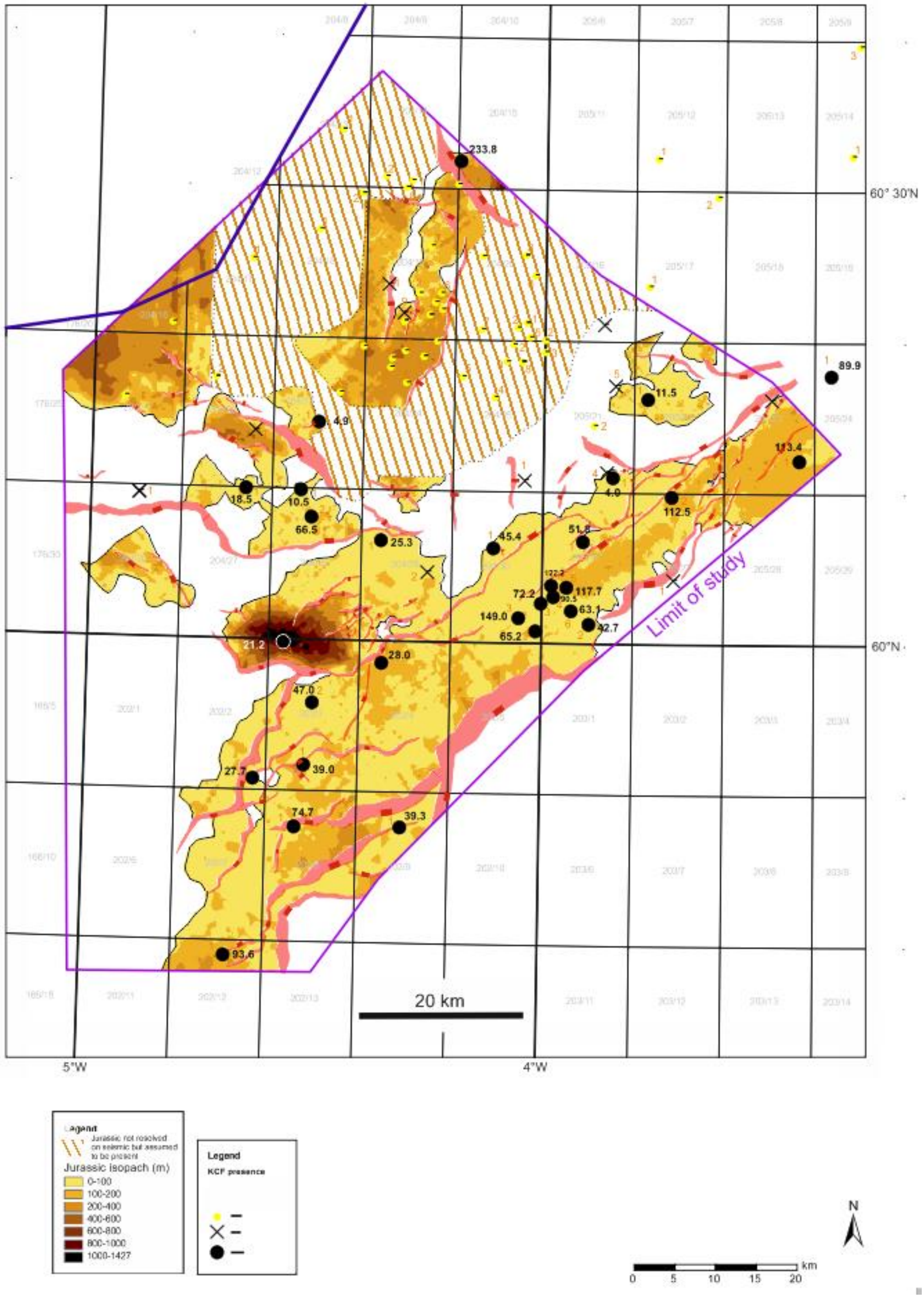

Figure 14 Distribution and thickness (m) of the Kimmeridge Clay Formation in the study area. Note that this refers to the Kimmeridge Clay Formation above the Rona Member, but includes the Solan Member which is encased in KCF.

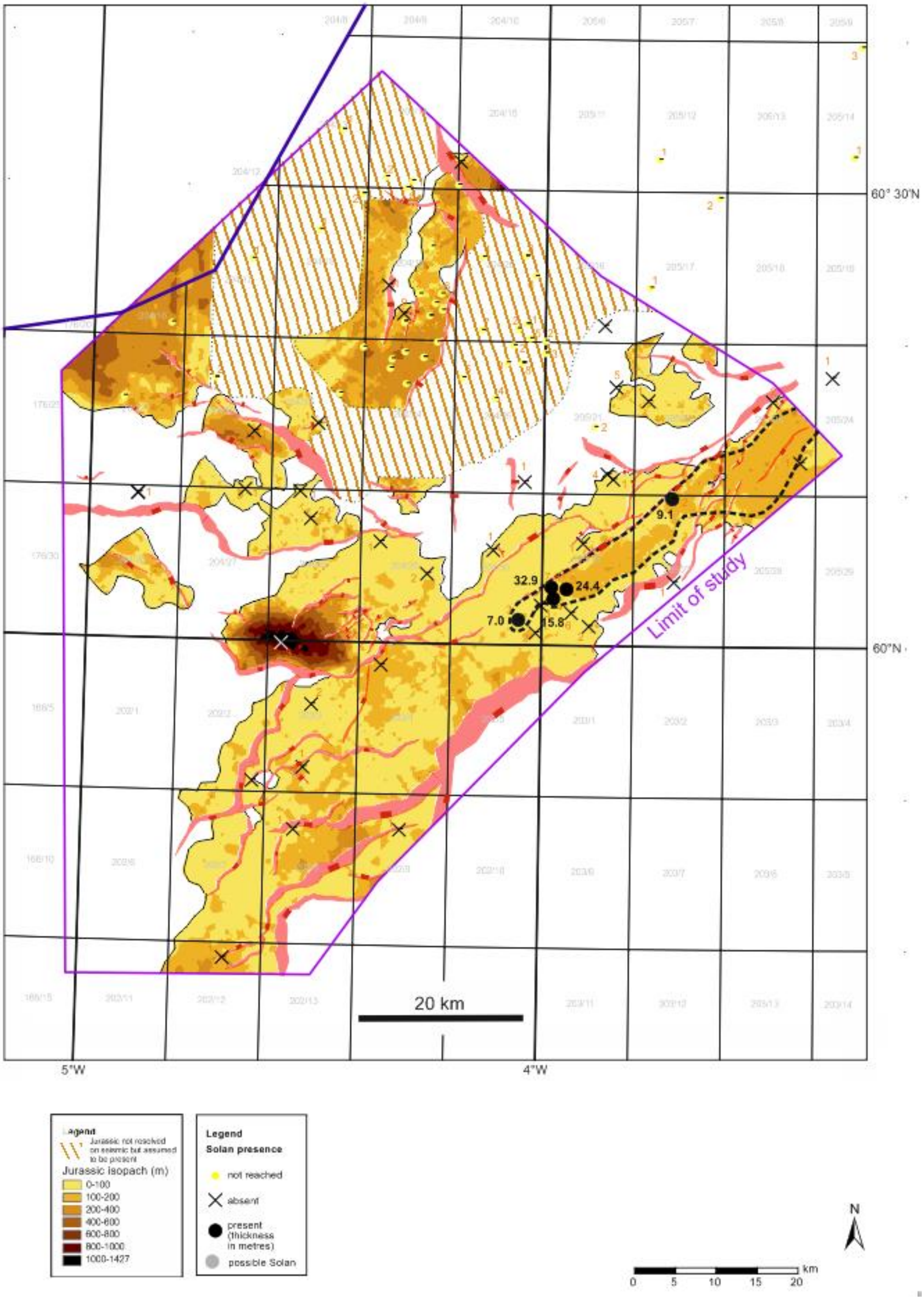

Figure 15 Distribution and thickness (m) of the Solan Sandstone Member in the study area.

8 Discussion of the Faroe-Shetland region during the Jurassic

8.1 INTRODUCTION

Section 2 introduced the proto-rift debate that surrounds the development of the NE Atlantic rift system. In simplified terms the debate either suggests that the Arctic and proto-Atlantic rift systems remained separate until the Late Jurassic or even Mid-Cretaceous, with only fragmented, discontinuous connections prior to this time (Roberts et al. (1999) and Doré et al. (1999)) or that a fully connected NE Atlantic rift system developed much earlier, from the Permian onwards (Ziegler, 1988; Coward et al., 2003; Pharaoh et al., 2010).

The Jurassic depositional environments and the distribution and thickness of the sediments of this age are key to solving this debate. The following text integrates all of the three individual studies undertaken in this project and considers the results in terms of the tectonic evolution of the area.

8.2 EARLY JURASSIC

The Early Jurassic in the Faroe-Shetland region is generally considered to be dominated by post-rift thermal subsidence and patchy deposition along the Triassic NE-SW trending topography, potentially, at times, linking or partially linking the proto-Atlantic and Arctic rift systems (Coward et al., 2003; Ritchie and Varming, 2011; Stoker et al., 2016). To the south, in the Hebrides, the Early Jurassic succession displays a marked asymmetry suggestive of footwall uplift during the Early Jurassic (Fyfe et al., 1993; Evans, 2013), with Morton (1989) providing evidence for renewed rifting during the Sinemurian to Toarcian in the Sea of Hebrides and Little Minch Basins. The first phase of true seafloor spreading was taking place in the central Atlantic, to the south of the Gibraltar fracture zone (Knott et al., 1993).

In the Faroe-Shetland region, proven instances of Lower Jurassic material are scarce. The most significant Lower Jurassic sequence is found in the West Solan Basin, where 770 m of Lower Jurassic sediments are proven in the well 202/03a-3. Previous work postulated that Lower Jurassic sediments were present in several wells located in the study area. Ritchie et al. (1996) and Ritchie and Varming (2011) interpreted Lower Jurassic sediments in wells 202/04-1, 206/05-1 and 206/05-2. With the exception of 202/04-1 which did not have any core material, the other wells have been re-dated through this study.

Ritchie et al. (1996) and Ritchie and Varming (2011, p.105) interpret the Stack Skerry Formation sediments in well 202/03a-3 as “shallow marine inner shelf deposits” and the Sule Skerry portion as “a shallow marine deposit”.

Dodd (2018) described the 17 m of core assigned to the Stack Skerry Formation (well 202/03a-3) as deposited in a marine, shelfal environment. The presence of turbiditic sands within the sequence indicated a period of lowstand during deposition.

New sedimentological analyses on the overlying Sule Skerry material (36 m of core) in well 202/03a-3 re-interpreted the sequence as being deposited in a deep marine, likely bathyal, setting. Evidence for this interpretation includes the presence of a *Raricostatum* ammonite fauna, which confirms a Late Sinemurian age and which are only found in fully marine basins. This interpretation opposes the views of Ritchie and Varming (2011, p.105) which defined the Sule Skerry Formation as “a shallow marine deposit”.

The aforementioned depositional environments support a model in which marine conditions were prevalent in West Solan Basin during the Early Jurassic. This in turn, supports the regional models which propose relatively well-established extensive marine connections through the Arctic and proto-Atlantic rift systems from the early Mesozoic onwards, such as Haszeldine et al. (1987) or Coward et al. (2003).

The presence of deep marine sediments albeit in only isolated, preserved locations support the theory that there was active extension in the Early Jurassic (Dean et al., 1999). The presence of *Raricostatum*-type ammonites in particular suggest a significant connection between the Arctic, proto-Atlantic and Tethyan regimes (see section 4.1.2). The results can be combined with other studies such as Booth et al. (1993) who used apatite fission track analysis to suggest the region underwent significant uplift and erosion in the Mid and Late Jurassic. He postulated that more than 1.5 km of Lower Jurassic material was removed from the Solan Basin, which would account for the lack of proven Jurassic strata across the study area.

8.3 MIDDLE JURASSIC

Seafloor spreading began in the central Atlantic during the Aalenian, as did the extension of the Arctic rift into the North Sea and a number of ‘pulses’ of Arctic rifting which affected the Faroe-Shetland region (see Figure 8 of Ritchie et al., 2011). Doré et al. (1999) and others describe a significant amount of uplift and erosion during this period, while Haszeldine et al. (1987) consider the Faroe-Shetland Basin proper to have undergone extension and relatively deep marine conditions.

Middle Jurassic strata are only confirmed within one well in this study (206/05-1). Ritchie and Varming (2011) did describe 23.8 m of sandstone in well 205/20-2 in the West Shetland Basin as Middle Jurassic Bajocian to Callovian in age but this work finds that these sands are Late Jurassic in age (Riding 2018c) and have been subsequently assigned to the Rona R3 facies. Ritchie and Varming (2011) also described 246 m of mudstones in the well 204/22-1 on the Judd High as Middle Jurassic, but no core material for this well was available for this study.

The type section for the Middle Jurassic was defined by Ritchie et al. (1996) in well 206/05-1 (in the Foula Sub-basin of the Faroe-Shetland Basin) as the Heather Formation (partly Upper Jurassic). Haszeldine et al. (1987) dated this sandstone as Bathonian to Oxfordian based on the presence of a single *Mancodinium semitabulatum* dinoflagellate cyst

In this study, the 3m of indurated sandstone from the type well 206/05-1 has also been assigned to the Heather Formation but no evidence was found to accurately age date the sediments due to the fact that all of the samples for the palynology were barren (Riding 2018g).

Based on the sedimentology work from the one existing core, the most likely depositional environment for the Middle Jurassic is a high-density turbidite flow which was deposited in a deep marine setting (although a deep lacustrine setting may be possible). This interpretation favours the Haszeldine et al. (1987) model where he states that the sands were deposited in a submarine fan setting and related their deposition to a period of extensional faulting during the Middle Jurassic.

However, it is not possible with the limited well data to disregard the alternative models that have been postulated for the region during this time period. For example Ritchie and Varming (2011) consider the overall Heather Formation succession to have been deposited in a shelfal, marine setting with oxygenated bottom waters. A series of deep, fault-controlled, lacustrine or isolated marine basins would provide a similar depositional setting without necessitating an extensive marine connection across the region. It is likely that even if the Faroe Shetland Basin developed deeper marine conditions, the more marginal basins and highs, such as the Solan Basin, underwent uplift and erosion in the Middle and Later Jurassic (Booth et al., 1993). In the Hebrides, the Middle Jurassic is characterised by a major hiatus in the Toarcian followed by deposition in relatively shallow water and non-marine conditions, also suggestive of significant periods of regional uplift and non-deposition (Fyfe et al., 1993; Hudson and Trewin, 2002).

Unfortunately the lack of data and evidence within the study area for the Middle Jurassic precludes a definitive answer to the amount of rifting and extension that occurred within this time period. Middle Jurassic sediments outside of the study area need to be identified and sampled to obtain a more extensive database prior to addressing the problem.

8.4 LATE JURASSIC

The latest Middle Jurassic and Late Jurassic saw significant extension and rifting along the Arctic and proto-Atlantic rift systems, with most authors considering the formation of a fully marine, linked connection between the two by the end of the Jurassic, extending from the Norwegian Vøring Basin south to Rockall and the Porcupine basins. (Ritchie and Varming, 2011; Ritchie et al., 2013). Doré et al. (1999), however, consider that extension during the Jurassic remained fairly restricted along an east-west trend, and that the rift systems were not fully linked until the Cretaceous, when true Atlantic seafloor spreading drove NW-SW extension.

In the Faroe-Shetland region, there is also disagreement about the amount of extension during the Late Jurassic. Verstralen et al. (1995b) define and describe younger Upper Jurassic sandstones in the Faroe-Shetland Basin as Rona Member, and as being deposited in a variety of environments that transition from sub-aerial fan deltas into shoreface/shallow marine, and finally deeper-marine environments, in response to a Late Jurassic regional transgression. According to Verstralen et al. (1995a and b), deposition of the shallower coarse clastic facies was mainly controlled by marine transgression of residual islands, probably elevated by footwall uplift along fault bounding highs such as the West Shetland, Rona and Judd highs. Haszeldine et al. (1987) and Hitchin and Ritchie (1987) interpret some of the same sandstones as forming within long-lived turbiditic fan systems, and postulate the presence of an extensive, marine environment which existed in in the Faroe-Shetland Basin, potentially throughout the Jurassic.

The Upper Jurassic strata are relatively widespread and in this study have been assigned to the Kimmeridge Clay Formation (KCF), with subdivision into the Rona and Solan Sandstone members (Verstralen et al., 1995a). From the new sedimentological work of Dodd (2018) and palynological analysis of Riding (2018a-i) and Thomas (2018a-j) a variety of depositional environments have been interpreted:

The Rona R1 sandstones are interpreted as being deposited within a meandering river system and confirm subaerial conditions within the North Rona Basin during the Late Jurassic.

The Rona R2 sandstone are defined as fan delta or debris flow deposits indicative of subaerial to shallow water/shoreface environments. . These immature debris flows within the R2 facies have been postulated as potentially resulting from fault activation (McPherson et al. 1987). They have been postulated to have resulted from fault activations (McPherson et al. 1987). There is a general lack of marine taxa. The new interpretation is in general agreement with that of Verstralen et al. (1995a), who consider these coarse clastics of the Rona Member to have been deposited initially in a subaerial environment, and to have been locally sourced due to footwall uplift. As is the case for the R1 facies above, the new Rona R2 interpretations confirm the existence of subaerial conditions within the North Rona and Solan basins during the Late Jurassic and suggests the presence of localised emergent highs in area during this time. The nature of the deposits also supports the existence for active tectonic influence in the Late Jurassic.

The Rona R3 facies is identified by Dodd (2018) as marginal marine deposits. There is a mixture of marine and non-marine taxa. This interpretation has not been previously described by other authors but supports the gradual inundation of the Solan/North Rona Basin area in the Late Jurassic.

The Rona R4 facies is interpreted to be shoreface or shallow marine deposits with evidence of wave-worked sandstones and minor mudstones, sometimes interbedded with storm deposits; with some evidence for cycles of progradation and migration. R4 deposits are often observed to interdigitate with the overlying Rona R2 deposits suggesting a vertical, and therefore spatial link between the shoreface/littoral setting and the in-draining fan delta. R4 deposits (defined here in wells 202/03a-1 and 204/27a-1) are described by Verstralen et al. (1995a) as 'Facies D' of the Rona Member, and interpreted as highly concentrated turbidite deposits.

The Rona R5 is described as a shallow marine to shelfal deposit which shows a progressive deepening of the depositional environment. Palynological analyses confirm a marine environment.

Verstralen et al. (1995a) classify the same section as their 'Facies E, F and G', deposited in lower shoreface to shallow marine to shelfal environments. The two interpretations are in agreement and indicate an overall transgressive succession.

The Solan Sandstone Member is considered to be deep marine turbidites or debris flows. There is evidence to suggest that deposition occurs at a significant distance from the shelf, which can be used as evidence to suggest a well-established deep marine environment in the East Solan Basin by the Late Jurassic.

The mudstones of the Kimmeridge Clay Formation are confirmed in this work to show deposition in deep marine anoxic environments, with evidence to show a major transgression during this time.

The Ridge Conglomerate Member is described as a sub-aqueous debris cone or debris flow and is considered to originate from a local sediment source. This is in agreement with the interpretation of Haszeldine et al. (1987), who describe the deposits as submarine scree deposits related to an (unidentified) active fault scarp. Given that the sedimentological and palynological analysis of the older parts of 206/05-1 carried out here suggest a relatively deep depositional environment from the Middle Jurassic onwards, a local, tectonically controlled submarine source of coarse clastic conglomerates seems reasonable to account for their presence.

Figure 16 summarises the various depositional environments encountered in the Rona Member of the Upper Jurassic.

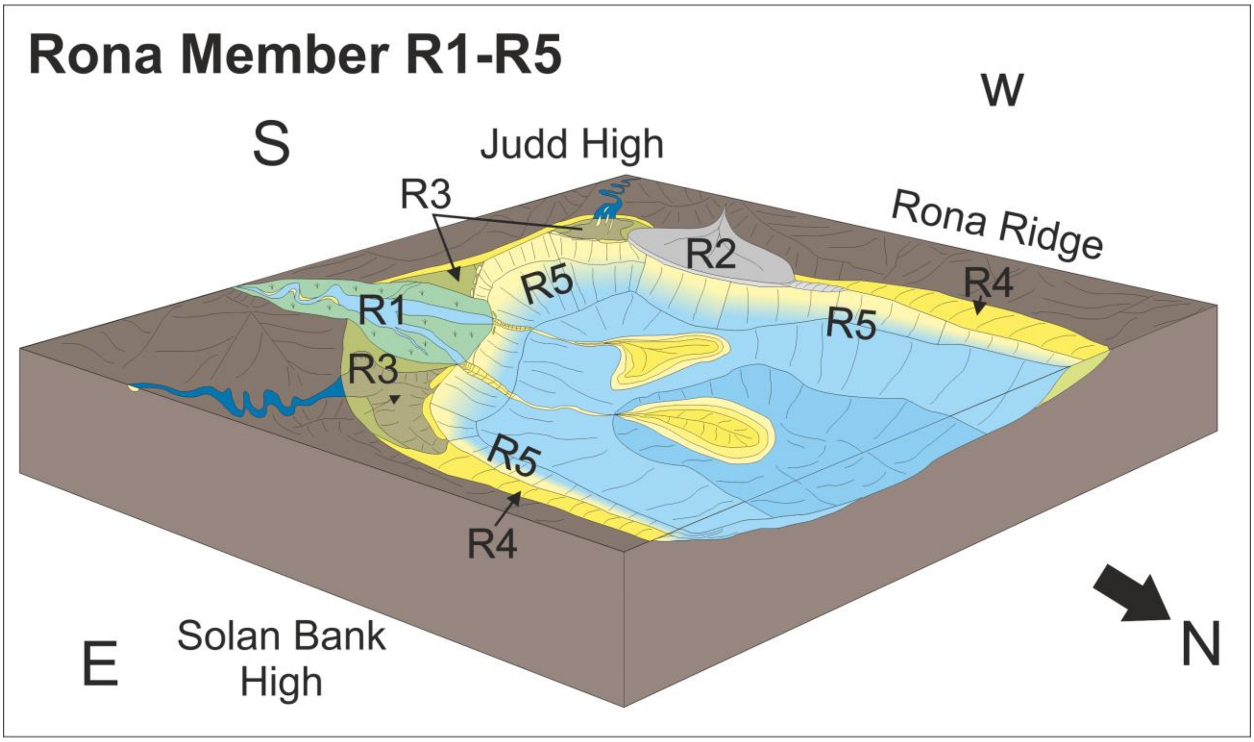

Figure 16 3D block diagram of the Rona Member R1-R5 facies in the Late Jurassic. R1 = Fluvial, R2 = Fan Delta, R3 = Marginal Marine, R4 = Shoreface/Littoral, R5 = Shallow Marine

Based on this study, it is apparent that there is significant variation within the depositional environments of the Upper Jurassic with evidence of marine, shallow water and fluvial conditions being observed throughout the study area. In particular the subaerial nature of the Rona R1 sandstones and Rona R2 sandstones rule out extensive continuous deep water connections across the whole of the Faroe-Shetland region instead suggesting that localised emergent highs and shallower water conditions were prevalent.

The interpretation from this study is broadly in agreement with the model for the Upper Jurassic produced by Verstralen et al. (1995b). He defined and described the younger Upper Jurassic sandstones in the Faroe-Shetland Basin as being deposited in a variety of environments that transition from sub-aerial fan deltas into shoreface/shallow marine, and finally deeper-marine environments, in response to a Late Jurassic regional transgression. According to Verstralen et al. (1995a and b), deposition of the shallower coarse clastic facies was mainly controlled by marine transgression of residual islands, probably elevated by footwall uplift along fault bounding highs such as the West Shetland, Rona and Judd highs.

8.5 EARLY CRETACEOUS

The Early Cretaceous in the Faroe-Shetland region saw the northward propagation of the proto-Atlantic rift system across the area, and associated NW-SE trending extension between Greenland and Eurasia. A series of basins developed all along the proto-Atlantic margin from the Bay of Biscay to the Barents Sea, and included the Faroe-Shetland, North Rona, West Shetland and Solan Basins (see Stoker and Ziska, 2011, and references therein). This study did not look in detail at the Cretaceous although three wells in this study were found to contain Cretaceous-age Cromer Knoll Group sediments 204/19-1; 205/21-1A and 205/26a-2. In well 204/26a-2 (in the Solan Basin), Cromer Knoll Group material is described as argillaceous siltstones and very fine-grained sandstones, interpreted as deposited in a marginal marine or shoreface setting. These latter shallow-water deposits described in 204/26a-2 are similar to those described as Rona R3 or R4 above, but palynological analyses put their age as Early Cretaceous. These findings are discussed in more detail in the two reference documents (Dodd 2018 and Riding 2018e).

9 Review of existing analysis of organic geochemistry from oil and gas shows in the Faroese sector

There are nine offshore exploration wells on the Faroese Continental Shelf, but none of these have penetrated strata older than the Palaeocene. However, oil, or oil or gas traces have been found in six of the wells. The six offshore wells containing hydrocarbons are numbers 4, 6, 7, 8, 10 and 12 on *Figure 16*. Additionally, a Synthetic Aperture Radar (SAR) seep survey from 1996 together with seabed core samples from 1995, 2005, 2006 and 2011 show indications on source rock seeps covering a large part of the Faroese Continental Shelf. Outcrop samples from onshore Faroe Islands and the deep scientific well Lopra-1 (No. 3 on *Figure 17*), drilled in 1981 and deepened in 1996, contained traces of hydrocarbons indicating the possibility of a deeper lying source rock in the area.

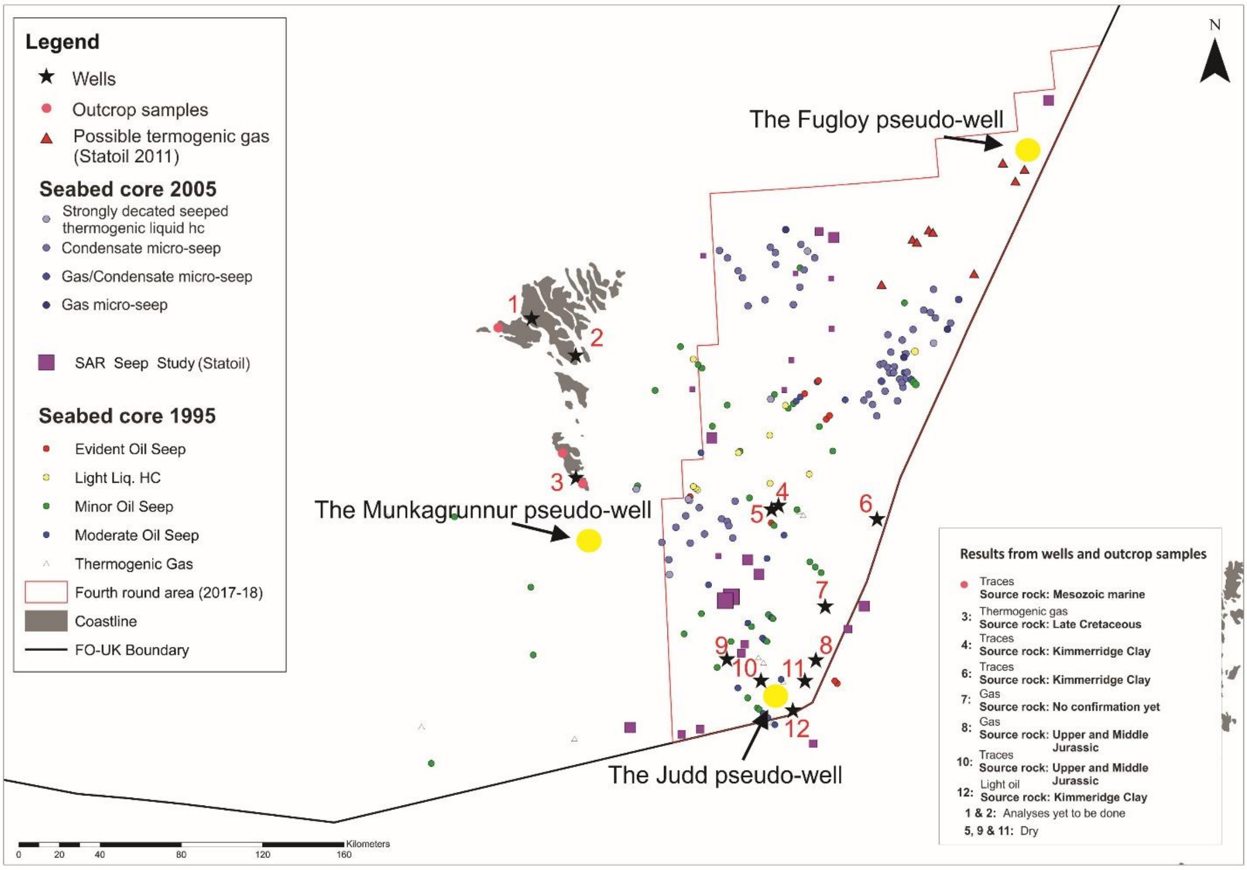

Figure 17 Summary map containing all seep samples, collected by different companies, which have been carried out on the Faroese Continental Shelf. Additionally, source rock information from wells and outcrop from the Faroe Islands and the Faroese Continental Shelf, are presented. (from Eidesgaard 2017; original figure courtesy of Statoil.)

Organic geochemical analyses where made on the hydrocarbons found in the six offshore wells (Eidesgaard, 2017).

- A poor quality oil sample from the core in well 6004/12-1 (No. 8 on *Figure 17*) indicates the hydrocarbon shows to come from a mixed Middle and Upper Jurassic source system. The oil is clearly correlatable to the dual Jurassic source system seen in the Quadrant 204 development area and very similar to fluids from the Schiehallion Field.
- In well 6004/16-1 (No. 12 on *Figure 17*), the presence of a hydrocarbon system has been proven and the source rock is assumed to be the Kimmeridge Clay Formation.
- In well 6005/15-1 (No. 10 on *Figure 17*), samples show indications of both Upper and Middle Jurassic source rock.
- In well 6004/8a-1 (No. 7 on *Figure 17*), analyses where made in order to estimate the maturity of the generating sediments, the source rocks, but no attempt to establish which source rocks.
- In well 6104/21-1 (No. 4 on *Figure 17*), biological marker profiles for extracts between 2382 m and 4155 m (except 3912 m) were investigated and they all appear effectively identical and consistent with a mature hydrocarbon signature generated from a marine siliciclastic source rock. It is possible that this represents traces of migrated hydrocarbons in the well, but the absence of indicators in the extract yields together with pyrolysis data suggest it must be at a very low level. The potential of drill mud additives/rig contamination cannot be discounted. In the sample at 3912 m depth the biomarker 28, 30-bisnorhopane, which can be found in the Kimmeridge Clay Formation, was also found. Additionally, this biomarker was also found in the Vágar sample onshore the Faroe Islands (light red circle to the north onshore the Faroes on *Figure 17*).

- The only indications on oil traces in well 6104/25-1 where based on the heavy components (C6-C7) which were present at top of the Eocene Hildasay Member (No. 6 on *Figure 17*) and they could not be discarded as possibly being due to contamination.

Based on the biological marker distribution, the oil found as traces in the Faroese basalt samples (light red circles on map in *Figure 17*) was generated by a marine shale source rock perhaps with a slight marly character.

Most likely the traces of crude oil found in the samples from the Palaeocene Beinisvørð Formation on the Faroe Islands indicate the presence of a Mesozoic marine source rock beneath the volcanic succession.

Traces of hydrocarbons were also found in the Lopra-1 well (No. 3 on *Figure 17*). The oil traces encountered in the Lopra-1 well were generated from a marine, siliciclastic source rock with a predominance of marine algal organic matter.

Based on the possibility of Kimmeridge Clay Formation and the Middle Jurassic Heather Formation source rocks to be present in the Faroes sector, 1D basin modelling on six chosen areas was attempted in 2016 and 2017 (Eidesgaard 2017). The modelled Jurassic source rocks at the Judd pseudo-well (see *Figure 17*) are still in the thermal maturity window at the present-day, though most of the generation took place in the Palaeocene and Eocene. The source rocks at the Munkagrunnur and Fugloy pseudo-wells are overmature at the present-day.

There is geochemical evidence from widely scattered wells and outcrops that points to the presence of a Jurassic source rock with an extensive distribution across Faroese waters, but the sparsity of these data precludes further analysis at this stage.

10 Conclusions

This project established a database of Jurassic well data and identified 19 cores which were used to undertake the detailed assessment of the sedimentology and biostratigraphy. Based on the results of these two studies, new interpretations of the depositional environments were produced. Simultaneously a seismic interpretation project across the study area was performed and the resultant depth, fault and thickness maps were incorporated into new sediment distribution maps. Well correlations and new range charts were also created for the Jurassic interval of the Faroe Shetland region. The final task was to integrate the various results into a tectonic framework and to discuss the implications of the new work with regard to the existing proto-rift models of the area.

Based on the new sedimentological and palynological analyses, a variety of depositional environments were identified in the Faroe-Shetland region during the Jurassic which can be summarised as follows:

The interpretation of the Early Jurassic sediments proved the existence of marine conditions across the study area. The presence of *Raricostatum*-type ammonites suggested that a significant marine connection to the southerly localised seaways existed during this time. The presence of deep marine sediments albeit in only isolated, preserved locations also supported the theory that there was active extension in the Early Jurassic.

The Middle Jurassic interpretation suggested that sands deposited in a submarine fan setting could potentially be related to extensional faulting. However the paucity of both well and seismic data for the Middle Jurassic reduces the confidence in this interpretation and it must be noted that there are alternative models which would fit the available information without invoking an extensive marine connection across the region.

The Late Jurassic can be subdivided into several depositional environments: meandering fluvial (Rona R1); debris cone or fan delta (Rona R2); marginal marine (Rona R3); shoreface/littoral (Rona R4) and shallow marine (Rona R5). Mudstones of the Kimmeridge Clay Formation were deposited in deep marine, sometimes anoxic conditions, while Solan Sandstone members are considered to be deep marine turbidites or debris flow deposits. From these varied environmental observations, it is most likely that this area underwent periods of localised uplift, erosion and deposition forming a series of emergent highs across the study area.

The results of this study were compared to the existing literature and models.

The suggestion of a marine environment in the Early Jurassic is in agreement with the majority of the regional models which propose relatively well-established extensive marine connections through the Arctic and proto-Atlantic rift systems from the early Mesozoic onwards, such as Haszeldine et al. (1987) or Coward et al. (2003).

The Middle Jurassic report's sedimentological interpretation is in relative agreement with that of Haszeldine et al. (1987) who interpret the sands as deposited in a submarine fan setting, potentially related to extensional faulting. Unfortunately the lack of data from the Middle Jurassic has prevented a definitive answer about the rifting and it has not been possible to make any conclusions about the timing of the linkage between the Artic and proto-Atlantic rift systems.

The current work for the Late Jurassic is similar to the model of Verstralen et al. (1995b) who defined and described the Upper Jurassic sandstones as being deposited in a variety of environments that transition from sub-aerial fan deltas into shoreface/shallow marine, and finally deeper-marine environments, in response to a Late Jurassic regional transgression

The work has shown that a simple tectonic model which invokes a continuous, extensive marine environment throughout the whole of the Jurassic is probably too simplified for the region. The Jurassic study instead suggests a more complex tectonic history with significant periods of localised uplift, erosion, and deposition, variable across individual basins and sub-basins in relatively close proximity.

11 Key Findings:

11.1 STRUCTURAL

- Compared to overlying and underlying successions, the Jurassic, mainly represented by the Upper Jurassic, is relatively thin and there is little evidence of thickening of the Jurassic succession against faults;
- The very thick Lower Jurassic succession in the West Solan Basin is a remnant of widespread deposition during Early Jurassic (and possibly Mid Jurassic) times;

  The Lower Jurassic is overlain by relatively thin, but complete, Upper Jurassic Kimmeridge Clay Formation, suggesting that widespread erosion must have occurred prior to Late Jurassic deposition. This erosive episode removed much of the Lower, and most of the Middle Jurassic strata.
- In the NE-SW trending West Solan Basin, the thick Lower Jurassic succession was preserved in a downthrown E-W trending basin. The basin is located at the juxtaposition of two major fault trends. The identification of this possible transtensional basin should shed light on the structural evolution of the area;
- The Top and Base Jurassic TWTT maps and seismic data in the West Solan Basin provide evidence of compression between the post-Lower Jurassic to end-Lower Cretaceous.

11.2 SEDIMENTOLOGICAL AND PALYNOLOGICAL

- This study finds new evidence to confirm the presence of relatively deep marine conditions in the West Solan Basin, with sediments in well 203/03a-3 confirmed as Late Sinemurian or older in age (Thomas 2018b).

  1. Specimens of *Echioceras* sp. and *Crucilobiceras* sp. (ammonites) from the Stack Skerry Formation of well 202/03a-3 identified by Dr Kevin Page of Plymouth University give a tightly constrained age of Late Sinemurian, Raricostatum Zone, Raricostatoides Subzone. This is by far the most northerly occurrence of these genera, indicating an open marine connection between Western Europe and the Faroe-Shetland Basin.
  2. Sediments of the Stack Skerry Formation for well 202/03a-3 record deposition within a marine shelfal environment. The overlying Sule Skerry Formation records a Deep(er) marine, anoxic setting, with little in the way of clastic input in the basin during this time.

- Middle Jurassic sediments in the well 206/05-1, in the Faroe Shetland Basin, is also found to be deposited in a submarine fan setting, potentially in a deep marine environment, but must be considered in the context of studies which show strong evidence for uplift and erosion in the Mid Jurassic within the Solan Basin (e.g. Booth et al., 1993).

- Upper Jurassic sediments are more widespread and, in this study, are interpreted to show a variety of depositional environments through time, with an overall deepening trend.

1. Palynological analysis provides age determinations for the Kimmeridge Clay Formation including the Rona, Solan and Ridge Conglomerate members. However, there is no new evidence to distinguish Rona and Solan on age.
2. On palynological evidence, a tentative new age determination is assigned to sandstones at 2578.7 to 2596.75 in well 205/26a-6. This interval is now regarded as Late Jurassic or Early Cretaceous Rona R1 but was previously assigned to the Triassic. Similarly sandstones at 3169.84 to 3172.49 m in well 206/05-2 are now regarded as Volgian or younger Rona R3, but previously Lower Jurassic.

- The Late Jurassic-aged Rona Member is represented by a large proportion of the core investigated for this study and has been separated into five different depositional "facies":
    1. Rona R1 (Fluvial); Rona R2 (Fan Delta); Rona R3 (Marginal Marine); Rona R4 (Littoral/Shoreface); and Rona R5 (Shallow Marine);
    2. The subdivision of the Rona Sandstone Member presented here provides evidence for fluvial to nearshore/shallow shelf environments, and highlights the complex evolution of the Solan Basin/Rona High region, as described by authors such as Verstralen et al. (1995a). Material from the Faroe-Shetland Basin proper shows a more straightforward history of transgression along the lines of that presented by Haszeldine et al. (1987);
    3. During the Late Jurassic, the Solan Sandstone Member (and the Ridge Conglomerate Member) was deposited in a deep-marine, turbidite fan environment;
    4. In this conceptual depositional model for the Early Jurassic, we suggest that the turbidite fan, which deposited the Solan Sandstone Member, may have been coeval with the deposition of the Rona Member (therefore could be considered as the "R6" facies);
    5. Unfortunately, new age determinations, completed as part of an accompanying study have failed to provide additional information concerning the relative ages of the Rona, Solan Sandstone and the Ridge Conglomerate Members.

A summary of the key changes to the Jurassic succession penetrated in wells in the area are shown in *Table 11* below.

205/26a-2	Top Triassic is moved down to below a shale at 2163.8 m (7099 ft) based on interpretation of core as Rona R1 and early Kimmeridge age determinations at 2148.8 m (7050 ft) and 2158.0 m (7080 ft) (BGS 1983). It is also influenced by a correlation with a comparable unit in well 205/26a-6 which has been re-dated as 'Late Jurassic or younger'.
205/26a-6	Top Triassic is revised at 2596.9 m (8520 ft) based on new age dating that assigns a 'Late Jurassic or younger' age at 2592.93 and 2593.97 m (but 'Indeterminate' ages below that). The base of a shale (correlated with a similar one in 205/26a-2) is taken as the base of the Jurassic.
205/20-2	'Middle Jurassic' succession re-dated Upper Jurassic based on (a) the recognition of facies as Rona R3 and (b) a Kimmeridgian to Mid Volgian age at 2968.08 m (9737.8 feet) and 2964.97 m.
205/26-1	Weathered granite beneath Base Jurassic boundary re-interpreted as Rona R4 beach conglomerates taking the Top

	Basement pick down slightly (to c.2104.6 m, 6905 ft) from that on the composite log (2103.1 m, 6900 ft).
205/21-1A	This study confirms as Rona Member R2 the succession interpreted as Rona Member by Ritchie and Varming (2011). The overlying shale ('?JU') on the composite log (4392-4405 ft) is assigned to the Kimmeridge Clay Formation (interpreted as Lower Cretaceous by Ritchie and Varming (2011)).
209/12-1	Core from a previously undivided Upper Jurassic unit has been interpreted as Rona R3 facies.
206/05-2	Dating from core samples indicates that at least part of this 'Lower Jurassic' unit is of 'Volgian or younger' age (Thomas 2018j) and has a facies interpreted as Rona R3 (Dodd et al. 2018). A new Top Lower Jurassic is placed at c. 3200.4 m (10,500 ft) giving a Rona thickness of 77.7 m and a thinning of the ?Stack Skerry Formation from 338.6 m to 260.9 m.

Table 11 Key new interpretations of the Jurassic succession based on sedimentological and Palynological analyses

11.3 IMPLICATIONS FOR HYDROCARBON EXPLORATION

- The location of the Upper Jurassic, Kimmeridge Clay Formation source kitchen may be to the west of the Westray High.
- An untested hydrocarbon play has been identified. The play is strengthened by proposed location of source rocks.
- 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 in the Stack Skerry Formation (reservoir lithologies); along with dark grey, organic-rich, anoxic mudstones in the Sule Skerry Formation (source or sealing lithologies). Given this, there may be potential for an Early Jurassic-aged hydrocarbon play West of Shetland.
- The Upper Jurassic, Rona R4 facies (littoral/shoreface) is composed of a relatively clean, fine to medium grained, thickly bedded sand-prone succession, making it an ideal candidate to present as a reservoir target. Furthermore, the predictability of this facies is relatively good, with littoral/shoreface deposition, generally draping the basin margin architecture or forming beach system along emergent, mid-basin high structures.
- The Rona R3 facies (marginal marine) comprises a thickly interbedded succession of sandstone and mudstones. The mudstones are particularly organic-rich, whilst there is a relatively high organic content within most of these sediments. Consequently, the Rona R3 facies could present as a potential source rock in areas/basins where the Kimmeridge Clay is not present/immature for oil generation.

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12 Appendices

12.1 APPENDIX A SEDIMENTARY CORE PANELS (SEE SEPARATE PDF)

12.2 APPENDIX B WELL LOG CORRELATION DIAGRAMS (SEE SEPARATE PDF)

12.3 APPENDIX C DELIVERABLES

- Standalone seismic interpretation report (Quinn, 2018),
- Detailed biostratigraphical reports for each of the 19 wells studied (Riding, 2018a-i; Thomas, 2018a-j).
- Summary spreadsheet of biostratigraphical results.
- Standalone sedimentological report (Dodd et al. 2018) including detailed sedimentological logs for all 19 wells studied, with biostratigraphical samples and their summary results added. Also summary logs.
- Spatial data in ArcGIS format containing grids and shapefiles. This includes well locations, seismic line/survey locations, stratigraphic surfaces, faults and limits. Grids cover – top and base Jurassic TWTT/depth (m) and Jurassic isochore (ms/m??),
- Stratigraphic database of wells studied with depths, thicknesses, and changes from past interpretations (see notes below). Revised range charts for all wells sampling Jurassic strata west of Shetland. Geophysical well log correlations between wells in the focus area.
- Final summary report including: stratigraphic framework, sedimentology, seismic interpretation; range charts; well correlations; stratigraphic framework; tectonic evolution; organic geochemistry.

Notes. The FSC 3 Jurassic Stratigraphic Database contains information regarding the tops, bottoms, age and thickness of the Jurassic successions examined within this study, and what they are based on. Depths are measured depths below Kelly Bushing (kb). The database also records if the age of Jurassic material was adjusted based on this work (indicated by a 'YES' in the 'New Dates from FSC 3 Results' column) or if a depth pick was adjusted (indicated by a 'YES' in the 'New Pick from FSC 3 Results' column). The reference column indicates which sources were used to provide depths and ages, including 'FSC 3 Results' for those changed related to this work.

13 References

British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: https://envirolib.apps.nerc.ac.uk/olibcgi.

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