Sedimentology and sequence stratigraphy of shallow-marine, coarse-grained siliciclastic deposits in the southern Utsira High: the Late Jurassic intra-Draupne Formation sandstones in the Johan Sverdrup Field (Norwegian North Sea).

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ABSTRACT

Thin, condensed coarse-grained shallow-marine successions can be difficult to describe and interpret, especially in the subsurface because they commonly lack finer grained intervals which are typically associated with sequence stratigraphic surfaces. This lack of mudstones and siltstones means that they also typically make excellent reservoir intervals. The Oxfordian to Volgian intra-Draupne Formation sandstones in the Johan Sverdrup Field, southern Utsira High, represent such a system. This study presents a new, basinwide sequence stratigraphic model that unravels the detailed depositional history of the succession and places its formation

within a regional Late Jurassic tectonostratigraphic framework. The succession is comprised of four parasequences deposited following a regional Kimmeridgian marine flooding event. Sediments were mainly supplied through Haugaland sourced fan deltas and longshore currents reworking the Avaldsnes High. The first parasequence shows a distinctive suite of facies consisting of fine-grained and mud-rich bioturbated sandstones deposited in a protected back-barrier lagoon. Subsequent parasequences lack fine grained sediments and are dominated by bidirectional cross stratified, coarse-to-very coarse sandstones and gravels deposited in a tidal strait. A progressive reduction of fault related subsidence in the Middle Volgian along with Late Volgian-Ryazanian sea level rise and inversion of pre-existing structures, promoted backstepping of the feeder systems, sediment starvation and the progressive deposition of the black and green-red shales of the Draupne and Asgard formations. This study accounts for features previously unidentified in the basin and which have implications for understanding the deposition of coarse-grained shallow marine successions around the Utsira High and other transgressed basement highs.

INTRODUCTION

The Late Jurassic period in the North Sea was one of the most prolific time intervals for the accumulation of source and reservoir rocks (Cornford, 1998; Gautier, 2005). A period of rift-related structural reconfiguration and widespread marine incursions promoted the development of a variety of shallow-to-deep marine sedimentary environments strongly influenced by inherited and syn-rift palaeotopograhy: tide-dominated deltas and coastal spits of the Sognefjord Formation (Dreyer et al., 2005), storm-influenced shorefaces of the Fulmar and Ula formations (Johnson et al., 1986; Howell et al. 1996; Baniak et al., 2014), shelf sand ridges of the Rogn Formation (Chiarella et al., 2020) and fan deltas, fault-block submarine fans and channels of the intra-Draupne Formation sandstones (Partington et al., 1993; Nøttvedt et al., 2000; Jackson and Larsen, 2010; Jackson et al., 2012; Henstra et al., 2023). The intra-Draupne Formation sandstones, in this case study, are part of an Oxfordian to Volgian marine clastic package present throughout the Norwegian North Sea which typically occurs close to the margins of fault blocks, structural highs and major landmasses (Henstra et al., 2023; Tillmans et al., 2021). In 2010, the intra-Draupne Formation sandstones were discovered on the Utsira High, a long-term basement high located in the South Viking Graben giving rise to the Johan Sverdrup Field, one of the largest hydrocarbon discoveries made in the Norwegian Continental Shelf (NCS), (Rønnevik et al., 2017; Ottesen et al., 2022). The intra-Draupne Formation sandstones in the Johan Sverdrup Field were deposited in a shallow marine environment, with grainsizes ranging mostly from coarse sandstones to pebbles and virtual no fine grained component (Olsen et al., 2017; Ottesen et al., 2022), These type of successions are relatively uncommon in the geological record, and are often more challenging to describe and interpret, than their finer-grained counterparts, especially in the subsurface. Sedimentological studies dealing with this type of successions are scarce, examples include the Viking and Cardium formations in the Cretaceous of Canada (Hart and Plint, 1995; MacEachern et al., 1998; MacEachern and Hobbs, 2004), the Neogene-to-Quaternary palaeostrait deposits in the Calabrian Arc (Longhitano, 2013), the storm dominated Miocene Sandstone of Floras Lake in SW Oregon (Leithold and Bourgeois, 1984) and the Late Carboniferous shallow marine conglomerates in Spitsbergen (Nemec and Steel, 1984). The coarse grained character of the intra-Draupne Formation sandstones in the Johan Sverdrup Field, promotes a rather homogeneous aspect making a detailed sedimentological interpretation and sequence stratigraphic subdivision challenging (Ottesen et al., 2022). Additional challenges lie in it’s limited stratigraphic thickness, (5 to 40 m), which is below seismic resolution in the area. Despite these difficulties, previous studies of the Johan Sverdrup Field developed several depositional and palaeogeographical models interpreting the deposits as wave and current reworked fan delta fronts and regolithic soils which were subsequently redeposited as different types of submarine barforms across a shallow marine shelf (Olsen et al, 2017; Scott and Ottesen, 2018; Ottesen et al, 2022). While these works provided diagnostic criteria for interpreting the succession, there remains scope for further work that captures the facies variability and provides sequence stratigraphic correlations that form a basis for reconstructing the basin evolution and fill.

This study revisited the core material from the field and produced a higher resolution sedimentological description and interpretation than was previously available. These were used to develop specific depositional models and a basinwide sequence stratigraphic correlation which emplaces the formation within a Late Jurassic tectonostratigraphic framework. The results of this study allow improved understanding of the coarse-grained shallow-marine successions on the Utsira High and the surrounding area, which is currently under explored (NPD, 2022). They also have implications for understanding transgressive systems on basement highs around the world.

GEOLOGICAL SETTING

The Utsira High is located in the Norwegian North Sea, 150 km off the coast of Stavanger (Fig. 1A). The structure is a N-S trending basement high interpreted as a Devonian-Carboniferous exhumed core complex (Phillips et al., 2019; Serck et al., 2022). It is bounded by the Mesozoic, South Viking half graben to the West (Thomas and Coward, 1996), the extensional Stord Basin to the East (Biddle and Rudolph, 1988) and the NE-

SW oriented Ling Depression to the South (Olsen et al., 2017) (Fig. 1B). The tectonic evolution and stratigraphic record of the Utsira High is complex and reflects the superimposition of several events, spanning from the Palaeozoic to the Cenozoic, and separated by regional unconformities. These events include periods of Devonian extension and exhumation, Permo-Triassic rifting, uplift and collapse of the Mid-North Sea Dome in the Early-Middle Jurassic, Late Jurassic rifting and Late Cretaceous-Palaeocene inversion (Underhill and Partington, 1993; Jackson and Larsen, 2008; Serck et al., 2022; Ottesen et al., 2022). Most of the Utsira High remained subaerially exposed from Late Triassic until the Early Cretaceous (Riber et al., 2015). Sedimentation was limited to narrow belts around it's flanks and in intra-high grabens, such as the Triassic and Late Jurassic sedimentary infill of the Edvard Grieg and Johan Sverdrup Fields (Olsen et al., 2017; Mahmic et al., 2018; Ottesen et al., 2022). The basement of the Utsira High is mainly composed of 409-482 Ma old granites and granodiorites, and subordinate metamorphic rocks (Riber et al., 2015). Chemical and physical weathering altered and weakened the basement rocks while they were subaerially exposed, promoting the development of weathering profiles or regoliths (Riber et al., 2015). Deflation of the Mid-North Sea Dome during the Callovian, along with the onset of Late Jurassic rifting promoted rejuvenation of the highs and a regional transgression of the South Viking Graben (Jackson and Larsen, 2010) (Fig. 1C). Subsequent marine and fluvial processes were responsible for eroding and redepositing the regolith across the Johan Sverdrup Field (Riber et al., 2017; Scott and Ottesen, 2018). The main rifting phase in the Utsira High occurred during Oxfordian to Volgian times, with a reduction in extensional tectonics and subsequent inversion of pre-existing structures in the South Viking Graben during the Early Volgian to Late Albian (Jackson and Larsen, 2010). While the Oxfordian and Kimmeridgian are regarded as periods of eustatic sea level rise, the Volgian succession, is punctuated with the deposits of multiple and abrupt shoreline progradation events caused by regional tectonic events (Ottesen et al., 2022) (Fig. 1C). Progradation of clastic wedges is typically correlated with periods of reduced fault activity whereas shoreline retrogradation occurs during periods of increased or renewed rates of fault related subsidence in pulsating rifts (Ravnås and Steel, 1998). Shallow-marine and deltaic systems sourced from relatively large catchments characterized the proximal portions of the Jurassic rift system, such as the prograding fan deltas of the Froya High (Henstra et al., 2023). These systems were responsible for supplying sediments to the deeper portions of the basins, where they formed gravity-flow dominated submarine complexes of channels and fans which were encased withi4n the deep marine black shales of the Draupne Formation (Tillmans et al., 2021). Increased rates of eustatic sea level rise during the Early Cretaceous promoted a regional flooding which drowned the previously emerged structural highs and depositing the shale-rich deposits of the Cromer Knoll Group (Copestake et al., 2003; Jackson and Larsen, 2008).

BASIN CONFIGURATION AND TECTONIC STRUCTURES

The Johan Sverdrup Field is located on the east flank of the southern Utsira High. The studied region is mainly characterized by the Augvald Graben, a SE-NW oriented half graben structure, which is flanked by the Haugaland High to the West and the Avaldsnes High to the East (Olsen et al., 2017) (Fig. 2). The Augvald Graben is filled with sediments from Permian (or older) to Early Cretaceous age (Fig. 3). Younger geological formations drape across and along the entire Johan Sverdrup Field. The pre-Cretaceous geological formations show a significant thickening towards the east margin of the Haugaland High, where the Main Boundary Fault (MBF), a SSE-NNW pre-Triassic structure dipping north-eastwards, is located (Scott and Ottesen, 2018). Additionally, the basin is affected by multiple faults with variable orientations including the SE-NW oriented Kvalen

Graben Fault (KGF) and a pair of SW-NE oriented faults, the Geitungen and Espevaer faults (GF and EF, respectively). Based on the late Jurassic ENE-WSW stress field reported by Zanella et al., (2004), Scott and Ottesen (2008) suggested that deformation during the Late Jurassic rifting phase was accommodated differently at each fault based on its orientation with respect to the stress field. Accordingly, the Main Boundary Fault experienced oblique slip movement, the Geitungen Fault and Espevaer Fault experienced strike-slip displacement and the Kvalen Graben Fault experienced extension.

METHODS

A total of 22 exploration well cores were studied during 2020-21. Given the international mobility restrictions due to the global COVID-19 pandemic, a remote logging technique based on very high resolution core images was developed. First, very high-resolution cores images (provided by Lundin Energy Norway now Aker BP) were imported into Inkscape, an opensource vector drawing software. The scales were calibrated from the images and measurements, such as grain size and bed thickness were made using a virtual ruler, an analogous process to sedimentary logging in the core store or the field (See examples in Fig. 4 of the Facies Analysis chapter). Sedimentary logs were created for each core, consisting of grain size, roundness, sorting, sedimentary structures and fossil content descriptions. Due to the homogeneity and coarse-grained character of the succession, the sedimentary logging was performed at 1:1 scale. Logging in this detail allowed the capture of all of the subtle variations in grain size, sorting, sedimentary structures and vertical stacking patterns. This in turn allowed a subdivision into facies and facies associations and a hierarchical classification of the succession in terms of bedforms and units. Age dating and palaeocurrent measurements were provided by Lundin Energy Norway (now Aker BP) and were included with the sedimentary logs and regional base maps after a detailed revision and quality control were performed. A well-to-well sequence stratigraphic correlation through the field, combining the lithostratigraphic, allostratigraphic and biostratigraphic data was created . 3D seismic data were available and studied in-house at Lundin Energy Norway (now Aker BP) headquarters in Oslo, where we interpreted multiple seismic sections in Petrel®. All the results from the stratigraphic and seismic analysis were compiled and used to create 4 palaeogeographical maps which summarize the depositional history of the intra-Draupne Formation sandstones in the Johan Sverdrup Field

RESULTS

Seismic sections

The intra-Draupne Formation sandstones are too thin to map any internal reflectors or observe internal thickness variations. The pre-Jurassic geological formations thicken towards the hangingwalls of the Main Boundary Fault and Geitungen Fault (Fig. 3A, 3B). Additionally, the different formations are significantly affected by a composite erosional surface of Middle-Late Jurassic age (Ottesen et al., 2022). This is a regional low-angle angular unconformity which mainly affects the NE and SE portions of the field, close to the Avaldsnes High where it erodes Triassic, Permian and Ordovician basement rocks (Fig. 3A). At a smaller scale, the Asgard Formation thins towards the hangingwall of the Geitungen Fault (Fig. 3B), where a regional anticline structure is developed. The same trend is observed close to the hangingwall of the Main Boundary Fault (Fig. 3A), where another anticline structure is developed.

Facies Analysis

Thirteen different facies and 9 facies associations were described and interpreted within the intra-Draupne Formation sandstones, the Draupne and Asgard formations (Fig. 4; Table 1 and Table 2). A dark coloured section, termed the condensed section, separates the intra-Draupne and Draupne formations. The deposits are described below for the different parts of the Johan Sverdrup Field (Fig. 5 and 6). A series of maps and pie charts summarize the distribution of the main facies types through the different units (Fig. 7).

No deposits of the intra-Draupne and Draupne formations were found on top of the Haugaland High Footwall. Across the rest of the field, the facies and facies associations that characterize the intra-Draupne Formation sandstones alternate and stack vertically forming up to 4 different coarsening upward units, 4 to 19 m thick each. Units have been subdivided in a basal and upper part, each dominated by sandstones and gravels, respectively. Unit 1 is the most variable in facies and extent. It is absent in the southernmost part of the Augvald Graben and at some local wells in the Avaldsnes Crest. Bioturbated fine-grained muddy sandstones (facies Sf) are restricted to the basal part of unit 1 and were mainly deposited in a narrow belt parallel to the Haugaland High (Fig. 7A). There, they are interbedded with either normally or reversely graded gravel beds (facies Gn and Gr, FA-1, Fig. 4A) or massive, locally cross stratified, coarse-to-very coarse grained sandstones (Facies Sm and Scx, FA-2, Fig. 4B). This facies disappears laterally towards the inner portions of the Augvald Graben and the eastern Avaldsnes margin, into a region with little sediment variability, dominated by massive intervals of coarse-to-very coarse grained sandstones (Fig. 4C). Exceptions occur in wells 16/2-7A and 16/2-7 of the southern Augvald Graben, which is characterized by bidirectional cross stratified gravel and coarse-to-very coarse sandstone deposits which occur as erosional based, upward finning bedsets in well 16/2-7A (FA-3, Fig. 4D) or cross stratified coarsening upwards bedsets in well 16/2-7A (FA-5, Fig.4E). The basal part of the overlying units lack the bioturbated fine-grained muddy sandstones and are characterized by massive and bidirectional cross stratified coarse-to-very coarse sandstones. The upper part of all of the units is dominated by granules and pebbles. The gravel content and grain size is higher at the eastern Haugaland margin and at the Avaldsnes Crest, from where it tends to reduce laterally, towards the Augvald Graben and the eastern Avaldsnes margin. Bidirectional cross stratification is specially well developed in wells paralleling the Haugaland High (wells 16/5-3T2, 16/2-15, 16/2-14T2 and 16/2U-19) (Fig.4F-I) and those at the Avaldsnes Crest (16/3-5 and 16/3-8S) (Fig. 4J), which are characterized by coarsening and fining upwards bedsets, 0.5 to 2 m thick, of alternating cross stratified sandstones and gravels (FA-5). In addition, well 16/2-16 of the Avaldsnes Crest shows a similar coarsening upwards facies association, however, it is composed of structureless and gradational deposits (FA-4, Fig.4K). Interbeds of massive sandstones and structureless, normally graded, poorly-to-moderately sorted gravels (Facies Gn) dominate the inner portions of the Augvald Graben and well 16/2-17S of the Haugaland eastern margin (FA-6, Fig. 4L). Units 1, 2 and 3 are vertically stacked, forming an overall coarsening-upwards trend. The 4th unit is relatively finer grained, thus giving a finning-upwards trend from this level upwards. While units 2 and 3 are deposited throughout the whole basin, unit 4 is only found at the hangingwall of the Main Boundary Fault, Geitungen Fault and at some local faults in the Avaldsnes Crest, being absent at most of the southern Augvald Graben and at the eastern margin of the Avaldsnes Crest. Where present, unit 4 grades transitionally into to a well-developed finning upwards interval composed of massive sandstones (facies Sm), locally dark in colour. The condensed section is present in all wells, and was deposited on top of the uppermost unit of the intra-Draupne Formation sandstones and immediately below the Draupne Formation. It is characterized by poorly sorted and dark coloured, nodule and belemnite rich deposits (Fig. 4M-N). The deposits of the condensed section are typically stacked forming a threefold division (FA-7) consisting of a basal conglomeratic layer (Facies CTra) and a middle and upper interval of massive and cross stratified fine-to-coarse grained sandstones (Facies Cm and Cx, respectively). The amount of nodules and belemnites increases progressively towards the upper divisions of the package.

The Draupne Formation is mainly characterized by massive and dark coloured shales (Facies Shb, Fig. 4O). It is absent along most of the Main Boundary Fault and Geitungen Fault hangingwalls. Additionally, a particular facies type appears at the vicinities of these regions, consisting of fine grained spiculitic sandstones (Facies Spi) interbedded with black shales (FA-9, Fig. 4P-Q) or more rarely, in well 16/2-12, gravel deposits (FA-8, Fig. 4R). These type of facies associations dominates the stratigraphic succession of the Geitungen Terrace, which is significantly different to the rest of the field given that the intra-Draupne Formation sandstones are mostly or completely absent, as in well 16/2-19A. Instead, a thin interval corresponding to the condensed section rests unconformably on top of the Statfjord group, which is highly bioturbated by *Thalassinoides*, penetrating up to 30 cm down into the underlying strata (Fig. 4S).

The Early Cretaceous Asgard Formation, characterized by green and red shale deposits (Facies Ash, Fig.4T-U), is present throughout the whole basin, either on top of the Draupne Formation, or if absent, the intra-Draupne Formation sandstones.

Palaeocurrent Analysis

Palaeocurrent data from dip-meter and FMI logs within the intra-Draupne Formation sandstones are highly bidirectional (Fig. 7C). Throughout most of the basin, especially along the margin of the Haugaland High and the axis of the Augvald Graben, directions are mainly parallel or slightly oblique to the trace of the Main Boundary Fault and the Geitungen Fault, with SE-NW palaeocurrents in the southern Augvald Graben and S-N palaeocurrents in the northern Augvald Graben. Additionally, there are subordinate NE directed palaeocurrents in some wells, especially in those paralleling the eastern margin of the Haugaland High. In contrast, near the Avaldsnes Crest and along its eastern margin, there is a predominance of bidirectional NE-SW palaeocurrents which are locally overprinted by a SE-NW bidirectional trend that follows the trace of the Avaldsnes High. Although palaeocurrents are unevenly sampled within and between wells, it is still possible to observe clusters, 0.5 to 2.5 m thick, with similar values. These clusters alternate vertically showing bidirectionality between at bedset scale. Bidirectional measurements were also observed at a bed scale, between packages which are 10-50 cm thick. The sampling distribution of the available palaeocurrent data did not allow analysis of any clear variation or shift in the palaeocurrent trends at the unit scale.

Allostratigraphy

The nature and characteristics of the bounding surfaces between the different units and geological formations differs depending on its position within the basin:

The base of the intra-Draupne Formation sandstones is a sharp and low angle erosional unconformity which erodes Ordovician to Lower Jurassic rocks. This surface is extensively colonized by *Thalassinoides* in wells 16/2-12, 16/2U-19, 16/2-19, 16/2-19A, 16/5-4, 16/3-8S, and 16/2-7 (Fig. 4V, 4S and 4W). The rest of the wells do not show signs of colonization at the base. Additionally, there are significant differences regarding the type and the composition of the deposits overlying this unconformity. In wells 16/2-15, 16/2-21, 16/2-8, 16/2-10 and 16/3-5, it is covered by a 1 to 80 cm thick, very poorly sorted, matrix-to-clast supported and highly amalgamated conglomeratic package (Fig. 4X). This deposit is a very heterometric mixture of angular to very well rounded pebbles, ranging from 0.3 up to 5 cm. The composition and the diameter of these clasts does not match the composition of the underlying basement, instead, they are mainly formed by outsized metamorphic and granitic clasts, while the basement is mainly composed of coarse to fine grained Lower-to-Middle Jurassic sandstones or clay-rich Triassic palaeosols. In contrast, at wells 16/3-4 and 16/2U-19, the intra-Draupne Formation sandstones directly overlie granitoids and the surface is covered by a 10 to 80 cm thick, moderate-to-poorly sorted, massive granule deposit (Fig. 4W). These are the only wells where the composition and size of the clasts within the basal intra-Draupne Formation sandstones matches the underlying basement. The surface in the rest of wells in the Johan Sverdrup Field is depleted of a basal outsized deposit and is directly covered by fine-to-very coarse grained sandstones and gravels of unit 1, 2 or, in well 16/2-19, the nodule and belemnite rich deposits of the condensed section.

The boundary between Unit 1 and 2 is a sharp and abrupt sub-horizontal boundary in the Avaldsnes Crest and most of the southern and northern Augvald Graben. It is a transitional boundary in the majority of wells paralleling the Haugaland High, the Main Boundary Fault and Geitungen Fault. It is not present at the southernmost portion of the Augvald Graben, in wells 16/5-4, 16/5-2S and 16/2-7A, given that Unit 1 is absent, hence the basal boundary constitutes a composite surface between the base of the intra-Draupne Formation sandstones and the underlying Triassic and Middle Jurassic rocks. The boundary between Unit 2 and 3 is a subtle and sharp boundary which is found in all wells throughout the basin. It separates the gravel dominated upper part of Unit 2 from the coarse-to-very coarse sandstone dominated basal part of Unit 3. Unit 4 is mainly found in the Haugaland eastern margin, the northern Augvald Graben and at some wells in the Avaldsnes Crest. Where present, its base is a sharp and very distinguishable abrupt surface which separates the underlying gravel dominated upper part of Unit 3 from the very well sorted, medium-to-coarse grained sandstones of Unit 4.

The boundary between Unit 3 or 4 and the condensed section is a sharp, abrupt and very distinguishable contact in most of the wells given the poorly sorted texture of the basal lag within the condensed section, and its dark colour, the high proportion of septarian nodules and belemnites. In the Haugaland eastern margin, the northern Augvald Graben and the Avaldsnes Crest, there is an upward finning sandstone dominated interval separating either Unit 3 or 4 and the condensed section. This interval grades from the underlying units and is abruptly overlain by the condensed section. The contact between the condensed section and the shale dominated expression of the Draupne Formation is a sharp and abrupt surface. The contact with the interbedded Draupne spiculitic package is a transitional boundary. Finally, the contact between the Late Jurassic Draupne Formation and the Early Cretaceous green-red shaly deposits of the Asgard Formation is a clean, sharp, subhorizontal boundary.

Biostratigraphy

Age dating reports were supplied by Lundin Energy Norway (Aker BP now). Dates are mainly based on palynomorphs, dinoflagellates and foraminifera among other faunal associations. Biostratigraphic data are scarce and unevenly distributed throughout the field. Additionally, some wells have indeterminate age dating for the whole succession, 16/2-8, 16/2-14, 16/2-17S, 16/2-10, 16/2-12 and 16/5-3T2. Given these circumstances, the age correlation between wells has a degree of uncertainty.

The intra-Draupne Formation sandstones are Oxfordian to Middle Volgian in age. The first centimetres and meters of some wells located in the Avaldsnes Crest and its eastern margin, 16/3-6, 16/2-13S, 16/3-7, 16/3-8S and 16/2-16, are Oxfordian in age. These are the oldest dates obtained from the intra-Draupne Formation sandstones and are limited to this particular portion of the Johan Sverdrup Field. Higher in the stratigraphy the analysis shows a dominance of Kimmeridgian age dates, in the Avaldsness High and Haugaland High/Augvald Graben regions. Kimmeridgian dates in the east margin of the Haugaland High and the Augvald Graben are well constrained and restricted to Unit 1. Similarly, in the Avaldsnes High, Kimmeridgian and Kimmeridgian/Early Volgian dates are restricted to Unit 1 and the basal part of Unit 2. Units 2,3 and 4 become younger away from the Haugaland and Avaldsness highs, dominated by Early Volgian age dates, towards the southern Augvald Graben, which is characterized by Middle Volgian dates. The condensed section is intra-Middle Volgian throughout the basin. The majority of the Draupne Formation at the eastern margin of the Avaldsnes High and at the Geitungen Terrace is late Middle Volgian to Ryazanian, and youngs towards the Haugaland High eastern margin, the Augvald Graben and the Avaldsnes Crest, where it is dated as Late Volgian-Ryazanian. The base of the Asgard Formation is mainly dated as Valanginian-Hauterivian in the Geitungen Terrace, the southern portion of the Avaldsnes Crest and the Augvald Graben, whereas in the rest of the field, especially along the Haugaland eastern margin and the northern Avaldsnes Crest it is younger, dated as mainly Barremian to locally Aptian in age.

Sedimentary architecture

Dip oriented stratigraphic correlations

The intra-Draupne Formation sandstones are relatively thin across the entire Johan Sverdrup Field (Fig. 8A). They attain a maximum thickness of 40 m close to the hanginwall of the Main Boundary Fault, in well 16/2-17S, and a minimum thickness of 9 m in well 16/2-7 in the Augvald Graben. They are absent on the wells drilled on top of the Haugaland High (Fig. 8A). In cross section, they display a clear wedge geometry, thinning towards the crest of the Avaldsnes High. The different units are correlatable throughout most of the section. The first two units are more variable in thickness than Unit 3 and 4. Unit 1 and 2 reach a maximum thickness of 13 and 17 m, respectively, in the hangingwall of the Main Boundary Fault (Fig. 8A). Thickness reduces progressively towards the East, where Unit 1 locally disappears, in well 16/2-7A. Local thickenings in

Unit 1 and 2 are observed at well 16/2-7, where they are 8 and 14 m thick, respectively (Fig. 8A). In contrast, Unit 3 and 4 have a maximum thickness of 5 and 3 m in the hangingwall of the Main Boundary Fault, respectively, which is reduced towards the Augvald Graben, where Unit 4 disappears. Deposits associated with Unit 4 are present in the hanginwall of some faults affecting well 16/3-5 at the Avaldsnes Crest. The condensed section shows a rather tabular geometry, with minor variations in thickness. It is overlain by the Draupne Formation, which wedges out towards the Haugaland High, where it is absent. It attains a maximum thickness of approximately 15 m in well 16/2-15 and at well 16/3-4 in the eastern Avaldsnes margin (Fig. 8A). It is thinner in the Augvald Graben, especially close to the hangingwall of the Kvalen Graben Fault, where it is 4 m thick. The Early Cretaceous Asgard Formation, ranges from 3 to 33 m, attaining its maximum thickness east of the Haugaland High. That unit typically shows a tabular geometry, but it tends to thin abruptly, close to the hangingwall of the Main Boundary Fault and at the top of the Haugaland High, where it is mainly represented by Barremian age sediments (Fig. 8A).

Strike oriented correlations

Two along strike correlation panels are presented, one runs parallel to the Main Boundary Fault/Haugaland eastern margin (Fig. 8B) and the other is parallel to the Avaldsnes Crest (Fig. 8C). The intra-Draupne Formation sandstones display a synform geometry along the Main Boundary Fault and is thickest at the point of maximum displacement of the fault, around wells 16/2-17S and 16/2U-19, where it attains a maximum thickness of 40 m (Fig. 8B). It wedges out progressively towards the South and the North, as it approaches the fault tips, where it reaches a minimum thickness of 3 m in well 16/2-19A. Unit 1 and 2, show the greatest thickness variation in the area. A significant thickness increase in Unit 4 is observed in the hangingwall of the Geitungen Fault which progressively reduces towards the southern tip of the Main Boundary Fault, where it pinches out (Fig. 8B). Additionally, Unit 4 is absent in the Geitungen Terrace and at the footwall crest of the Geitungen Fault. The condensed section reaches its maximum thickness at the Geitungen Terrace, where it is 3 m thick. It tends to show a thiner but rather constant thickness along the Main Boundary Fault. The Draupne Formation is absent along most of the Main Boundary Fault hanginwall, except for well 16/2-15, 16/2U-19, 16/2-12 and at the Geitungen Terrace, where it reaches a maximum of 12 m (Fig. 8B). The Asgard Formation contains a Valanginian-Hauterivian package, that is only present in wells 16/2-19A and 16/2-15, and a younger Barremian package, which was deposited along the whole section displaying a progressively thinner wedge geometry towards the SW, passing from 15 to only 2 m in well 16/5-3T2 (Fig. 8B).

In the Avaldsnes region (Fig. 8C), the intra-Draupne Formation sandstone thickens northwards and southwards from well 16/2-16, where it reaches a minimum thickness of 7.5 m. A remarkable and abrupt thickness increase occurs northwards of well 16/2-16, just after the deposition of Unit 1. A scoop shaped depression is developed between well 16/2-19, in the Geitungen Terrace, and well 16/2-16 (Fig. 8C). As observed, the thickness of the succession increases drastically, reaching a maximum thickness of 35 m in well 16/2U-19, and thinning towards the Geitungen Terrace, where it reaches a minimum thickness of 3 m (Fig. 8C). It is noted that the thickness increase within this depression mainly affects Unit 2,3 and 4, and that Unit 1 is relatively tabular and continuous along the section. The condensed section is continuous across the whole section (Fig. 8C). It reaches its maximum thickness on the Geitungen Terrace, where it is 3 m thick. It progressively thins towards the SW, where it reaches a minimum thickness of 0.2 m in the southernmost Avaldsnes Crest. The Draupne Formation and Asgard Formations show a similar thickness distribution between them. Both formations tend to become progressively thicker away from the scoop shaped depression affecting the area between the Geitungen Terrace and well 16/2-16 (Fig. 8C). The Draupne Formation and the Valanginian-Hauterivian sediments of the Asgard Formation thin abruptly along this depression, where they are absent or mostly absent. Both formations attain its maximum thicknesses at the northernmost part of the Geitungen Terrace and at southernmost part of the Avaldsnes Crest.

DISCUSSION

Significance of depositional units and their bounding surfaces

The base of the intra-Draupne Formation sandstones is a low angle erosional unconformity as seen in the seismic data (Fig 3) and from the variety of sub-cropping geological formations.. The basal surface is a transgressive marine surface illustrated by the presence of marine deposits overlying much older continental deposits. The surface is associated with extensive *Thalassinoides* and other firm ground traces which suggest the deposits were at least semi-lithified prior to erosion and burrowing. (Fig.4S). The stratigraphy of the intra-Draupne Formation sandstones has been subdivided into 4 main units which are vertically stacked and bounded by regional surfaces which separate gravel rich marine sediments below from finer grained sediments above. These boundaries are interpreted as regional flooding surfaces and the units between them therefore represent . parasequences (sensu Van Wagoner et al., 1988). The biostratigraphic dating suggests that the individual parasequences young basinwards, towards the Augvald Graben. The grain size distribution within the parasequences also shows a basinward finning from the Haugaland and Avaldsnes Highs towards the Augvald Graben or eastern Avaldsnes margin. Thickening of the parasequences towards the hangingwall of the Main Boundary Fault and the Geitungen Fault indicate that they were deposited during active extensional tectonics (Howell et al., 1996). Parasequence 1, 2 and 3 are strongly progradational while parasequence 4 shows a subtle back stepping. There is a marked thickness increase of parasequence 4 towards the hangingwall of the Geitungen Fault. This might indicate a shift from the Main Boundary Fault to the Geitungen Fault during its deposition. This suggests that a slight rotation of the stress field might have taken place so that extension was mainly accommodated along SW-NE oriented faults during this time interval, although this is somewhat speculative. The thickness distribution of the intra-Draupne Formation sandstones clearly suggests syn-depositional growth due to fault-related subsidence. However, thinning of the Draupne and Asgard formations towards the hangingwall of the different faults suggests there is also compression. This is discussed further in the following sections. The local thickness increase observed in well 16/2-7 was interpreted in Ottesen et al., (2022) as the result of salt generated subsidence associated with the underlying Zechstein Group. As observed in our Fig. 8A, this period of salt movement is synchronous with the period of maximum fault-related subsidence at the Main Boundary Fault, during deposition of parasequence 1 and 2 in Kimmeridgian and Early Volgian-Middle Volgian times, respectively.

Oxfordian

Oxfordian aged strata are restricted to the lowermost part of the succession on the eastern margin of the Avaldsnes High (Olsen et al., 2017). The Oxfordian interval in the Johan Sverdrup Field is very thin, however, it is difficult to fully quantify given the limited number of age dates and the high degree of amalgamation. The limited data suggest that an Oxfordian shoreface existed on the east margin of the Avaldsnes High, prior to the main rifting phase and flooding of the Augvald Graben during the Kimmeridgian-Early Volgian transition. This is also supported by the distribution and age dates of the Heather and Hugin formations in Olsen et al. (2017), who described a Callovian-Oxfordian shoreline in this region.

Kimmeridgian to Early Volgian

Parasequence 1 is mainly Kimmeridgian in age (Fig. 8A, 8B and 8C). Bioturbated fine-grained muddy sandstones were mainly deposited in a narrow belt parallel to the Haugaland High (Fig. 7A). Fine grained sandstones displaying mud-draped ripples and intense bioturbation by *Macaronichnus segregatis* typically occur in the foreshore-to-upper shoreface transition in storm-influenced and tidal-influenced shorefaces (Dashtgard et al., 2012). This facies passes basinwards into lower-coarse and very coarse grained sandstones. A basinward increase in grain size is typically recorded in restricted tidal systems such as lagoons and embayments, where fine grained sediments are located in supra tidal marshes and muddy inter-tidal flats passing seaward into coarser sediments in sand inter-tidal and subtidal portions of the system (Gao, 2019). Consequently, the eastern margin of the Haugaland High was characterized as a low energy lagoonal area with a higher energy, more open marine setting in the inner portions of the Augvald Graben (Fig. 9A). This lagoon was: 1) enclosed towards the northernmost and southernmost portion of the Augvald Graben, as indicated by the progressive onlap and eventual termination of parasequence 1 in wells 16/2-19, 16/2-19A, 16/5-2S and 16/5-4 (Fig. 7A and 8B) and 2) partially enclosed towards the Avaldsnes Crest, as evidenced by the absence of parasequence 1 in wells 16/2-7A and 16/2-6, which are interpreted as basement highs (Fig. 7A). Such basement highs are interpreted as local features because they alternate with areas in which parasequence 1 is present (wells 16/2-16, 16/3-5, 16/3-8S and 16/3-7). The deposits in these wells are mostly characterized by coarsening upwards, moderate-to-well sorted, massive and bidirectional cross-stratified gravel rich sediments that were sourced extra-basinally instead from the reworking of the Permian Zechstein carbonates or mud rich Triassic and Lower Jurassic rocks that characterize the Avaldsnes High basement in the study area(Ottesen et al., 2022). These gravel rich sediments in the

Avaldsnes Crest are interpreted to have been sourced from an external area, transported and deposited by SE-NW longshore and/or tidal currents, forming a gravel spit or barrier (Fig. 7A, 7C and 9A). Tidal inlets through the gravel spit and between basement elevations, connected the lagoon with the open marine environment east of the Avaldsnes Crest. Evidences for these tidal inlets is seen as, erosively based, upward-finning intervals of cross stratified sandstones and gravels in well 16/2-21, indicating bedform migration within active channels (Fig 4D and 9A). These channels are typical in systems with a moderate to high tidal range and explain the coarse grained sandstones in the inner portions of the Augvald Graben and the presence of cross stratified barforms interbedded with muddy sandstones in well 16/2-15 and 16/2U-19A.

There is a significant change in basin configuration between the deposition of the Kimmeridgian aged parasequence 1 and the Volgian deposits of parasequences 2 – 4. There is an absence of fine grained facies in parasequences 2,3 and 4 which are dominated by well sorted very coarse sandstones and gravels with dominantly N-S/NW-SE oriented bidirectional cross stratification (Fig. 6, 7B, 7C). The grain-size, cross bedding and a *Skolithos* ichnofacies indicates deposition in a higher energy shallow marine environment with strong axial circulation. Consequently, it is interpreted that the basin has become more open, with a very effective marine circulation in contrast to the lagoonal system of parasequence 1. Evidence for a pulse of strong tectonic activity during the transition from the Kimmeridgian-to-Early Volgian, just after deposition of parasequence 1, is suggested (Fig 8) by fault-related thickness variations in parasequence 2, 3 and 4 in the hanging wall of the Main Boundary Fault, the Geitungen and Espevaer faults, and probably the Kvalen Graben Fault. Together these faults created a narrow and relatively deep, scoop-shaped trough between well 16/2-16, in the northern Avaldsnes Crest, and the Geitungen Terrace. This trough is interpreted as a strait (Fig. 9B). Funnelling of water between topographic barriers, as in seaways or straits, enhances the strength of circulating current, facilitates the transport of coarse grained particles and prevents deposition of fine grained material (Longhitano, 2011; Longhitano, 2013; Longhitano and Chiarella, 2020). The opening of the strait in Early Volgian times increased the energy regime in the basin and hence modified the type of depositional systems in parasequence 2 to 4.

Early to Middle Volgian

The source area for the Late Jurassic deposits is the Haugaland and Avaldsnes granitic basement which was weathered into regolithic solids and then transported (Riber et al., 2015). Previous studies interpreted fan deltas as the main mechanism for sediment delivery to the basin, identifying 3 different entry points, coincident with the position of the coarsest wells in the Haugaland eastern margin, 16/5-3T2, 16/2-17S and 16/2-12 (Olsen et al., 2017; Ottesen et al., 2022). Our observations of the ubiquitous presence of normally and reverse graded, moderate-to-poorly sorted gravel beds, isolated or stacked forming complex lobes, indicates the existence of one or multiple, long term, fan delta systems but suggest a greater degree of reworking than previously proposed. Deflection of fan delta fronts and reworking of pre-existing deposits is commonly observed in modern and ancient tide dominated seaways and straits (Longhitano and Steel, 2016). Sediment feeder systems are reworked and redeposited along and/or oblique to the shoreline in the form of cuspate forelands, spits and a range of submarine barforms. These barforms classically fall into three main categories: compound tidal dunes/sandwaves; sand sheets/sand banks and, tidal bars/sand ridges (Olariu et al., 2012; Desjardins et al, 2012; Messina et al., 2014). These are all characterized by cross stratified deposits, some of them vertically stacked forming coarsening or finning upwards sedimentary packages separated by reactivation surfaces. Compound tidal dunes and sand sheets/sand banks tend to migrate forward while tidal bars and sand ridges have a stronger lateral or oblique component respect to the main current (Olariu et al., 2012; Messina et al., 2014). It is challenging to differentiate them in subsurface datasets compared with modern or outcrop examples. Based on the facies and palaeocurrent distribution in the Johan Sverdrup Field (Fig. 6, 7B and 7C), the isolated or vertically stacked coarsening and finning upwards bedsets composed of bidirectional cross stratified gravels and sandstones (FA-5) are interpreted as the result of dune and barform migration resulting from the reworking of fan delta fronts and coastal regoliths. Given the oblique bidirectional palaeocurrents in most of the deposits on the eastern margin of the Haugaland High (Fig. 7C) we suggest that fan delta fronts were predominantly reworked as tidal bars and sand ridges. Basinwards and in the inner portions of the Augvald Graben, where palaeocurrents are more parallel to the graben axis and the faults strike (Fig. 7C), sediment could have been accumulated in compound dune fields. Bed and bedset scale palaeocurrent clusters showing opposite orientations indicate that individual bedforms and compound barforms in the intra-Draupne Formation sandstones where likely generated during both ebb and flood periods. This periodic variability in the current orientation is probably responsible for the coarsening-to-finning upwards pattern, interpreted as the resulting of a wanning-to-waxing sequence (Longhitano, 2011). Similar patterns in stacked gravity flow deposits (FA-6) is interpreted to result from fluctuations in the sediment input, with periods of increased and reduced discharge reflecting progradation and retrogradation of the fan delta lobes. The dominant eastward and westward directed palaeocurrents in some wells of the Avaldsnes Crest along with the presence of coarsening-upward packages of massive and structureless sandstones grading vertically to gravels (FA-4) is interpreted to reflect onshore and offshore sediment transport and reworking by waves. This is a common process observed in modern coastlines forming swash and backswash nearshore bars or offshore bars in barrier islands and spits (Robin et al., 2020).

Middle-to-Late Volgian/Ryazanian

The creation of accommodation started to exceed the rate of sedimentation during the deposition of parasequence 4 which back steps compared to parasequence 3. This process was accelerated during the deposition of the condensed section, which records a regional flooding of the area. This flooding is associated with a backstepping of the feeder systems and, subsequent sediment starvation leading to the deposition of fine-grained, dark, poorly sorted, nodule and belemnite rich sediments of the condensed section. Biostratigraphic dates suggest this started during the Middle Volgian, coevally with the Draupne Formation black shales and spiculitic sandstones in the eastern Avaldsnes margin and Geitungen Terrace, respectively (Fig. 8A, 8B and 8C). The Draupne Formation sediments progressively onlapped onto the Avaldsnes Crest and the Augvald Graben during the Late Volgian-Late Ryazanian (Fig. 8A). The thickness of the condensed section is relatively constant throughout the basin, because it is dominated by the slow rate of sediment supply rather than the rate of accommodation creation.

The overlying Draupne Formation shows some local and regional thickness variations that contrast with the rather constant thickness of the condensed section and do not correlate with the wedge geometries observed within the intra-Draupne Formation sandstones. As shown in the seismic lines (Fig. 3), the correlation panel (Fig. 8C) and the facies map (Fig. 7D), the Volgian-Late Ryazanian package of the Draupne Formation thins and disappears towards the hanginwall of the Main Boundary Fault and Geitungen Fault, coincident with the position of some relatively broad anticline structures. These structures mainly affected the upper Asgard Formation and are interpreted as propagation folds generated during an Early Cretaceous inversion phase and are discussed in detail in the next section. The progressive onlap and pinchout of the Draupne Formation around these folds suggest that they may have been active when it was deposited, however this is somewhat uncertain (see next section). Spiculitic facies of the Draupne Formation are commonly on the Geitungen Terrace and around the anticline folds (Fig. 7D). They are the result of erosion and redeposition of siliceous sponge reefs, which were common in the Jurassic (Leinfelder, 2001), and proliferated during and after the drowning of the clastic source areas and the reduction of current strength. No preserved or in situ sponge reefs have been observed in the cores. The concentration of the spiculitic sediments around the anticline structures suggests that the original reefs grew on top of them but were lately eroded, shedding fragments to the surrounding areas (Fig. 9C).

Early Cretaceous

Deposition of the Asgard Formation mainly began during the Valanginian-Hauterivian period and continued up into the Barremian and Albian periods (Fig. 7E and 9D). The progressive thinning of the Asgard Formation towards the main faults (Fig 8A, 8B and 8C), along with the identification of hangingwall anticline structures (Fig. 3) is indicative of an inversion phase in the Johan Sverdrup Field. Inversion of pre-existing structures is much clearly recorded in the Barremian and younger packages of the Asgard Formation, which are continuous throughout the whole basin and show a clear thinning towards the hanginwall of the Main Boundary Fault and Geitungen Fault compared with the underlying thickening pattern of the intra-Draupne Formation sandstones (Fig. 8A, 8B and 8C). The progressive thinning and disappearance of the Valanginian-Hauterivian Asgard Formation and the Late Volgian-Ryazanian Draupne Formation is less clear and more challenging to interpret. It could result from progressive onlap towards growing hanginwall anticlines, or it could be the result of post depositional erosion associated with anticline growth and uplift during the Barremian inversion phase. Similar inversion of pre-existing structures, starting in the late Early Volgian and lasting until the Late Albian, was documented by Jackson and Larsen (2008) in the South Viking Graben, supporting the interpretation of an inversion phase starting in the Late Volgian-Ryazanian in our study area. Late Jurassic inversion in the Johan Sverdrup Field has further implications for fault scarp reconstructions. The thickness of the Asgard Formation at the footwall and hanginwall of the Main Boundary Fault is 3 and 7 m, respectively (Fig. 8A). The migration of depocentres may occur during inversion of pre-existing faults (Cooper and Warren, 2020), and sediment accumulations tend to be thicker at the footwall than at the hangingwall sides. The similar thickness of the Asgard Formation on both sides of the Main Boundary Fault suggest that both sides occupied a similar structural level during sedimentation of the Barremian aged deposits. The Asgard Formation is much thicker away from the influence of the Main Boundary Fault, showing a constant thickness of 25 to 35 m across the entire Johan Sverdrup Field. If thickness in these areas is considered to reflect the structural regional elevation (Cooper et al., 1989b), then the Main Boundary Fault hanginwall must have experienced a 18-28 m uplift, which suggests a Late Jurassic backstripped fault scarp of 25-35 m. Consequently, the catchment and drainage systems of the Haugaland High would have been highly incised and characterized by rather steep gradients during the deposition of the Intra-Draupne Formation sandstones.

Comparison with previous intra-Draupne Formation models and interpretations in the Johan Sverdrup Field

Olsen et al., (2017) and Ottesen et al., (2022) are the main previous works in the Johan Sverdrup Field. Both dealt with the facies description and interpretation of the intra-Draupne Formation sandstones. Sedimentary logs at 1:50 scale and correlation panels are mainly provided in Olsen et al., (2017), while palaeogeographic reconstructions are the main output of Ottesen et al., (2022). Both studies stated that they found difficulties recognizing internal surfaces of sequence stratigraphic significance, therefore hindering a detailed breakdown and correlation of the succession. Although we generally agree with the overall facies analysis in both studies, there are several important divergences which are discussed in detail in the following sections.

Correlation panels and palaeogeographic reconstructions of the intra-Draupne Formation sandstones

Correlation panels of the intra-Draupne Formation sandstones are only available in Olsen et al. (2017) and consist of one section across the Augvald Graben. Olsen et al. (2017) propose that most of the deposits at the Avaldsnes Crest and its eastern margin, corresponding to our parasequence 1, 2 and 3, were older and disconnected from the succession observed in the Augvald Graben and Haugaland eastern margin, and that parasequence 4 changed laterally to the condensed section and Draupne Formation deposits. As discussed before, none of the intra-Draupne Formation parasequence in our model are considered coeval, at least in the study area, to the condensed section or the Draupne Formation. The palaeogeographic reconstructions of Olsen et al. (2017) suggest that Kimmeridgian sedimentation was limited to a narrow shoreface or spit located in the Avaldsnes Crest and its eastern margin. The terrain separating the Haugaland eastern margin from the Avaldsnes Crest was a vast and relatively flat area with no deposition. In Early-Middle Volgian times, the Avaldsnes region was completely transgressed and the Augvald Graben flooded, as a consequence of the tectonic subsidence generated during reactivation of the Main Boundary Fault. The shoreline quickly retrograded westwards towards the Haugaland eastern margin where it occupied a relatively stable position above fair weather wave base, which prevented the deposition of fine grained particles, also influenced by longshore and tidal currents. In the Middle-Late Volgian, a progressive sea level rise flooded the area and the system was drowned.

In contrast, the model proposed in the current work suggests that Kimmeridgian sedimentation in the Augvald Graben took place in a semi enclosed lagoon, coevally with the development of a gravel spit or barrier in the Avaldsnes Crest, which would continue into the Early and Middle Volgian. The opening of a narrow strait in the transition from the Kimmeridgian to the Early Volgian (Fig. 8C and 9B) promoted a renewed incursion into the Augvald Graben and an increase of the energy regime, which enhanced reworking of fan delta fronts and regoliths by strong axial currents which deposited bidirectional cross stratified coarse grained barforms and prevented the deposition of fine grained particles. The proposed gravel spit system was contemporaneous to the reworked fan delta systems at the Haugaland High, giving as a result a series of thin, but laterally extensive and correlatable parasequence throughout the area. Both works agree on the syn-tectonic origin of the intra-Draupne Formation sandstones, recognizing the Early-Middle Volgian as the period of main deposition and tectonic activity, the presence of fan deltas in the Haugaland eastern margin, and the signature of longshore, tidal and landward and seaward directed palaeocurrents in the Avaldsnes Crest deposits, reflecting wave reworking processes.

Our interpretation of the Early-Middle Volgian palaeogeography is more in line with the Early-Late Tithonian reconstruction of Ottesen et al., (2022) who emphasized 1) the existence of a long term barrier or shoal in the Avaldsnes Crest and 2) the reworking of fan delta front deposits and regoliths in a high energy environment. These reworked sediments were redeposited as subaqueous coarse grained barforms along the Augvald Graben and the Avaldsnes Crest. Some important dissimilarities lie in the palaeogeography of the Kimmeridgian period and the transition from our parasequence 1 and 2 at the Kimmeridgian-Early Volgian boundary. Ottesen et al., (2022) included the corresponding deposits of both parasequence into a single Late Kimmeridgian-Early Tithonian reconstruction, with coeval fine grained muddy sandstones sedimentation in the Haugaland margin, strong fan delta front reworking and migration of bidirectional cross stratified coarse grained barforms. Our results suggest that their reconstruction mixes two depositional parasequences of significantly different characteristics as discussed in our study. Ottesen et al., (2022) interpreted the bioturbated fine grained sandstones of parasequence 1 as part of fan delta toe-sets deposited in a shelfal setting, however, no further attempts are made to frame them in a regional Kimmeridgian setting neither to interpret the significance behind the disappearance of this facies type and the basinwide general grain size increase and abundance of cross stratified deposits during the Early-Middle Volgian. A connection between the northern Augvald Graben and the eastern side of the Avaldsnes Crest seems to be suggested in their reconstructions, which could be potentially analogous to our strait, the lack of correlation panels and no mentions to straits or other types of marine connections makes this comparison difficult.

Deposition of the Draupne Formation

Ottesen et al. (2022) suggest that deposition of spiculitic sandstones of the Draupne Formation in the Geitungen Terrace began in the Early Kimmeridgian, synchronous with the intra-Draupne Formation sandstones. Our correlation panels suggest that spiculitic sandstones began to accumulate after deposition of parasequence 4, in the Middle Volgian, once sediment supply and energy regime in the basin had decreased. Consequently, we interpret that the deposition of the Draupne Formation was not coeval with the four parasequence described within the intra-Draupne Formation sandstones. They explain the progressive thinning of the Draupne Formation towards the West as a regional eastern tilting of the Avaldsnes High, mainly as a consequence of the syn-sedimentary tectonic activity of the Øygarden Fault Zone in the eastern margin of the Stord Basin (Fazlikhani et al., 2021). Our correlation panels suggest that inversion of the preexisting structures along with regional sea level rise is a plausible alternative or complement to explain the thickness variations and facies distribution of the Draupne Formation in the Johan Sverdrup Field.

Inversion and its implications on palaeotopograhy, catchments and drainage system type.

The Haugaland High/Main Boundary Fault footwall in Ottesen et al., (2022) is depicted as a gently dipping and smooth flank structure drained by shallowly incised streams or river systems. As discussed above, Late Volgian-Barremian inversion in the Johan Sverdrup Field has further implications for reconstructing the palaeotopograhy of the Late Jurassic period. A 25 to 35 m high Late Jurassic fault scarp is interpreted after restoring the inversion of the Main Boundary Fault. Consequently, the eastern flank of the Haugaland High was more elevated with respect to the shoreline. Based on our results, we suggest that catchment and drainage systems of the Haugaland High must have been highly incised and characterized by steep gradients, which would have favoured the formation of fan deltas and coarse-grained sediment delivery to the Augvald Graben.

CONCLUSIONS

In this study a new basinwide sequence stratigraphic correlation has constrained the evolution of the intra-Draupne Formation sandstones, the Draupne and Asgard formations in the Johan Sverdrup Field, southern Utsira High. High resolution logging allowed the identification of subtle grain size trends within a rather homogeneous coarse grained shallow marine succession which in turn led to the identification of multiple, previously undocumented sequence stratigraphic surfaces. This has subdivided the the sedimentary package into 4 parasequences which can be tied to the different tectonic events which affected the basin. New finding include:

1. Demonstrate the influence of extensional tectonics in creating fault-controlled Late Jurassic depocenters and in controlling the deposition of the intra-Draupne Formation sandstones in the Johan Sverdrup Field.

2. Describe and interpret 4 parasequences along with the facies and facies associations which constitute the fundamental building blocks of this expression of the intra-Draupne Formation sandstones.

3. Reconstruct the shoreline trajectories and palaeogeographical evolution of the area, with a dynamic basin configuration changing from a Kimmeridgian semi enclosed lagoon to a shallow marine shelf strongly influenced by the opening of a strait in the Early Volgian and finally a sediment starved marine shelf in the Middle Volgian-Late Volgian transition.

4. Identify a Late Volgian-Barremian inversion phase affecting the Draupne and Asgard Formations, complementing previous studies in the south Viking Graben and extending this event to the Johan Sverdrup Field.

These results have implications for assessing the potential of nearby regions and places the new discoveries within a Late Jurassic regional framework for the Norwegian North Sea that predicts this type of play around the Utsira High and other basement highs.. The recognition of the Late Volgian-Barremian inversion phase has important implications for the distribution and preservation potential of seal rocks around the Utsira High. Finally understanding the depositional environment of the intra-Draupne Formation sandstones has important implications for our understanding of coarse grained shallow marine which can be used to study similar successions around transgressed structural highs, epeiric seas and continental margins.

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FIGURE AND FIGURE CAPTIONS

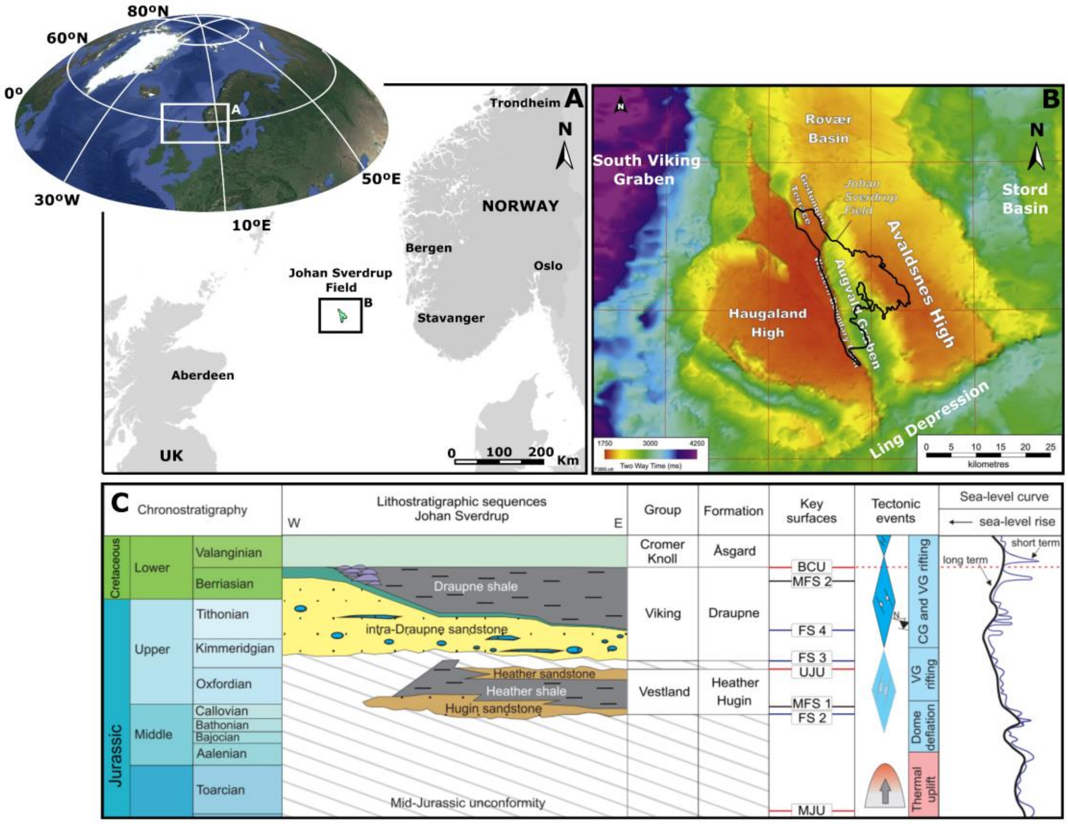


Fig. 1: (A) Location of the study area. The extent of the Johan Sverdrup Field is depicted in light green colour and framed in the black square rectangle (globe map modified from Google Earth; local map modified from the NPD). (B) Two-way-time map of the top basement surface in the southern Utsira High (from Olsen et al., 2017). The extent of the Johan Sverdrup Field corresponds with the area within the black envelope. The Augvald Graben is bounded by the Haugaland and the Avaldsnes highs. (C) Chronostratigraphic and lithostratigraphic chart of the Johan Sverdrup Field (from Ottesen et al., 2022).

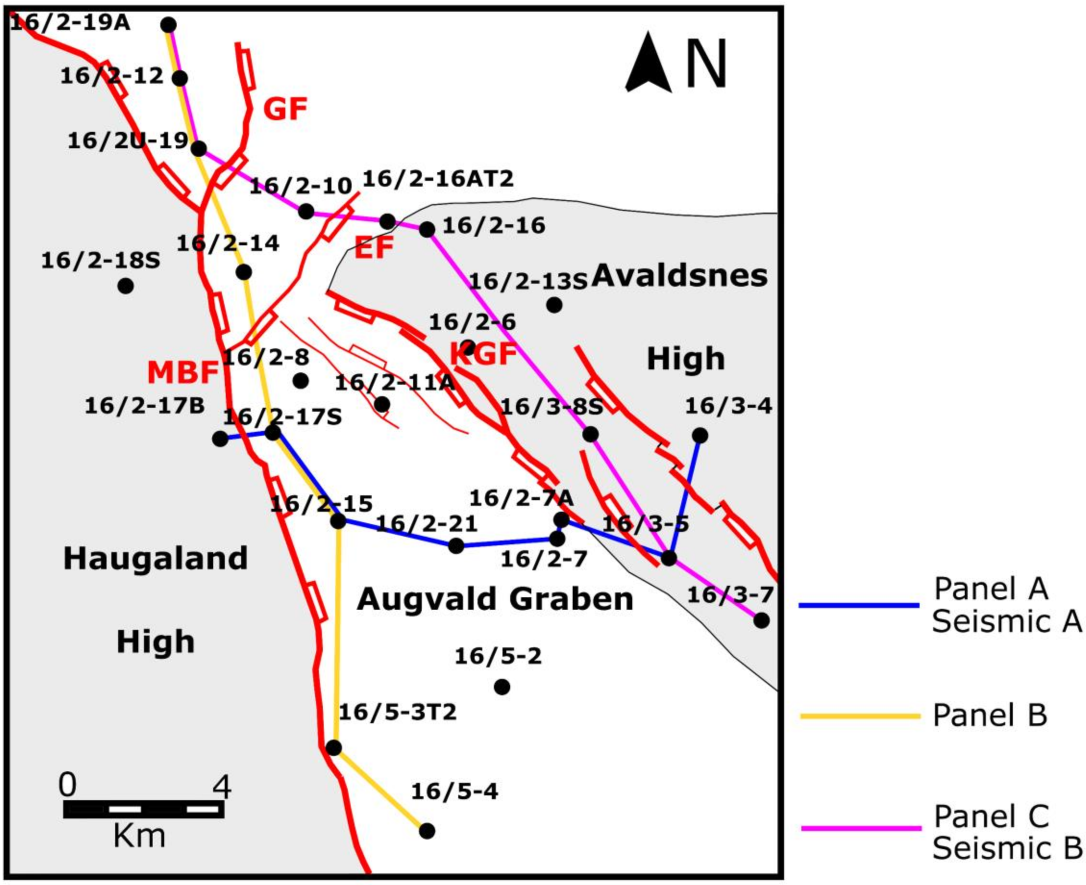


Fig. 2: Simplified structural map of the Johan Sverdrup Field (MBF: Main Boundary Fault, GF: Geitungen Fault, EF: Espevaer Fault, KF: Kvalen graben Fault, CAF: Central Avaldsnes Fault, NBF: Northern Boundary Fault). The location of the different well cores studied is shown. The blue, yellow and purple coloured lines correspond with the seismic lines and correlation panels shown in Fig. 3 and Fig. 8, respectively.

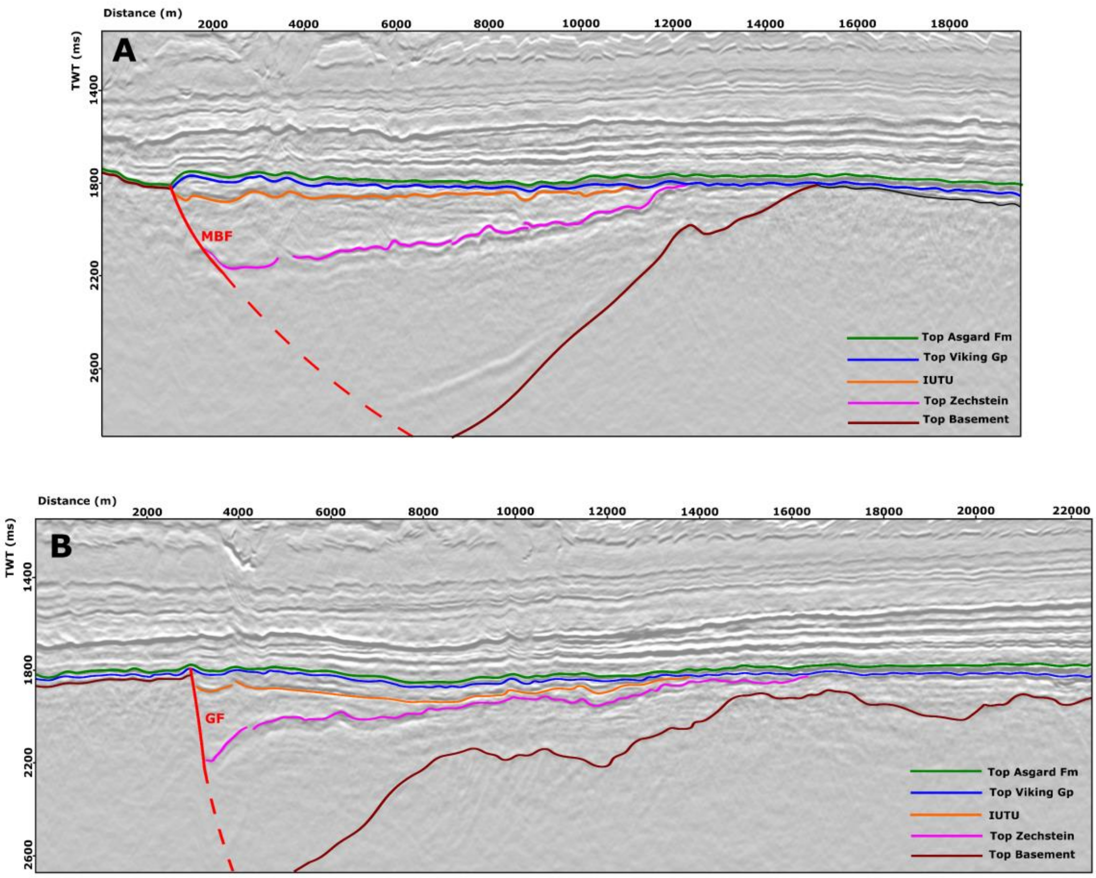
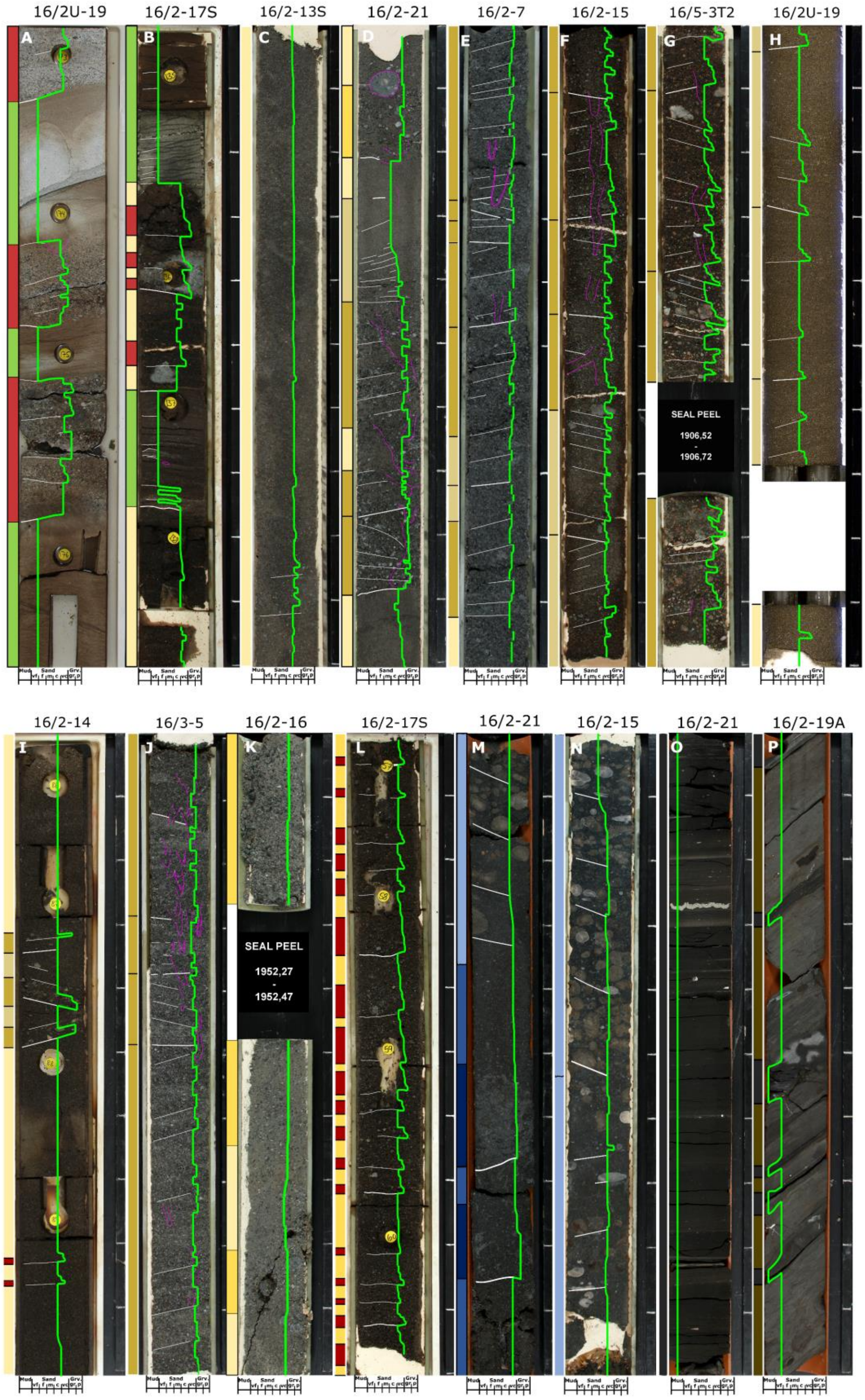


Fig. 3: (A) Seismic line in TWT across the Augvald Graben. Note the half graben geometry and the hanginwall anticline at the Main Boundary Fault (MBF). (B) Seismic line in TWT along the Avaldsnes Crest. Note the half graben geometry and the hangingwall anticline at the Geitungen Fault (GF). The Jurassic interval is thin, hence the whole interval is approximated to the Top Viking Group reflector. Note how the Viking Group reflector is highly erosional in the proximities of the Avaldsnes High (IUTU: Intra Upper Triassic Unconformity)



16/2U-19
16/2-17S
16/2-13S
16/2-21
16/2-7
16/2-15
16/5-3T2
16/2U-19
A
B
C
D
E
F
G
H
SEAL PEEL
1906,52
-
1906,72
16/2-14
16/3-5
16/2-16
16/2-17S
16/2-21
16/2-15
16/2-21
16/2-19A
I
J
K
L
M
N
O
P
SEAL PEEL
1952,27
-
1952,47
Mud
Sand
Grv.

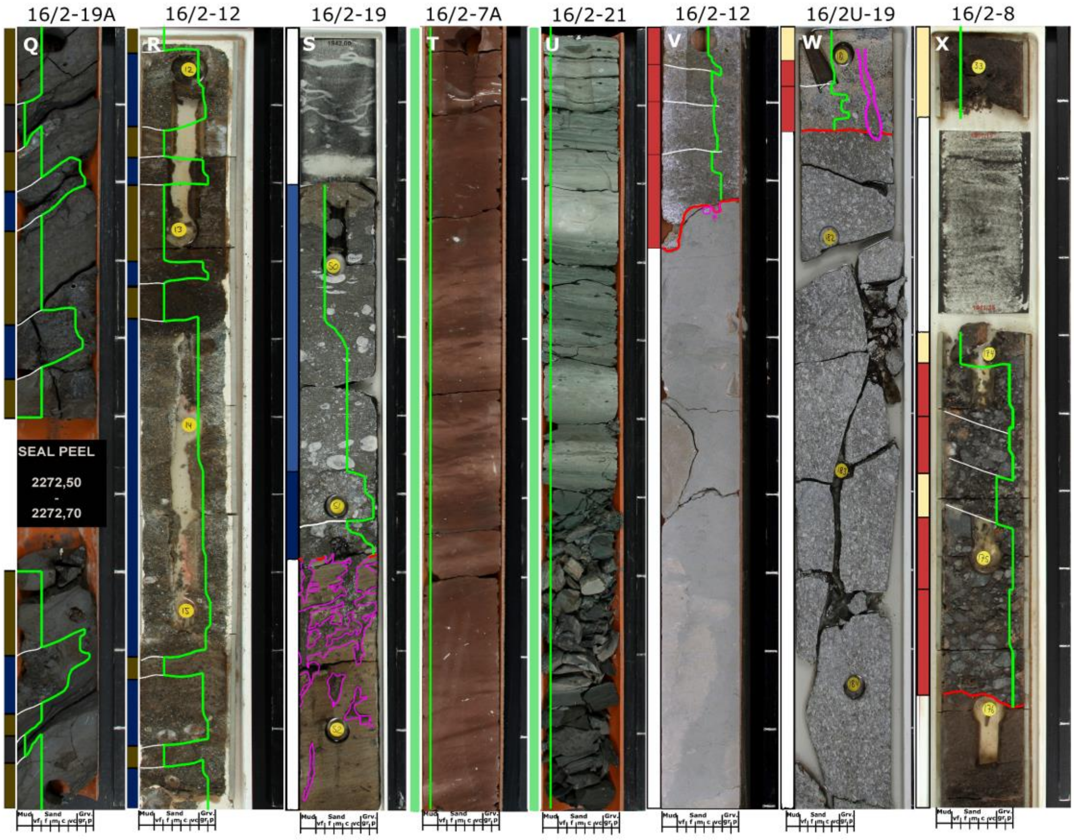


Fig. 4: Core images of the different facies and facies associations. (A, B) Interbedded, well-to-very well sorted, massive, rippled or laminated highly bioburbated fine grained sandstones of facies Sf and massive or normally graded, well-to-very sorted, coarse-to-very coarse grained sandstones and poorly-to-moderately sorted granules and pebbles, FA-1. (C) Massive, well-to-very well sorted, coarse-to-very coarse grained sandstones of facies Sm. (D) Highly erosional, finning upwards bedsets of interbedded, massive or bidirectional cross stratified, moderately-to-well sorted lower coarse sandstones, granules and pebbles, FA-3. (E, F, G, J) Moderately-to-well sorted, coarsening upwards bedsets of bidirectional cross stratified coarse-to-very coarse sandstones, granules and pebbles, FA-5. (H) Well-to-very well sorted, bidirectional cross stratified, coarse-to-very coarse grained sandstones, facies Scx. (I) Massive, well-to-very well sorted coarse-to-very coarse grained sandstones of facies Sm and bidirectional cross stratified, moderately-to-well sorted granules and pebbles of facies Gx. (K) Massive, non-bedded, coarsening upwards coarse-to-very coarse sandstones and gravels, FA-4. (L) Interbedded massive, normally or reversely graded poorly-to-moderately sorted coarsening and finning upwards bedset of coarse-to-very coarse sandstones, granules and pebbles, FA-6. (M,N) Dark coloured, belemnite and nodule rich, poorly-to-moderately sorted, massive and cross stratified, fine-to-coarse grained sandstones of the condensed section, FA-7. (O) Massive and thinly

laminated black shales of the Draupne Formation, facies Shb. (P, Q) Interbedded well sorted spiculitic fine grained sandstones and shales of the Draupne Formation, FA-9. (R) Interbedded poorly-to-moderately sorted fine grained spiculitic sandstones and massive or normally graded gravels of the Draupne Formation, FA-8. (S) Poorly sorted facies of the condensed section resting directly on top of the Statfjord Group. Note the Thalassinoides burrows deeply penetrating into the underlying rocks. (T, U) Red and green shales of the Asgard Formation, facies Shg. (V, W, X) Poorly-to-moderately sorted transgressive lag at the base of the intra-Draupne Formation sandstones.

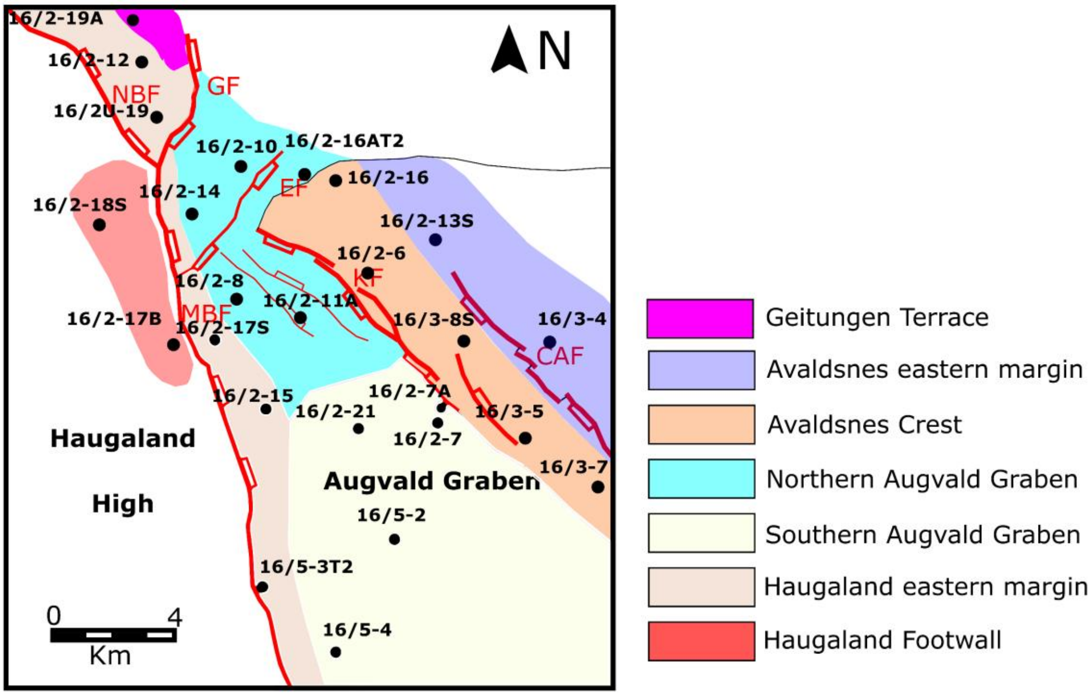
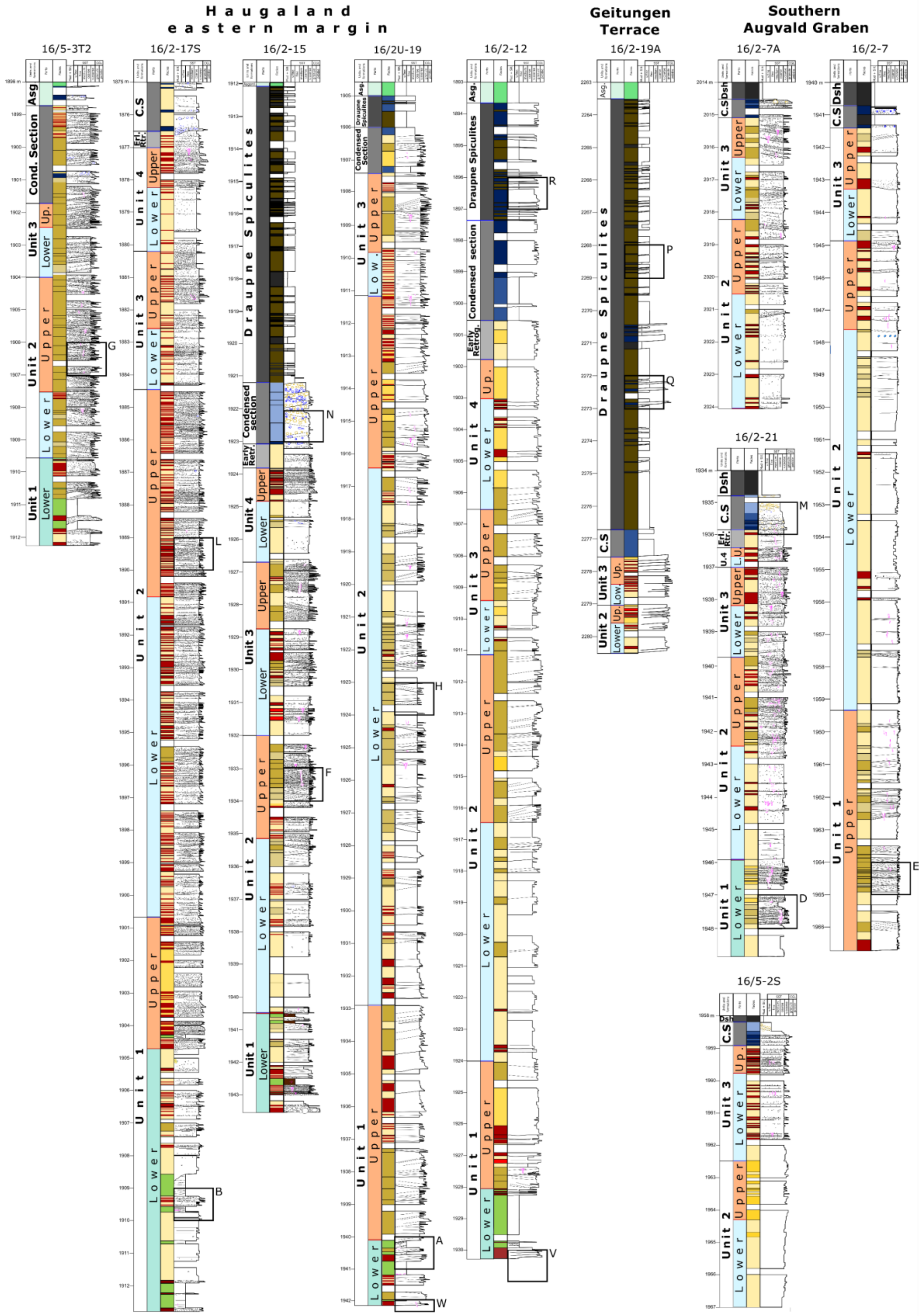


Fig. 5: Stratigraphic domains in which we have subdivided the description of the Late Jurassic succession in the Johan Sverdrup Field.


Haugaland eastern margin
Geitungen Terrace
Southern Augvald Graben
16/5-3T2
16/2-17S
16/2-15
16/2U-19
16/2-12
16/2-19A
16/2-7A
16/2-7
16/2-21
16/5-2S

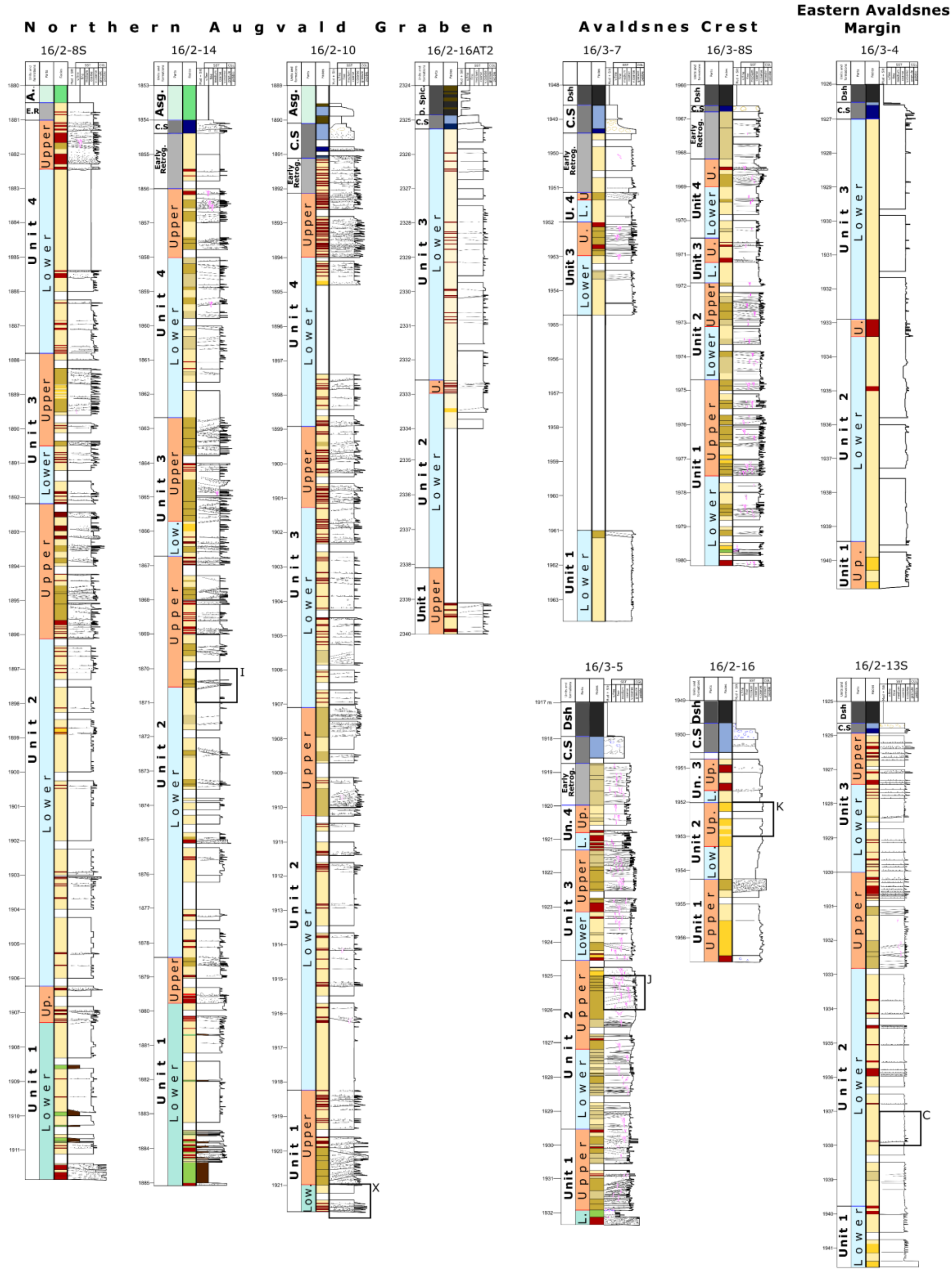


Fig. 6: Sedimentary logs resulting from the 1:1 well core descriptions of the intra-Draupne Formation sandstones. The stratigraphic succession has been described and subdivided in terms of units, parts and facies. Colour code for facies is located in Table 1. Color code for the Units is located in Fig. 8. Black square boxes correspond to the position of the different images shown in Fig. 4.

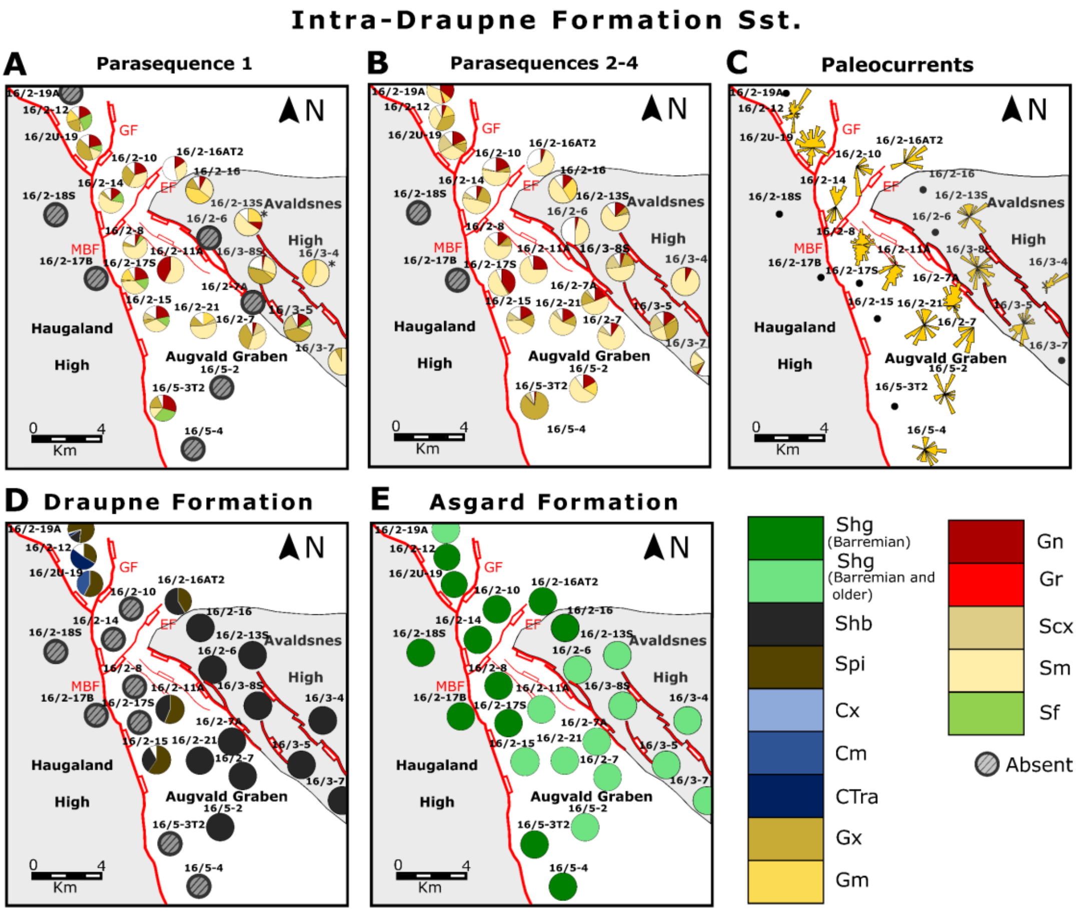


Fig. 7: Facies and palaeocurrent maps. Maps and pie charts show the distribution of the different facies which characterize the multiple parasequences at each well and that have implications for later palaeogeographical reconstructions.

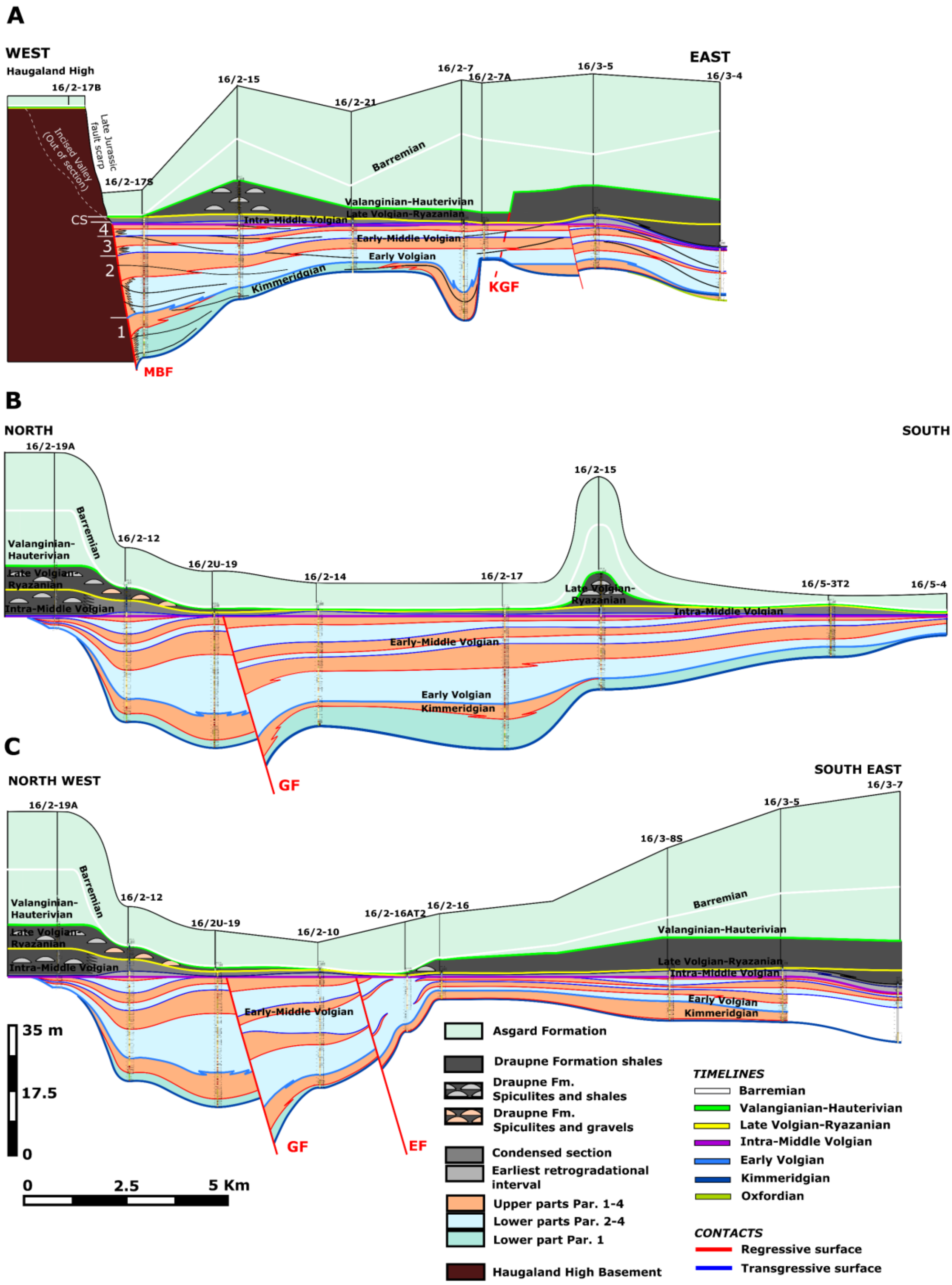


Fig. 8: (A) Correlation panel across the Augvald Graben. (B) Correlation panel along the hanginwall of the Main Boundary Fault. (C) Correlation panel along the Avaldsnes Crest (GF: Geitungen Fault, EF: Espevaer Fault, KGF: Kvalen Graben Fault, MBF: Main Boundary Fault). The location of the panels is provided in Fig. 2.

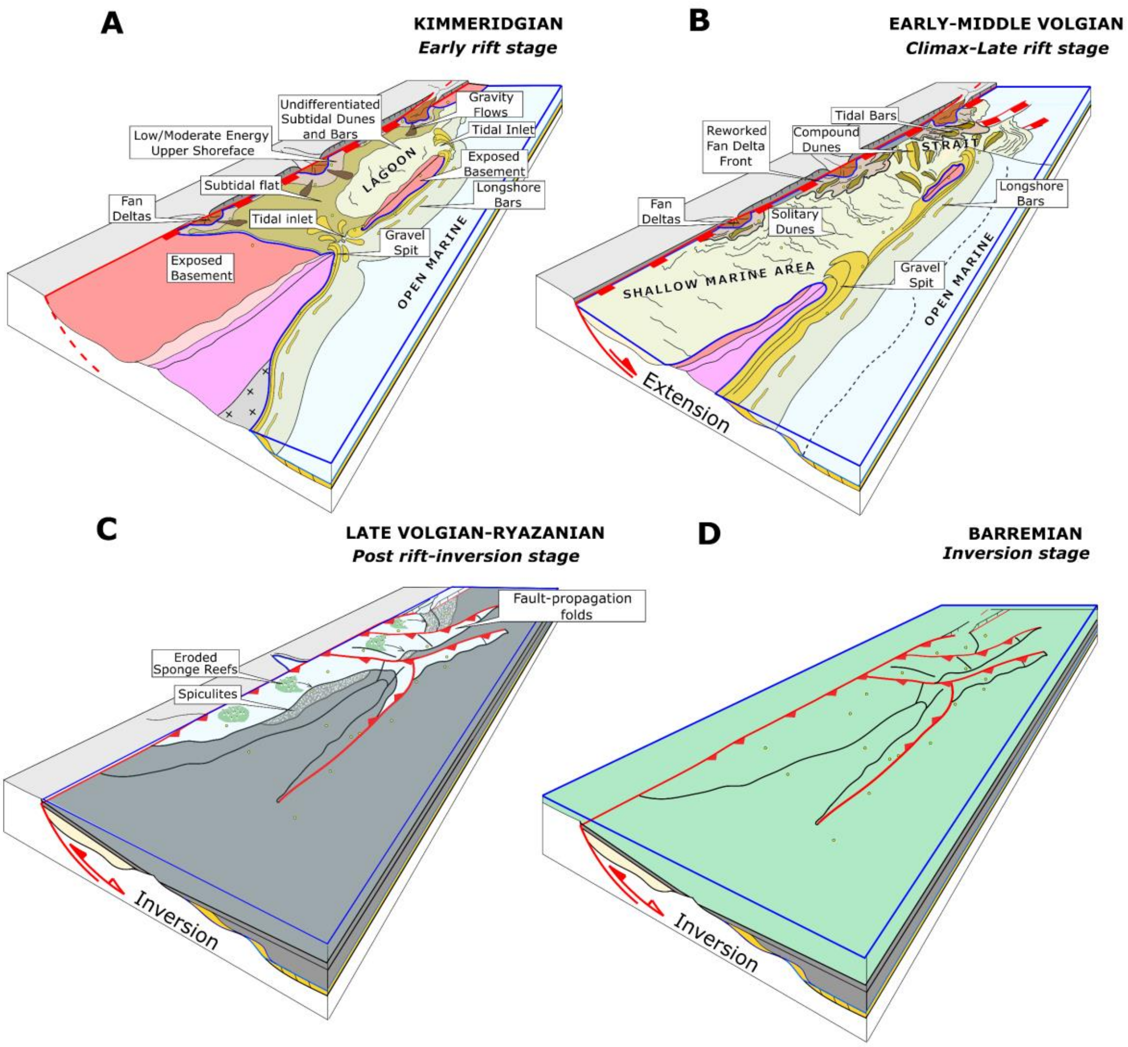


Fig. 9: Palaeogeographic reconstructions of the different episodes in the depositional history of the intra-Draupne Formation sandstones, Draupne and Asgard formations. (A) Kimmeridgian: Localized fault activity and inherited basement elevations promoted the development of a semi enclosed lagoon during the Early rift stage. Gravity flow deposits sourced from active fan deltas in the Haugaland High were accumulated in the Augvald Graben, characterized in low-to-moderate energy conditions, which favoured the deposition and preservation of fine grained sandstones and mud. Gravel rich deposits accumulated around the Avaldsnes High, forming a gravel spit. Tidal inlets acted as local connections between the lagoon and the open marine environment east from the Avaldsnes High enhancing current circulation and promoting the deposition of coarser sediments. (B) Early-Middle Volgian: Increased tectonic activity promoted general subsidence and the structuration of a narrow strait in the area between the Avaldsnes High and the Geitungen Terrace. Current energy was enhanced, causing a strong reworking of the fan deltas and coastal regoliths and the deposition of different types of coarse grained

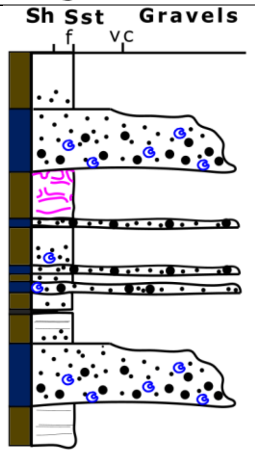
submarine barforms along the Augvald Graben. In contrast, the Avaldsnes Crest was dominated by longshore drift and across-shore wave processes which promoted the development of a gravel spit (C): Late Volgian-Ryazanian: Eustatic sea level rise promoted drowning of the clastic source areas and deposition of the Draupne Formation black shales and spiculites. Inversion of preexisting structures created broad anticline folds as a result of fault propagation. These folds controlled the deposition of the Draupne Fm. Sponge reefs, which grew on top of the anticline folds, where eroded and redeposited around these structures in the form of spiculitic sediments. (D) Barremian: Continued sea level rise ended up flooding the Haugaland High and promoting the widespread deposition of the Asgard Formation at the same time that inversion progressed.

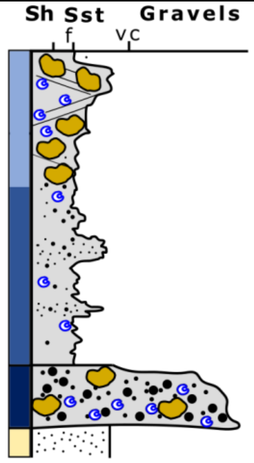
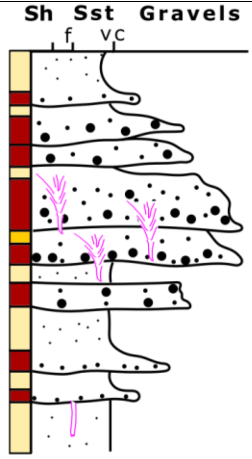
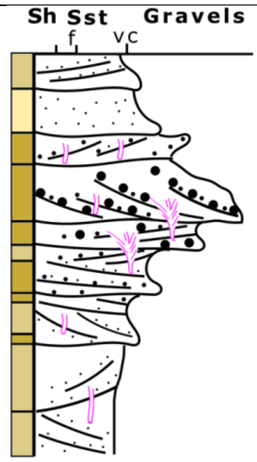
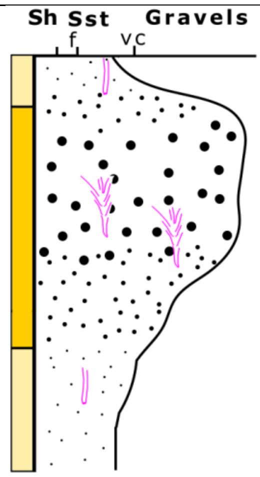
FACIES	GRAIN TEXTURE AND BIOTURBATION	SEDIMENTARY STRUCTURES AND BED THICKNESS	INTERPRETATION
Shg	Well-to-very well sorted, green and red coloured shales of the Asgard Formation. Bioturbated by *Planolites*, *Thalassinoides* and other cryptic burrowers.	Massive or showing millimetre scale thin laminations of lighter coloured shale or slightly siltier and sand-prone laminaes.	Pelagic shales reflecting background sedimentation. These are deposited after the drowning of the nearby clastic source areas in a deep marine shelf.
Shb	Well-to-very well sorted black coloured shales of the Draupne Formation. Bioturbated by *Planolites*, *Thalassinoides* and other cryptic burrowers.	Massive or showing millimetre scale thin laminations of lighter coloured shale or slightly siltier and sand-prone laminaes. Beds are 1 to 15 cm thick when they are interbedded with the spiculitic facies.	Pelagic shales reflecting background sedimentation. These are deposited after the drowning of the nearby clastic source areas in a deep marine shelf.
Spi	Poorly-to-very well sorted spiculitic fine grained sandstones with variable amounts of floating granules and belemnites. Attributed to the Draupne Formation. Might be intensely bioturbated by *Planolites* and *Thalassinoides*, completely destroying the original fabric.	Whenever the original fabric is preserved, spiculitic beds show millimetre scale sub-horizontal laminations, ripples or a massive aspect. Spiculitic beds are 3 to 15 cm thick. Bed boundaries might be diffuse due to amalgamation. Amalgamated packages might reach up to 1 meter in thickness.	Current reworked siliceous sponge reefs redeposited during a period of low clastic input in a relatively deep marine shelf.
Cx	Moderate-to-poorly sorted, dark coloured, fine-to-coarse grained sandstones very rich in floating gravels, septarian nodules and belemnites. This facies is typically found at the top of the condensed section, directly underneath the Draupne Formation.	Bidirectional cross stratification. Beds are 5 to 20 cm thick.	Ebb and flood current generated submarine dunes formed during a period of low clastic input and sediment starvation in a relatively low-to-moderate energy deep marine shelf.

Cm	Moderate-to-poorly sorted, dark coloured, fine-to-coarse grained sandstones rich in septarian nodules and belemnites.	Massive.	Condensation package reflecting low sedimentation rates and sediment starvation during the transition from shallow marine conditions to a progressively deeper marine shelf.
CTra	Moderate-to-poorly sorted, dark coloured, granules and pebbles with variable amounts of coarse-to-very coarse sandstone, belemnites and septarian nodules. This facies is typically found within or at the base of the condensed section.	Massive or normally graded. If it is found at the base of the condensed section it typically forms a 10 to 20 cm thick amalgamated deposit.	Transgressive lag and gravity flow deposits formed as the result of a regional relative sea level rise which drowned the majority of the clastic source areas.
Gx	Moderately-to-well sorted granules and pebbles, locally poorly sorted. Interlaminated well-to-very well sorted coarse-to-very coarse grained sandstones appear subordinately. Burrowed by *Skolithos* showing escape traces.	Bidirectional cross stratification. Beds are 3 to 25 cm thick, displaying coarsening and finning upwards patterns. Beds are internally laminated, showing mm to 2 cm thick laminaes of alternating granules, pebbles and sandstones.	Ebb and flood gravelly dune deposits generated under strong axial or alongshore currents in a shallow marine shelf.
Gm	Moderate-to-poorly sorted granules and pebbles. Bioturbated by *Skolithos*, sometimes displaying escape traces.	Massive. Beds are 2 to 15 cm thick whenever they are interbedded with other facies. Otherwise, this facies might be in transitional contact with the underlying or overlying facies, showing no clear boundary between beds or facies type.	Gravity flow deposit, wave generated/ wave reworked submarine barform foreset or massive due to bioturbation.
Gn	Moderate-to-poorly sorted granules and pebbles. Bioturbated by *Skolithos*, sometimes displaying escape traces.	Normal grading. Beds are 1 to 20 cm thick.	Gravity flow deposit
Gr	Moderate-to-poorly sorted granules and pebbles. Bioturbated by *Skolithos*, sometimes displaying escape traces.	Reverse grading. Beds are 2 to 15 cm thick.	Gravity flow deposit
Scx	Moderate-to-very well sorted, medium-to-very coarse grained sandstone. Moderately-to-well sorted granules may appear locally within beds. Burrowed by *Skolithos* showing escape traces.	Bidirectional cross stratification. Beds are 5 to 25 cm thick, displaying coarsening and finning upwards patterns. Beds are internally laminated, showing mm to 2 cm alternating laminaes of sandstone and granules, locally.	Ebb and flood sandy dune deposits generated under strong axial or alongshore currents in a shallow marine shelf.
Sm	Moderate-to-very well sorted, medium-to-very coarse grained sandstones. Bioturbated by *Skolithos*.	Massive. Beds are 2 to 15 cm thick whenever they are associated with other facies, however it is more common to find	Background sedimentation, interdune/interbar deposits formed in areas of weaker current

		them amalgamated forming meter thick massive packages.	activity, wave generated/ wave reworked submarine barform bottomset or massive due to bioturbation.
Sf	Well-to-very well sorted fine grained sandstones. Intensely bioturbated by *Macaronichnus segregatis* and, subordinately, *Thalassinoides.*	Sedimentary structures include symmetric and slightly asymmetric ripples with mud drapes and horizontal, mm to 1 cm thick, interlaminated fine grained sandstones and muds. Massive sometimes due to intensive bioturbation. Beds are 1 to 60 cm thick.	Tidal influenced rippled upper shoreface characteristic of a low-to-moderate energy shallow marine environment.

Table 1: Facies catalogue.

FACIES ASSOCIATIONS	DESCRIPTION	INTERPRETATION	GRAPHIC LOG
FA-9	Fine grained spiculitic sandstones (facies Spi) interbedded with massive black shales (facies Shb). Non apparent vertical trends. Bioturbated by *Thalassinoides*, *Planolites* and cryptic burrowers.	Reworked siliceous sponges redeposited close to inactive feeder systems or far offshore in a starved shelf.	
FA-8	Fine grained spiculitic sandstones (facies Spi) interbedded with massive or normally graded, moderate-to-poorly sorted granules and pebbles very rich in belemnites and septarian nodules (Facies CTra). Non apparent vertical trends. Bioturbated by *Thalassinoides*, *Planolites* and cryptic burrowers.	Reworked siliceous sponges redeposited close to an active fan delta system in a starved shelf.	

FA-7	Dark coloured, poorly sorted nodule and belemnite rich gravels (Facies CTra) passing upwards to dark coloured, moderately-to-poorly sorted, fine-to-very coarse grained massive sandstones (facies Cm), and locally, cross stratified nodule rich sandstones in the uppermost part of the section (facies Cx).	condensed section indicating low sedimentation rates. The section is generated during the drowning of the clastic source areas following a regional relative sea level rise. Current circulation in the basin might still be active as suggested by the presence of cross stratified deposits.	
FA-6	Coarsening and finning upwards bedsets, 0.5-2.2 meters thick, of alternating massive, normally or reversely graded, moderately-to-poorly sorted granules and pebbles beds (facies Gm, Gn and Gr) and moderately-to-well sorted massive coarse-to-very coarse grained sandstones (Sm). Bioturbated by *skolithos* showing escape traces.	Gravity flow dominated progradational and retrogradational submarine fan delta lobes deposited in a low, moderate or high energy environment.	
FA-5	Bidirectional cross stratified coarsening and finning upwards bedsets, 0.5-2.2 m thick, consisting of a basal well-to-very well sorted, coarse-to-very coarse grained sandstone member (facies Scx) passing vertically to a moderately-to-well sorted granule and pebble dominated upper member (facies Gx). Bioturbated by *skolithos* showing escape traces.	Bidirectional cross stratified barforms generated as a consequence of fan delta front and regoliths reworking under strong ebb and flood axial or alongshore currents.	
FA-4	Massive, coarsening and finning upwards bedsets, 0.5-1.5 m thick, characterized by a basal member consisting of moderate-to-very well sorted, coarse-to-very coarse grained sandstones (facies Sm) passing transitionally to an upper member consisting of massive, moderately-to-well sorted granules and pebbles (facies Gm).	Wave generated nearshore and swash bars or wave reworked current generated barforms.	

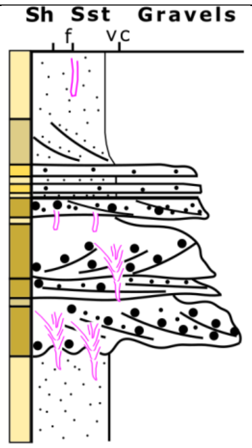
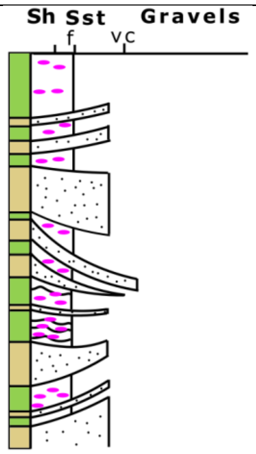
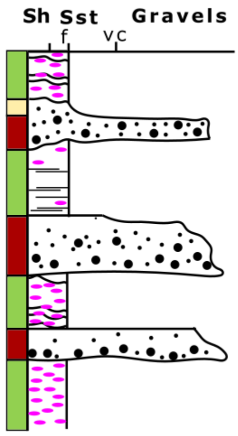
	Bioturbated by *skolithos* showing escape traces.		
FA-3	Highly erosional finning upwards bedsets, 0.2 to 0.7 m thick, consisting of a basal member dominated by bidirectional cross stratified deposits of facies Gx and, subordinately, facies Gm and Gn. The upper member is dominated by massive or cross stratified lower coarse-to-very coarse grained sandstone beds of facies Sm and Scx. Multiple vertical burrows showing escape traces are found at the base of each bedset, sometimes destroying the original fabric and promoting a rather structureless fabric.	Channel fill. Bedforms migrate within an active channel which is progressively abandoned. Its offshore position and the proximity to the Avaldsnes spit suggests these are tidal channels.	
FA-2	Bidirectional cross stratified very well sorted lower coarse-to-very coarse grained sandstones (facies Scx) interbedded with bioturbated fine grained sandstones (facies Sf) forming up to 0.5 m thick cross stratified bedsets. Bioturbated by *Macaronichnus* and *Thalassinoides.*	Tidal influenced upper shoreface barforms generated under low-moderate energy currents	
FA-1	Interbedded bioturbated fine grained sandstones (facies Sf) and massive or normally graded moderate-to-poorly sorted granules and pebbles (facies Gm, Gn and Gr). Contact between both facies tends to be abrupt. Gravel bed's basal boundary is sharp or slightly erosional. Bioturbated by *Macaronichnus* and *Thalassinoides.*	Gravity flow submarine fan delta lobes deposited in a shallow marine, low-to-moderate energy fine grained upper shoreface.	

Table 2: Facies association catalogue.