Sedimentology and facies analysis of ancient sand ridges: Jurassic Rogn Formation, Trøndelag Platform, offshore Norway

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Abstract

Sand ridges represent a common type of sedimentary bedform of modern shelves seldom used as analogues to interpret isolated marine sandbodies recognised in the subsurface. Lack of extended literature on outcrop and subsurface examples limits the possibility for their recognition and seems one of the reason behind this underrepresentation. The Draugen discovery made in the early 80`s represents an *unicum* in the Trøndelag Platform, offshore Norway. After more than 30 years the Froan Basin and Frøya High area are still underexplored and the Late Jurassic Rogn Fm play not well understood. Predicting reservoir distribution, and its internal architecture and properties requires the understanding of factors controlling sedimentation (e.g. palaeocirculation, depositional processes). North-south elongated sandbodies pertaining to the Rogn Formation are recognised in the Froan Basin and Frøya High encased within thick shaly deposits. Sandbodies develop above a ravinement or flooding surface (i.e. Callovian Unconformity) of regional extent where local depressions occur with a non-erosional concave-up top. Depressions representing the depositional loci for the accumulation of sand and development of the ridge. The presence of eastward and westward dipping reflections within the sandbodies allows identifying their large-scale architectures. Sediments form coarsening-upward vertical units characterised by a shaly base evolving upwards to medium- and coarse-grained sand forming tabular and trough cross strata. Locally, a fining upward trend characterised by plane-parallel stratification and coarse-grained massive layers is recognised. Sediments results well organised and sorted, which positively affects final porosity and permeability with values up to 30% and 6 Darcy, respectively - typical values for many sand ridges. Accordingly, sand ridges encased within thick shaly deposits can form stratigraphic traps with the potential for large hydrocarbon accumulations. The aim of the present study is to help the understanding of distribution, and internal architectures and properties of the Rogn Fm in the Trøndelag Platform.

Introduction

The main depositional processes controlling sediment distribution on shelf areas are tides, waves and storms being responsible for the remobilisation and accumulation of sediments according to the main longitudinal or transverse motion. Shelf sand bars, known also as sand ridges, are typical bedforms of shallow continental shelves and coastal regions (Kenyon et al., 1981; Dyer and Hunter, 1999; Snedden and Dalrymple, 1999; Leva-Lopez et al., 2016; Michaud and Dalrymple, 2016; Leszczyński and Nemec, 2019) formed usually during transgressive phases (Posamentier, 2002; Snedden et al., 2011) if sufficient sand-size sediment is available and the hydrodynamic conditions are favourable (Swift, 1975; van den Meene et al., 2000). The typical evolution of shelf sand ridges generally oriented subparallel to the prevailing current with a progradational component almost perpendicular respect to the palaeoshoreline (Suter, 2006; Snedden et al., 2011) makes complicated (i) their recognition in the ancient record and (ii) spatial distribution prediction due to the presence of internal architectures easily misinterpreted at seismic scale as shorefaces, or, more generally, coastal prograding bodies (e.g. infralittoral wedges *sensu* Hernandéz-Molina et al., 2000).

Sand ridges are extensively documented on Quaternary shelves (e.g. Belderson et al., 1982; Dalrymple, 1992; Reynaud et al., 1999; Le Bot and Trentesaux, 2004; Liu et al., 2007; Snedden et al., 2011; Soo son et al., 2012; Simarro et al., 2015), but recognition of ancient examples in the subsurface or outcrop is not so obvious and only few examples have been identified to date (e.g. Provan, 1992; Olariu et al. 2012; Schwarz, 2012; Messina et al., 2014; Leva-Lopez et al., 2016; Yin et al., 2016). Seismic-scale outcrop examples of sand ridges are limited in the literature although in the last years several examples have been studied in different settings (e.g. Siderno paleo-straits, Western Interior Seaway, West Laurentia continental shelf) producing relevant knowledge advances on the topic (Chiarella et al., 2012; Desjardins et al., 2012; Longhitano et al., 2014; Leva-Lopez et al., 2016; Rossi et al., 2017).

The main reason for such lack of confidence in recognising ancient sand ridges in subsurface and outcrop can tentatively be related to the lack of well-defined and widely accepted facies models and clear reference frameworks defining distinctive depositional architectures (Leva-Lopez et al., 2016). Their detection seems less problematic in modern shelves using high-resolution seismic data (e.g. sparker, unibbom, etc.) and cores. Studies have shown that the main diagnostic character recognisable in seismic sections is the presence of internal inclined reflectors with a typical angle ranging from 5-10° in active ridges to less than 2° in moribund (inactive) ridges (Suter, 2006). Internally sand ridges are organised with a typical coarsening-upward vertical trend (Leva-Lopez et al., 2016), and can occur as either isolated or vertically stacked bodies. Nevertheless, sand ridges distribution, and relative prediction for exploration purposes, can still be problematic when dealing with palaeoshelves where oceanographic conditions and palaeogeographic settings are not fully defined.

The Trøndelag Platform (offshore Norway) is an important underexplored hydrocarbon province located up-dip of a very prolific basin (i.e. Halten Terrace) and characterised by a successful Jurassic play. In particular, the syn-rift Upper Jurassic Rogn Fm can potentially host significant oil resources (e.g. Draugen field) but sand distribution and internal heterogeneities are difficult to predict over the entire platform due to the current limited well penetrations. In the Trøndelag Platform, the Rogn Fm has been interpreted as shallow marine sand bar (Provan, 1992), but detailed sedimentological analysis has not been so far performed.

The aim of the present study is to characterise the distribution and sedimentology of the Rogn Fm in the southern part of the Trøndelag Platform (i.e. Froan Basin and Frøya High). Accordingly, using seismic, wireline logs and core data, a geometrical- and facies-based approach has been used to demonstrate as the depositional architectures and sedimentological features match with the characteristic elements of sand ridges.

Geological setting

Structural setting and evolution

The Trøndelag Platform is one of the major structural elements of the Norwegian Sea and includes subsidiary elements like the Nordland Ridge, Froan Basin and Frøya High (Fig. 1A; Blistad et al., 1995). The Froan Basin is a NNE elongated Permo-Triassic basin filled with Triassic and Jurassic deposits. It is ~250 Km long and ~50 Km wide and consists of a set of half-grabens of alternating polarities along strike (Blystad et al., 1995). The Basin is bounded towards the east by the Vingleia Fault Complex in the northern and central sectors, and the Frøya High in the southern one. The Frøya High is a ~120 Km long and 40 Km wide north-south trending structure located between 63°N - 64°30`N on the mid-Norwegian Continental Shelf (Blystad et al., 1995; Slagstad et al., 2011). The Frøya High is located south of the Halten Terrace and is bounded to the west by the Rås Basin through the Klakk and Vingleia Fault complexes and to the east by the fault structures of the Froan Basin (Fig. 1A). During the Late Jurassic, the central and southern portion of the Froan Basin and the Frøya High experienced an uplift phase characterised by shallow-water deposition and erosion. The top of the Frøya High consists of a flat Late Jurassic-Early Cretaceous unconformity surface dipping gently towards west-northwest. Internally, the Frøya High consists of a granite basement clearly expressed by a strong positive magnetic anomaly (Blystad et al., 1995).

The Frøya High experienced a long tectonic history possibly associated with the Early Permian rifting episode (Blystad et al., 1995; Surlyk et al., 1984), with the eastern flank active during the Late Permian and Triassic, while on the western side, the major tectonic event resulted in the Middle Jurassic-Early Cretaceous rift (Blystad et al., 1995). Both western and eastern sides should be active during the Early Cretaceous with the top unconformity suggesting exposure during the same time interval (Blystad et al., 1995 and producing the cannibalisation of the Middle Jurassic succession. Drainage of the Frøya High is expected to have occurred towards both the west and the east away from the uplifted crest with sediments redistributed along the eastern margin up to the Froan Basin (e.g. Draugen Field area) and down-thrown along the Klakk and Vingleia fault complexes into respectively the Rås Basin and Halten Terrace (Fig. 1A). The lack of sediment deposition on the Frøya High between the Late Jurassic and Late Cretaceous suggests that it may have been subaerial or close to sea level at that time (Bell et al., 2014). Palaeogeographic reconstructions (e.g. Ziegler, 1988; Dorè, 1992; Nøttvedt et al., 2006) suggest that during the middle-late Jurassic the Trøndelag Platform was part of a 250 km wide and 1500 km long seaway separating the present-day Norway and Greenland (Figs. 2A and 2B).

Stratigraphic framework

The Middle and Late Jurassic stratigraphy of the Norwegian Sea represents the early syn-rift stratigraphic interval pertaining to the Viking Group (Fig. 1B; Dalland et al., 1988), characterised by sandstone reservoirs interbedded with source rocks and comprised either in stratigraphic or structural traps (Koch and Heum, 1995). The Viking Group is dominated by open-marine shale deposits (Melke and Spekk fms) as response to the normal fault-controlled subsidence, which resulted in drowning of the Halten Terrace area (Dalland et al., 1988; Swiecicki et al., 1998). The Melke Fm (Bajocian-Oxfordian) is dominantly a claystone deposit with siltstone and limestone interbeds, and sandstone (Dalland et al., 1988). The Spekk Fm (Oxfordian-Tithonian) consists of non-calcareous bituminous dark brown to dark grey shale with very high organic content deposited under starved conditions (Dalland et al., 1988; van der Zwan, 1989). Locally, around tectonic highs or structural controlled depocentres, coarse-grained clastic successions accumulated (Rogn Fm and intra-Melke Sandstone). The Rogn Fm (Kimmeridgian-Tithonian?)

occurs as lenticular units within the Spekk Fm. These units consist of massive to bioturbated medium-to coarse-grained sandstones with parallel- and cross-lamination with coarsening-upward grain-size trends, interpreted as shallow marine sand bar deposits (van der Zwan, 1989; Provan, 1992).

The Rogn Formation

The Rogn Fm represents a sandstone dominated deposit encased within the shaly Spekk Fm (Fig. 1B). Analysis of well data and 3D seismic surveys across the mid-Norwegian Continental Shelf (i.e. Froan Basin, Frøya High, Trøndelag Platform and Halten Terrace) suggests that the Rogn Fm encompasses different depositional environments (Fig. 2C) and that deposition was not synchronous across the area. In the Froan Basin and Frøya High, the Rogn Fm developed in a shallow-water environment (0 - 100 m depth) typically forming coarsening-upward units. The lower interval of the unit consists of sandy shales passing upwards to micaceous, fine-grained sandstones, whose primary sedimentary structures are obliterated by the intense bioturbation (Ellenor and Mozetic, 1986). Upwards, the unit is characterised by generally structureless, moderately- to well-sorted, fine- to coarse-grained sandstones, with scattered very coarse-grained clasts. This uppermost interval is commonly bioturbated although cross stratifications is locally recognised. Individual strata have gradational upper and lower contacts or may be amalgamated forming several meters thick strata-sets.

Database and Methodology

Stratigraphic and sedimentological analysis has been conducted on time-migrated 3D seismic dataset covering an area of ~1,275 km^2, penetrated by 13 wells (Fig. 2C). Each well contains an extensive and consistent suite of wireline logs, including gamma ray (GR), neutron porosity (NPHI) and bulk density (RHOB) logs, with a high-quality core coverage from 4 wells (144 m of total core length). Conventional sedimentological logging has been used, with a bed-thickness measurement accuracy of 0.5 cm (scale 1:50). Facies analysis has been carried out based on lithology, grain-size and sorting, primary sedimentary structures, bioturbation index (BI, Bann et al., 2008) and trace fossil assemblages. Facies have been grouped into facies associations. Facies associations have been calibrated with correspondent wireline log profiles, in order to determine their diagnostic log expression and reservoir properties. Data distribution allow us to have (i) the southern area (i.e. Frøya High) covered by a 3D seismic survey and three wells (only one of them located within the seismic survey), with cores coverage over the Rogn Fm, and (ii) the northern area (i.e. Froan Basin) covered by ten wells, including three cores over the Rogn Fm interval (Fig. 2C). Finally, in order to reproduce a palaeotopography representative of the Upper Jurassic conditions effects of sediment compaction, thermal subsidence and post-rift fault reactivation discussed by Bell et al. (2014) have been taken into account.

Seismic characterisation and distribution of the Rogn Fm

The syn-rift Upper Jurassic stratigraphic interval is defined by the Callovian (CU) and Base Cretaceous (BCU) unconformities (Figs. 1B, 3 and 4A). The Callovian Unconformity is a sharp ravinement or flooding surface related to a regional-scale uplift. The thickness of the interval between the Callovian Unconformity and BCU remains constant except for the presence of localised zones of thickness increase due to depressions characterising the CU surface. These topographic lows seem to represent a preferential locus of sedimentation for the Rogn Fm. The Rogn Fm shows a cross-sectional asymmetric shape consistent throughout the study area further characterised by the occurrence of internal, either east or west oriented, dipping reflectors representing accretionary surfaces associated with mechanisms of lateral migration (Fig. 5). Deposits are elongated along a preferential NNE-SSW direction parallel to the Late Jurassic palaeoshoreline (Fig. 2C).

The Rogn Fm has been mapped on 3D seismic data over the southern portion of the Frøya High (Fig. 2C). Four NNE-SSW oriented asymmetrical sandbodies referred to the Rogn Fm, and encased within the Spekk Fm, have been mapped above the CU in the southern area (Figs. 2C and 4). The sandboby 1 is the northernmost one and not completely mapped due to its extension out of the area covered by the available seismic survey (Figs. 2C and 4B). The sandbody is penetrated by the exploration well 6306/6-1 and is ~5 Km long (referred to the visible mapped extension) and ~3.8 Km wide with a flattened thinning bulge structure SE of the main body (Fig. 5A). The sandbody is ~93 m thick in the well position corresponding to ~60 ms. The eastern edge of the sandbody generally maintains a steeply dipping termination with a marginally shallower western closure and an overall convex up shape morphology. Internally, the east-west cross section shows high angle westwards downlapping internal reflectors. The sandbody 2 shows a lenticular morphology punctuated by small irregularities at the base and top (Fig. 5B). The sandbody is ~8.2 Km long and ~3.7 Km wide with a maximum thickness of ~55 ms. The main peculiar characteristic is an elongated protuberance that stacks from the main body pinching out towards the north. Internal downlapping reflectors migrate towards the east. The sandbody 3 shows a pronounced concave base morphology, and is ~4 Km long and ~3.5 Km wide (Fig. 5C). The typical N-S elongated shape common to the other sandbodies is not so obvious in this particular one. Internally, downlapping reflectors show an eastward migration marked by a lateral progradation of the body. The sandbody 4 is the southernmost one, and is not completely mapped due to its extension out of the area covered by the seismic survey (Figs. 2C and 5D). The internal reflectors downlap towards the east against a steep surface with a pronounced aggradation style.

Facies analysis

Facies analysis has been carried out on core material available from four wells (Fig. 2C). Based on grain-size variability and sorting, nature of bed contacts, sedimentary structures, and degree of bioturbation, three main facies associations (FA) have been identified.

Description

Deposits pertaining to the Rogn Fm lie conformably on top of the fine-grained open/shelf sediments of the Spekk Fm (Figs. 6, 8 and 10). Facies can be grouped into three main facies associations (FA1, FA2 and FA3) organised to form coarsening-upward trends up to ~40 m thick, in turn capped by a fining-upward or blocky serrate interval up to ~20 m thick.

Facies association FA1 represents the lower portion of the succession and consists of moderate to well-sorted fine- to medium-grained sandstone containing plane-parallel stratification and ripples- to dune-scale cross-stratification (Fig. 8D). Cross bedding is highlighted by the presence of fine-grained laminae producing a rhythmic alternation. Belemnite rostrums are scatterly distributed (Figs. 8C and 8D). Bioturbation is moderately to commonly present (BI = 1-3) and trace fossils consist of vertical and horizontal burrows including *Skolithos* and *Planolites*. FA1 is characterised by high upward decreasing GR values (60-90 API) (Fig. 6).

Deposits of facies association FA2 gradually overlies facies association FA1. FA2 consists of well-sorted medium- to very coarse-grained sandstone characterised by up to ~1 m thick tabular and trough cross-strata (Figs. 8-10). Scattered granule-size clasts of quartz and glauconite, and more rarely coal and lignite fragments occur (Figs. 9 to 11). Facies association FA2 is locally highly bioturbated (BI = 4 - 5) and trace fossils consist of vertical burrows including *Diplocraterium* and *Ophiomorpha* (Figs. 8 and 10). Wireline logs of FA2 show a slightly blocky to coarsening-upward shape with GR values higher than what generally expected for well sorted sand (40-80 API).

Facies association FA3 is usually thinner respect to facies associations FA1 and FA2 except that in wells 6407/12-1 and 6306/6-1 where it reaches a thickness up to ~30 m (Figs. 6A and 7). It consists of medium- to coarse-grained sandstone characterised by massive and plane-parallel stratification rich in organic material (Fig. 11). Mudstone intervals are also recognised in the wireline logs. These lithofacies commonly alternate each other capping the cross-strata set of facies association FA2. Bioturbation is moderately to commonly present (BI = 1-3) in the coarse-grained intervals, and trace fossils consist of vertical and horizontal burrows including *Skolithos* and *Planolites*. FA3 is characterised by a high GR (100-140 API) response (Fig. 6).

Interpretation

The correlation of sedimentological and wireline logs (Fig. 6) suggests that the studied deposits of the Rogn Fm form mound-shaped, broadly lenticular sandstone bodies roughly elongated in the north-south direction. This feature may be indicative of accreting bedforms characteristically elongated in one dominant direction typical of ridges in modern environments (Snedden et al., 2011; Boyd et al., 2004). Sediments are interpreted to have been deposited under currents characterised by a strong unidirectional component, periodically changing in strength and possible direction through time, as testified by the rhythmical alternation of fine- and coarse-grained sandstone laminae. This type of alternation in sand-dominated deposits has been interpreted by Longhitano & Nemec (2005) in Tortonian similar successions exposed in southern Italy as evidence of modulated currents. Plane-parallel and ripple cross lamination (FA1) are interpreted to be deposited by currents characterised by wave influence in inter-ridge swales (Swift and Field, 1981; Liu et al., 2007). Currents were interacting with waves forming long-crested vertically-stacked subaqueous 2D and 3D dunes (FA2) as part of flow-aligned sand ridges. The alternation of massive and plane-parallel lithofacies in bar capping (FA3) indicates fluctuating wave orbital velocity (Komar and Miller, 1975) possibly including episodic erosion by storm waves (Clifton and Dingler, 1984). The swales are thought to have funnelled the near-bottom current, boosting it to the upper flow regime at tidal current peaks producing plane-bed transport and considerable downflow bypass of sand (Messina et al., 2014). In this setting, mud and fine-grained sediments are not typically deposited due to the persistent turbulence related to the interaction of waves and strong currents (Montenat et al., 1987; Keene & Harris, 1995; Longhitano & Nemec, 2005; Longhitano et al., 2014). The presence of both horizontal and vertical trace fossils corroborates the rhythmic alternation of weaker and stronger currents respectively (MacEachern et al., 2012). Scattered granule-size clasts, as well as the abundance of vertical escape traces suggest high rate of erosion and sedimentation, justifying the upward increase of the compositional maturity of sandstone, the scarce amount of fine sediments, and the presence of irregular/erosional stratal discontinuities.

The presence of glauconite, and the very slow sedimentation rate required for its formation could contrast with the strong unidirectional currents necessary for the formation of sand ridges. According to Odin and Matter (1981), a break in sedimentation of 10^5-10^6 years is necessary for the formation of well-crystallized glauconitic micas. However, given enough time, sideritization of clay layers and clasts in sand units within a ridge could occur after deposition and shallow burial (Gaynor and Swift, 1988). Coal material suggests the presence of paralic environments in close proximity of the depositional area. Trace fossils assemblages can be referred to *Skolithos* and *Cruziana* ichnofacies.

Petrographic composition

Description

Compositional analysis of the arenitic fraction of the Rogn Fm in the Frøya High (wells 6307/7-U-02 and 6307/7-U-03) indicates a quartz-feldspatic dominance (*Qt53 F36 L11*), rich in microcline in the lower portion, with subordinate lithic fragments (Fig. 12). In order of abundance, the lithic grains (L) consists of quartzite, gneiss, sedimentary (e.g. chert) and volcanic rocks. Detrital clay minerals include kaolinite, minor illite, and trace amount of chlorite (Goesten and Nelson, 1992). Rare authigenic minerals comprising feldspar overgrowths with localised pyrite, siderite and calcite cements forming concretions are also present. Common accessory heavy minerals are short prismatic to tabulate euhedral and subhedral zircon, rutile, tourmaline, opaques, garnet and apatite, and, in places, amphibole, staurolite and kyanite (Mørk and Johnsen, 2005. Garnet minerals locally form up to 8% of the bulk volume. Petrographic data indicate a compositional change, from the base to the top of the Rogn Fm, from arkosic to sub-arkosic sandstone (Fig. 12; Mørk and Johnsen, 2005).

Interpretation

A dominance of the stable heavy minerals suggests an origin from plutonic source rocks. This is also supported by an apparent lack of rounding: the zircons are short prismatic to tabulate euhedral and subhedral, and with no distinct evidence of mechanical abrasion. In the Draugen Field, reworking of Early and Middle Jurassic sediments has been recognised in the Rogn Fm (van der Zwan, 1990). This indicates that the main sediments source area was possibly related to fault uplift along the western margin of the Trøndelag Platform, suggesting that both crystalline basement rocks and Mesozoic sedimentary deposits were involved in the erosion (Mørk and Johnsen, 2005).

Reservoir characterisation

The Rogn Fm is generally characterised by petrophysical values showing a coarsening upward pattern in the lower interval of the unit followed by constant values producing a blocky shape in the middle and upper intervals. In the Froan Basin, wireline logs penetrating the Rogn Fm indicate the presence of a single unit up to 50 m thick (Fig. 6). The combination of wireline logs and core data support the interpretation of this unit as an individual prograding sand ridge. Conversely, in the Frøya high well data indicate the presence of two coarsening upward units (each up to 25 m thick) capped by a fining upward interval (Fig. 7). This interpretation is in agreement with the presence of multiple sand ridges characterised by a more complex internal organisation than in the Froan Basin. Accordingly, the overall trend recognised in well 6306/6-1 can represent the result of two vertically stacked complexes possibly capped by deposits pertaining to inter ridge areas. Unfortunately, core material from the upper interval has not been recovered and thus is not possible to perform a detailed facies analysis. Comparing the GR with the Vshale well-track of the borehole 6306/6-1 (Fig. 13), both logs correlate well with an increases in GR generally being mirrored by the Vshale log and both showing varying values throughout the formation. A strong negative separation has been observed between the shallow and deep resistivity logs that persists through the whole formation. Both shallow and deep resistivity make a positive jump when a low GR and low Vshale is reached and resides to background resistivity values when GR and Vshale increase again. Vsand values produce extremely variable results with sand content reaching 0% in some interval and increasing to a maximum of 81%. These fluctuations are recognised only in well 6306/6-1 in the middle of the formation with peaks and troughs generally being sustained over short depth intervals. Beds with low sand content are ~1 m thick in most cases.

The porosity and permeability logs correlate well with Vsand values with fluctuations in Vsand being imitated across both permeability and porosity well tracks. The permeability curve displays sharp deviations from high to effectively values at contacts between high and low Vsand responses. In the Draugen Field (Froan Basin), the Rogn Fm shows porosity up to 30%, permeability up to 6 Darcy at a depth of ~1700 m. In the Frøya High (well 6306/6-1), total porosity remains constant throughout the formation with average value of ~24%. For this well, effective porosity is ~10% less than total porosity, on average. The difference between effective and total porosity is accounted for isolated pores, which may indicate the presence of clay content. Prolonged high porosity and permeability figures are recorded in correspondence with thick high Vsand sections, which are locally marked by very high Vsand values at their top and bottom limits. An average NTG of ~75% has been calculated. Due to the unusually high GR readings in some of the wells (e.g. 6306/6-1), NTG was not achieved using a GR cut-off value but instead by analysing the Vsand content, in association with porosity and permeability logs. In particular, intervals with >30% Vsand, >0.05D and >10% effective porosity were categorised as sands. The elevated GR readings are likely to be related to the abundance of K-rich minerals such as micas and glauconite. The negative separation between the shallow and deep resistivity logs is interpreted as response to fracturing and permeability.

Discussion

The Rogn Fm deposits indicate accumulation of sand in the shelf area where patchy or isolated sand ridges developed (Snedden et al., 2011; Desjardins et al., 2012; Leva-Lopez et al., 2016). Similar linear sand ridges characterised by frontal growth and oblique lateral migration have been reported from different shallow marine depositional environments including continental shelves, narrow seaways and straits, coastal embayments and large estuaries (Caston, 1972; Swift, 1975; Swift & Freeland, 1978; Swift & Field, 1981; Huthnance, 1982; Harris et al., 1992; Liu et al., 2007; Chiarella et al., 2012; Longhitano et al., 2014; Messina et al., 2014; Leva-Lopez et al., 2016; Rossi et al., 2017). Recently, Hernandéz-Molina et al. (2018) documented sandy bedforms referable to sand ridges to deep marine settings dominated by bottom-currents.

Paleogeography

Regional-scale paleogeographic reconstructions suggest that during the Late Jurassic, sedimentation in the Norwegian Sea occurred in a shelf condition as part of a seaway extending southwards from the open Boreal Sea (Fig. 2B). Seismic analysis of the Rogn Fm in the study area, supported by stratigraphic and facies analysis performed in available wells and core material, suggests a sandy shallow marine depositional system where tidal currents and storms were able to rework the entrapped sand into elongated bedforms. Main paleocurrent circulation (northward *versus* southward) is still questionable due to the lack of dipmeter data.

Latitudinal shifts in paleobiogeographic ammonite provinces can provide an indication of the net seaway current directions in the Jurassic (Bjerrum et al., 2001). In particular, Arctic influences on seaway waters are indicated by faunal dominance and southward spread of boreal ammonites and cooler climatic conditions inferred from palynology and clay mineralogy. Conversely, Tethys-influenced seaway waters may be inferred from the presence of sub-Mediterranean fauna and indicators of warmer water/climate (Bjerrum et al., 2001). Overall, the paleobiogeographic provinces of the Jurassic suggest that southward-flowing seaway currents dominated in the Toarcian, Early Callovian, latest Callovian to Early Oxfordian, late Middle and Late Oxfordian, and in the Kimmeridgian (Bjerrum et al., 2001). In intervening periods the currents flowed northwards or were blocked by very shallow sills or land as in much of the Middle Jurassic. Accordingly, although in the studied area northward-directed currents have been proposed by van der Zwan (1997), the contemporaneous presence of eastward and westward dipping internal surfaces (Fig. 5) suggests the presence of southward paleocurrents as well. This condition is common to large seaways where currents with opposite directions may co-exist promoting the migration of bedforms accreting accordingly. Moreover, enrichment in diagnostic heavy minerals recognised in core material (i.e. 6307/7-U-02 and 6307/7-U-03) indicates a contribution from slightly weathered metamorphic and igneous mafic rocks (located north of Frøya High) suggesting a southward sediment transport (Mørk and Johnsen, 2005). Southward paleocurrents and current-dominated sandstone bodies have been recognised also in the adjacent East Greenland seaway (Surlyk, 1991, 2003) and documented in the Halten Terrace in Middle-Jurassic (Bajocian-Bathonian) deposits of the Garn Fm (Messina et al., 2008).

Sand ridges architecture

Integrated sedimentological and facies analysis using seismic and core data allow to characterise the studied internal sandbody geometry in terms of both large- and small-scale architectures. Seismic analysis performed in the southern area shows how the sandbodies of the Rogn Fm result completely encased within the thick marine mud interval of the Spekk Fm. In particular, the Rogn Fm has a sharp basal ravinement or flooding surface corresponding to the regional Callovian Unconformity (Figs. 4A and 5). The Callovian Unconformity is characterised by patchy distributed erosional depressions forming the sedimentation loci for the subsequent development and accumulation of the sandbodies (Fig. 4A). The growth of a linear shelf ridge from a small sea-floor perturbation, not necessarily elongated according to the future ridge orientation, was first modelled by Huthnance (1982). In this model, the bottom friction associated with the sea-floor depression delays the upslope current more than it accelerates the downslope one. Therefore, the transport of sand towards the ridge crest will be higher than the off-ridge transport producing ridge growth dominantly over ridge advancement (Reynaud and Dalrymple, 2012). Accordingly, the characters of the Callovian Unconformity and the resulting palaeotopography seem to represent a key factor in order to predict the distribution of the Rogn Fm in the Trøndelag Platform.

The top of the Rogn Fm is non-erosional with a convex up geometry passing upwards to the Spekk Fm. The large-scale geometry of the sandy deposits shows a lenticular shape in both N-S and E-W directions (Figs. 5 and 14A). The sand ridges were formed slightly parallel to the main palaeocurrent and palaeoshoreline (Fig. 2C). The bedforms are characterised by the presence of dipping internal surfaces showing direction of lateral accretion at a high oblique angle relative to the prevailing palaeocurrent direction (Fig. 5). The sandbodies thickness show an asymmetry with gradual increase followed by a rapid decrease towards the main direction of migration (Fig. 14A). Similar features are visible at different scales in present-day examples (Figs. 14B and 14C). In these modern sand ridges, strata are arranged to form single, or occasionally multiple, vertically stacked coarsening-upward units covering the entire thickness of the bedform (Fig. 6). Smaller bedforms are typically oriented at an oblique angle to the crests (Fig. 14C). Sediments are organised into two-dimensional and three-dimensional dunes with subordinate amount of plane parallel stratification and trace fossils (Figs. 8 to 11, 14B and 14C). Modern examples of sand ridges show that dunes developing on active ridges have orientations with angles of ~40 degrees with respect to the ridge axis (Figs. 14B and 14C).

The development of sand ridge along the shelf can be related to forced regressive and transgressive system tracts dominated by storms or tides (Leva-Lopez et al., 2016 and references therein). Following Snedden & Dalrymple (1999), conditions that seem to be necessary in order to promote the development of sand ridges after the formation of the Callovian transgressive ravinement (CU) are (i) pre-existing irregularities in the seafloor topography, (ii) sufficient sand sediment supply, (iii) presence of tidal and/or storm-driven currents able to rework sand-sized sediment, and (iv) sufficient time for the sand to be moulded into a ridge or ridge field. Measured velocities of ridge-forming currents are in the range of 0.5−2.5 m/s (McBride, 2003). In particular, bathymetric irregularities on the sea floor accelerate the flow due to constriction. Analysis of modern examples shows that tidal sand ridges may reach ~50 m in height with their width and length up to 10 km and 180 km, respectively. Shallow seismic investigations reveal internal dipping reflectors having angles ranging from less than 2 degrees in moribund (inactive) ridges up to 5-10 degrees in actively accreting ridges. Ridges generally migrate with an oblique angle of ~20 degrees in the direction of the dominant regional current. Moreover, regardless the nature of the currents generating the ridges (i.e. waves or tides), all ridges share similar morphological external and internal architectures. The only significant difference recognised studying present-day examples is that tidal-built ridges are commonly more elongated respect to the main current direction than storm-built ridges (Desjardines et al., 2011). Accordingly, the Rogn Fm deposits recognised in the Draugen Field, bedforms 1 and bedform 2 could be potentially related to tidal-modulated currents, while the bedform 3 to storms (Figs. 1 and 4B). Bedform 4 is not possible to be referred to any of the two proposed processes due to its extension outside the area covered by the available seismic survey (Fig. 4B).

Reservoir potentiality

Shelf sand ridges can represent a significant type of reservoir. The process of ridge evolution and its development above a ravinement surface after the transgressive phase, improve the sandbody properties from a textural standpoint, which often positively affects subsurface porosity and permeability (Snedden et al. 1999). The typically high content of K-rich minerals like glauconite can have an impact on the reading of GR respons that need to be taken into account for a correct Net-to-gross evaluation. The Rogn Fm deposited in the Trøndelag Platform represents a successful example of good reservoir. In particular, the Draugen Field discovered in 1984, and brought into production in 1993, has produced as today around 147 million Sm3 o.e. of the original recoverable reserves, with ~3 million Sm3 o.e. representing the remaining reserves (NPD, 2019). Moreveor, petrophysical analysis suggests that the Rogn Fm reservoir properties are good in the sandbody tested in the Frøya High as well. That suggests that sand ridges represent an underestimated type of reservoir in the Trøndelag Platform worthy of further attention.

Conclusions

The Upper Jurassic syn-rift Rogn Fm deposited in the Froan Basin and Frøya High, Trøndelag Platform, offshore Mid-Norway represents a good example of sand ridges developed along an ancient continental shelf. 3D seismic reflection, core and wireline log data allow us to investigate their architecture as well as their sedimentological and reservoir properties. The principal results of this study are as follows:

- Sandbodies seems to have been controlled by the geometry produced by the Callovian Unconformities suggesting that the palaeotopography played a crucial role in favouring the enucleation of the sandbodies in their embryonic phases. This aspect is extremely important during the exploration phase because it can highlight areas characterised by the presence of a potential reservoir.
- Although palaeocurrent towards the north have been reported for the Draugen Field deposits, regional-scale distribution of palaeobiogeographic ammonite provinces as well as variation in the mineralogical composition of the Rogn Fm from suggest a southward direction of main sediment transport during the Middle Jurassic, as identified in the Kristin Graben (Halten Terrace).
- The architecture of the Rogn Fm shows a lenticular shape with a convex-up top where the sandy deposits result encased within a shale unit (Spekk Fm). Internally, they are characterised by dipping reflectors recording the lateral migration of the ridge during the growing phases. The external shape of the sandbodies (elongated *versus* rounded) could be related to the main process controlling the distribution of sand. Analysis of present-day examples suggests that the elongated ones are typically related to tidal currents whilst the rounded ones to storms.
- Core analysis shows that sediments form coarsening-upward units characterised by a shaly base evolving upwards to medium- and coarse-grained tabular and trough cross strata. However, when the crest of the ridge developed under the influence of high-energy processes, an alternation of plane-parallel stratification and coarse-grained massive layers occurs.
- From a reservoir point of view, sediments result well-sorted positively affecting the final porosity and permeability and NTG. In the Draugen Field, the Rogn Fm shows values of porosity and permeability up to 30% and 6 Darcy respectively, supporting the interpretation that sand ridges represent excellent reservoirs.
- Seismic-scale outcrop analogues are important to better understand the sub-seismic stratigraphic architectures and facies distributions, and may help to further characterise and broaden our understanding of the risks associated with the exploration of subsurface sand ridges.

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References

Bann K.L., Tye S.C., MacEachern J.A., Fielding C.R. & Jones B.G. (2008) - Ichnological and sedimentological signatures of mixed wave- and storm-dominated deltaic deposits: examples from the Early Permian Sydney Basin, Australia. In: Hampson G.J., Steel R.J., Burgess P.M. & Dalrymple R.W. (eds.), Recent advances in models of siliciclastic shallow-marine stratigraphy, SEPM Spec. Pub., 90, 293-332.

Bell R.E., Jackson C.H-L., Elliott G.M., Gawthorpe R.L., Sharp, I.R & Michelsen L. (20149 - Insights into the development of major rift-related unconformities from geologically constrained subsidence modelling:HaltenTerrace, offshore mid Norway. Basin Research, 26, 203-224.

Belderson, R.H., Johnson, M.A., & Kenyon, N.H., 1982, Bedforms, in Stride, A.H., ed., Offshore Tidal Sands; Processes and Deposits: London, Chapman & Hall, p. 27–55.

Bjerrum C.J., Surlyk F., Callomon J.H., Slingerland R.L. (2001) Numerical Paleoceanographic Study of the Early Jurassic Transcontinental Laurasian Seaway. PALEOCEANOGRAPHY, 16, 390-404.

Blystad, P., Brekke, H., Faerseth, R.B., Larsen, B.T., Skogseid, J. & Torudbakken, B. (1995) Structural Elements of the Norwegian Continental Shelf: Part Ii the Norwegian Sea Region. NPD. Bulletin No 8.

Boyd R., Ruming K., Davies S., Payenberg T. and Lang S. (2004) Fraser Island and Hervey Bay-a classic modern sedimentary environment. PESA Eastern Australasian Basins Symposium II Adelaide, 19–22 September.

Caston, V.N.D. (1972) Linear sand banks in the southern North Sea. Sedimentology, 18, 63–78.

Chiarella D., Longhitano S.G., Muto F. (2012) Sedimentary features of the Lower Pleistocene mixed siliciclastic–bioclastic tidal deposits of the Catanzaro Strait (Calabrian Arc, south Italy). Rend. Online Soc. Geol. Ital. 21, 919–920.

Clifton, H.E. and Dingler, J.R. (1984) Wave-formed structures and paleoenvironmental reconstruction. Mar. Geol., 60, 165−198.

Dalland, A., Worsley, D. & Ofstad, K. (1988) A Lithostratigraphic Scheme for the Mesozoic and Cenozoic Succession Mid – and Northern Norway, Norwegian Petroleum Directorate. NPD Bulletin No 4.

Dalrymple, R.W., 1992, Tidal depositional systems, in Walker, R.G., and James, N.P., eds., Facies Models: Response to Sea Level Change: Geological Association of Canada, p. 195–218.

Desjardins, P.R., Buatois, L.U., Pratt, B.R. and Gabriela Màngano, M. (2012) Sedimentological–ichnological model for tide-dominated shelf sandbodies: Lower Cambrian Gog Group of western Canada. Sedimentology, 59, 1452–1477.

Doré, A.G. (1992) Synoptic palaeogeography of the Northeast Atlantic Seaway: Late Permian to Cretaceous. In: Basins on the Atlantic Seaboard: Petroleum Geology, Sedimentology and Basin Evolution (Ed. J. Parnell), Geol. Soc. London. Spec. Publ., 62, 421–446.

Dyer, K.R., & Huntley, D.A., 1999, The origin, classification, and modeling of sand banks and ridges: Continental Shelf Research, v. 19, p. 1285–1330

Harris, P.T., Pattiaratchi, C.B., Cole, A.R. and Keene, J.B. (1992) Evolution of subtidal sandbanks in Moreton Bay, Eastern Australia. Mar. Geol., 103, 225–257.

Hernández-Molina, F.J., Fernández-Salas, L.M., Lobo, F., Somoza, L., Díaz-del-Río, V., Alveirinho Dias, J.M., 2000a. The infralittoral prograding wedge. A new large-scale progradational sedimentary body in shallow marine environments. Geo-Mar. Lett. 20, 109–117.

Huthnance, J.M. (1982) On one mechanism forming linear sand banks. Estuar. Coast. Shelf Sci., 14, 79–99.

Jones, G. (2016) Spatial and temporal distribution of coarse-grained submarine fan deposits and their context within the syn-rift tectono-stratigraphic evolution of the Upper Jurassic Spekk and Melke formations, Southern Halten Terrace. *In*: Folkestad, A., Mader Kayser, N., Bryn, B. K., Polonio, I., Chiarella, D., Mydland, T. (Eds) Advanced in siliciclastic and carbonate sedimentology: concepts and case studies from the Norwegian Continental Shelf.

McBride, R.A. (2003) Offshore sand banks and linear sand ridges. In: Encyclopedia of Sediments and Sedimentary Rocks (Ed. G.V. Middleton), pp. 737-739. Kluiver Academic Publishers, Dordrecht.

Keene, J.B. and Harris, P.T. (1995) Submarine cementation in tide-generated bioclastic sand dunes: epicontinental seaway, Torres Strait, north-east Australia. In: Tidal Signatures in Modern and Ancient Sediments (Eds B.W. Flemming and A. Bartholomä), Int. Assoc. Sedimentol. Spec. Publ., 24, 225–236.

Kenyon, N.H., Belderson, R.H., Stride, A.H. and Johnson M.A. (1981) Offshore tidal sand banks as indicators of net sand transport and as potential deposits. In: Holocene Marine Sedimentation in the North Sea Basin (Eds S.-D. Nio, R.T.E. Shüttenhelm and T.C.E. van Weering), Int. Assoc. Sedimentol. Spec. Publ., 5, 257–268.

Koch, J.-O. and Heum, O.R. (1995) Exploration trends of the Halten Terrace. In: Petroleum Exploration and Exploitation in Norway (Ed. S. Hanslien), Norw. Petrol. Soc. (NPF) Spec. Publ., 4, 235–251.

Komar, P.D. and Miller, M.C. (1975) The initiation of oscillatory ripple marks and the development of plane-bed at high shear stresses under waves. J. Sedim. Petrol., 45, 697–703.

Ellenor, D.W. and Mozetic, A., 1986. The Draugen oil discovery, In: A.M. Spencer et al. (Editors), Habitat of Hydrocarbons on the Norwegian Continental Shelf. Graham and Trotman, London, pp.313 316.

Gaynor, G.C. & Swift, D.J.P., 1988, Shannon Sandstone depositional model: sand-ridge formation on the Campanian Western Interior Shelf: Journal of Sedimentary Petrology, 58, 868–880.

Goesten, M.J.B.G., and Nelson, P.H. (1992) Draugen Field Norway, North Sea Basin, Haltenbanken area, in: Foster N.H. and Beaumont E.A., (Eds.), structural Traps VI, AAPG Treatise of Petroleum Geology, Atlas of oil and gas fields, 37-54.

Le Bot, S. & Trentesaux, A. (2004) Types of internal structure and external morphology of submarine dunes under the influence of tide and wind-driven processes (Dover Strait, northern France): Marine Geology, 211, 143–168.

Leszczyński, S. & Nemec, W. (accepted) Sedimentation in a synclinal shallow-marine embayment: Coniacian of the North Sudetic Synclinorium, SW Poland. The Depositional Record, DOI: 10.1002/dep2.92

Leva-López J., Rossi V.M., Olariu C., Steel R.J. (2016) Architecture and recognition criteria of ancient shelf ridges; an example from Campanian Almond Formation in Hanna Basin, USA. Sedimentology, 63, 1651-1676.

Liu, Z., Berné, S., Saito, Y., Trentesaux, H.Y.A., Uehara, K., Yin, P., Liu, J.P., Li, C., Hu, G. & Wang, X. (2007) Internal architecture and mobility of tidal sand ridges in the East China Sea: Continental Shelf Research, 27, 1820–1834.

Longhitano, S.G. and Nemec, W. (2005) Statistical analysis of bed-thickness variation in a Tortonian succession of biocalcarenitic tidal dunes, Amantea Basin, Calabria, southern Italy. Sedim. Geol., 179, 195–224.

Longhitano, S.G., Chiarella, D., Muto, F., 2014. Three-dimensional to two-dimensional cross-strata transition in the lower Pleistocene Catanzaro tidal strait transgressive succession (southern Italy). Sedimentology 61, 2136-2171.

MacEachern, J.A., Dashtgard, S.E., Knaust, D., Catuneanu, O., Bann, K.L., Pemberton, S.G., 2012. Sequence stratigraphy. In: Knaust, D., Bromley, R.G. (Eds.), Trace Fossils as Indicators of Sedimentary Environments. Developments in Sedimentology, vol. 64. Elsevier, Amsterdam, pp. 157 - 194.

Messina, C., Nemec, W., Martinius, A.W. and Elfenbein, C. (2014) The Garn Formation (Bajocian-Bathonian) in the Kristin Field, Halten Terrace. In: From Depositional Systems to Sedimentary Successions on the Norwegian Continental Margin (Eds A.W. Martinius, R. Ravnas, J.A. Howell, R.J. Steel and J.P.Wonham), IAS Spec. Publ., 46, 513–550.

Michaud, K. & Dalrymple, R. W. (2016). Facies, architecture and stratigraphic occurrence of headland-attached tidal sand ridges in the Roda Formation, Northern Spain. In: (Tessier B. and Reynaud J.Y.) Contributions to Modern and Ancient Tidal Sedimentology. IAS Spec. Publ., pp. 313-341.

Montenat, C., Barrier, P. and Di Geronimo, I. (1987) The Strait of Messina, past and present: a review. Doc. Trav. IGAL (Paris), 11, 7–13.

Mørk M.B.E., Johnsen S.O. (2005) Jurassic sandstone provenance and basement erosion in the Møre margin – Froan Basin area. Norges geologiske undersøkelse Bulletin 443, 5–18.

Nøttvedt A., Johannessen E.P., Surlyk F. (2006) The Mesozoic of Western Scandinavia and East Greenland. Episodes, 31, 59-65.

Odin, G.S. & Matter, A., 1981, De glauconarium origine: Sedimentology, 28, 611–641.

Olariu, C., Steel, R.J., Dalrymple, R.W. and Gingras, M.K. (2012) Tidal dunes versus tidal bars: the sedimentological and architectural characteristics of compound dunes in a tidal seaway, the lower Baronia Sandstone (Lower Eocene), Ager Basin, Spain. Sed. Geol., 279, 134–155.

Posamentier, H.W., 2002, Ancient shelf ridges—a potentially significant component of the transgressive systems tract: case study from offshore northwest Java: American Association of Petroleum Geologists, Bulletin, v. 86, p. 75–106.

Provan, D.M.J., 1992. Draugen Oil Field, Haltenbanken Province, Offshore Norway. In: M.T. Halbouty (Ed.), Giant Oil and Gas Fields of the Decade 1978-1988. AAPG Special Volumes, Volume M 54, pp. 371 - 382.

Reynaud, J.-Y., Dalrymple, R.W., 2012. Shallow-marine tidal deposits. In: Davis Jr, R.A., Dalrymple, B.W. (Eds.), Principles of Tidal Sedimentology. Springer, New York, pp. 335–370.

Reynaud, J.-Y., Tessier, B., Proust, J-N.L., Dalrymple, R.W., Marssett, T., De Batist, M., Bourillet, J-F. & Lericolais, G., 1999, Eustatic and hydrodynamic controls on the architecture of a deep shelf sand bank (Celtic Sea): Sedimentology, v. 46, p. 703–721

Rossi, V.M., Longhitano, S.G., Mellere, D., Dalrymple, R.W., Steel, R.J., Chiarella, D., Olariu, C., 2017. Interplay of tidal and fluvial processes in an early Pleistocene, deltafed, strait margin (Calabria, Southern Italy). Marine and Petroleum Geology, 87, 14-30.

Simarro G., Guillén J, Puig P., Ribó M., Lo Iacono C., Palanques A., Muñoz A., Durán R., Acosta J. (2015) Sediment dynamics over sand ridges on a tideless mid-outer continental shelf. Marine Geology, 361, 25-40.

Slagstad, T., Davidsen, B. & Daly, J.S. (2011) Age and composition of crystalline basement rocks on the Norwegian continental margin: offshore extension and continuity of the Caledonian-Appalachian orogenic belt. J. Geol. Soc., 168, 1167–1185.

Snedden, J.W., Dalrymple, R.W., 1999, Modern shelf sand ridges; from historical perspective to a unified hydrodynamic and evolutionary model, in Bergman, K.M., and Snedden, J.W., eds., Isolated Shallow Marine Sand Bodies; Sequence Stratigraphic Analysis and Sedimentologic Interpretation: SEPM, Special Publication 64, p. 13–28.

Snedden J.W., Tillman R.W., Culver S.J. (2011) Genesis and evolution of a mid-shelf, storm built sand ridge, New Jersey Continental Shelf, U.S.A. Journal of Sedimentary research, 81, 534-552.

Soo son C., Flemming B.W., Chang T.S. (2012) Sedimentary facies of shoreface-connected sand ridges off the East Frisian barrier-island coast, southern North Sea: climatic controls and preservation potential. Int. Assoc. Sedimentol. Spec. Publ. 44, 143–158.

Surlyk, F., Piasecki, S:, Rolle, F:, Stemmerick, L., Thomsen, E: & Wrang, P. (1984) The Permian basin of East Greenland. *In:* Spencer, A.M. et al., (Eds) Petroleum Geology of North European Margin. Graham & Trotman, London, 303-315.

Suter J.R. (2006) Facies models revisited: clastic shelves. Facies Models Revisited, SEPM Special Publication 84, 339-397.

Swiecicki, T., Gibbs, P.B., Farrow, G.E. & Coward, M.P. (1998) A tectonostratigraphic framework for the mid-norway region. Mar. Pet. Geol., 15, 245–276.

Swift, D.J.P. (1975) Tidal sand ridges and shoal-retreat massifs. Mar. Geol, 18, 105–134.

Swift, D.J.P. and Field, M.E. (1981) Evolution of a classic sand ridge field: Maryland Sector, North American inner shelf. Sedimentology, 28, 461–482.

Swift, D.J.P. and Freeland, G.L. (1978) Mesoscale current lineations on the inner shelf, Middle Atlantic Bight of North America. J. Sedim. Petrol., 48, 1257–1266.

van den Meene, J.W.H., 1994, The Shoreface—Attached Ridges along the Central Dutch Coast: Universiteit Utrecht, Nederlandse Geograpfische Studies, v. 174, 222 p.

van der Zwan (1990) Palynostratigraphy and Palynofacies Reconstruction of the Upper Jurassic to Lowermost Cretaceous of the Draugen Field, Offshore Mid Norway. Review of Palaeobotany and Palynology, 62, 157-186.

Ziegler, P. (1988) Evolution of the Arctic – North Atlantic and the western Tethys. AAPG Mem., 43, 198.

Figure captions

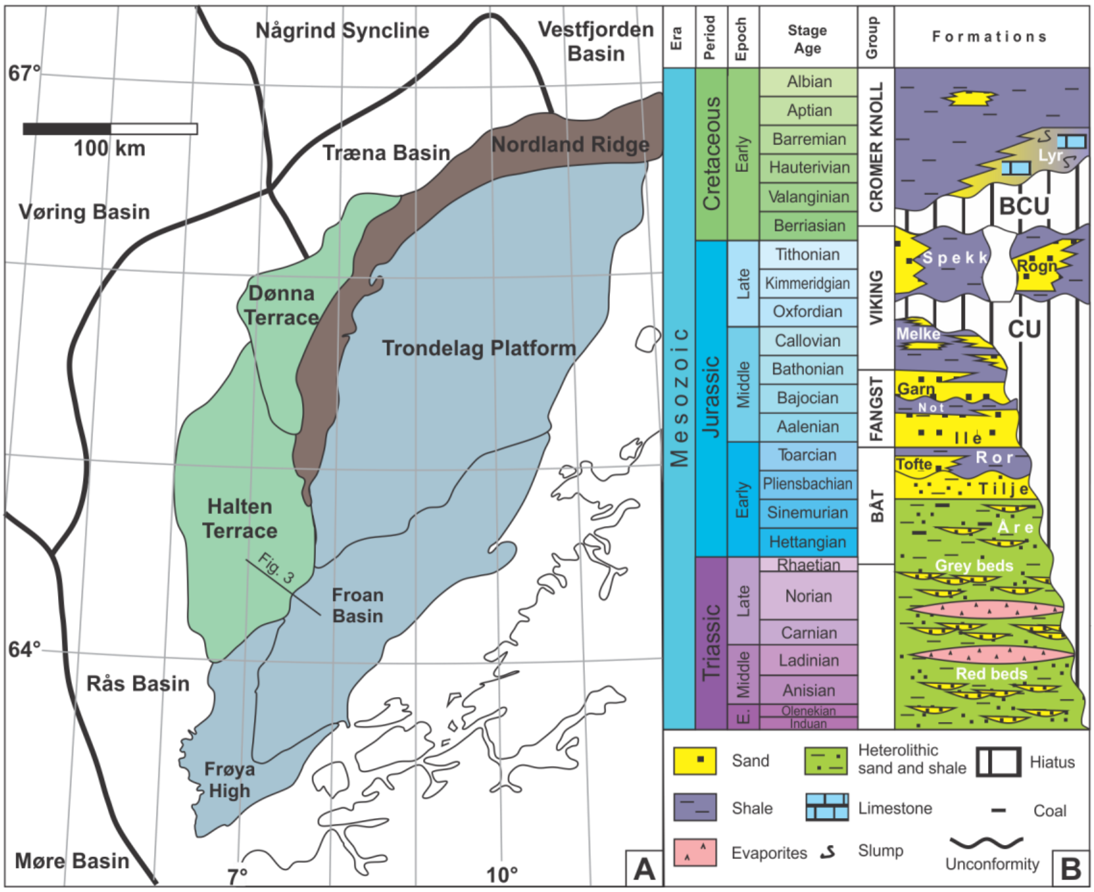

Figure 1 - A) Map of the main structural elements defined in the Haltenbanken area (modified after Blystad et al., 1995). (B) Stratigraphic column for the Mid-Norwegian shelf (based upon Dalland et al., 1988) highlighting the Triassic to Early Cretaceous stratigraphy. BCU: Base Cretaceous Unconformity; CU: Callovian Unconformity

Figure 2 – A) Global palaeogeographic reconstruction of the northern Hemisphere in the Late Jurassic period 150 Ma. (Deep Time Maps^{TM}) B) Schematic reconstruction of the seaway between Norway and Greenland in the Late Jurassic, based on plate tectonic reconstructions by Ziegler (1988) and Dorè (1992). C) Reconstruction of a portion of the Norwegian Sea during the Late Jurassic (Kimmeridgian) across the Froan, Halten and Rås basins, and the Frøya High with used wells, and outline of seismic data used. Scree apron deposits located along the Klakk Fault Complex (KFC) and Vingleia Fault Complex (VFC), and shallow marine sand ridges accumulated in the Trøndelag Platform (i.e. Froan Basin and Frøya High) are represented.

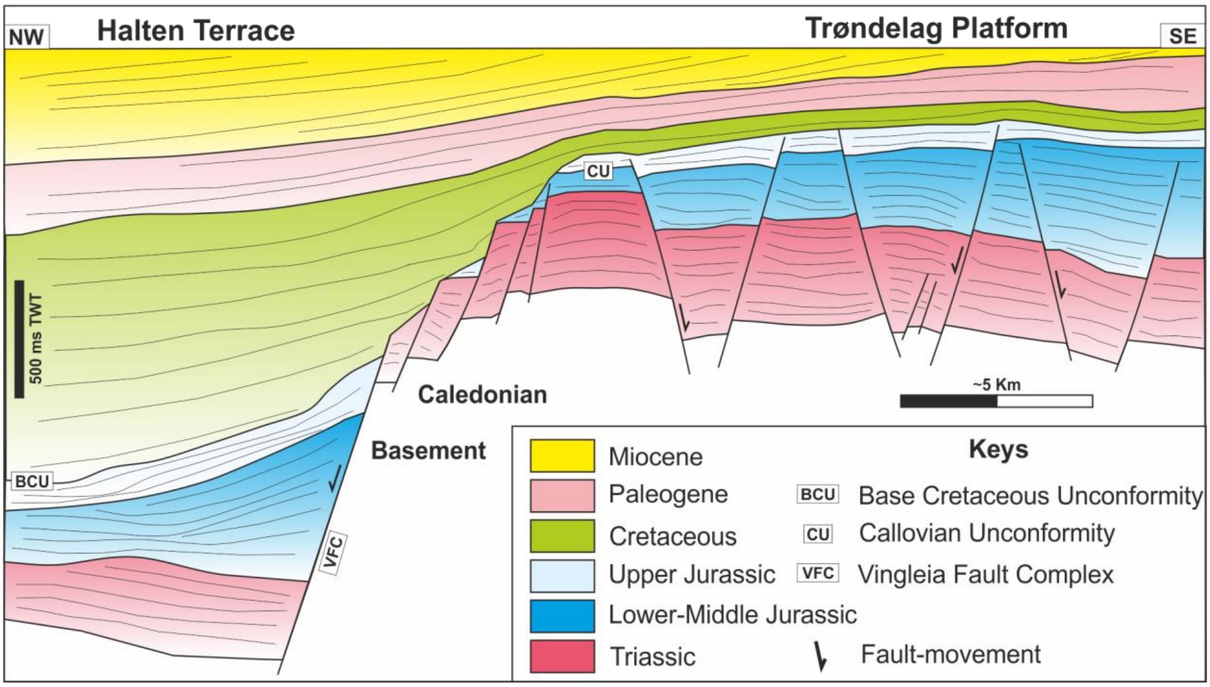

Figure 1 - Schematic cross-section over the Halten Terrace and the Trøndelag Platform. See Fig. 2 for orientation.

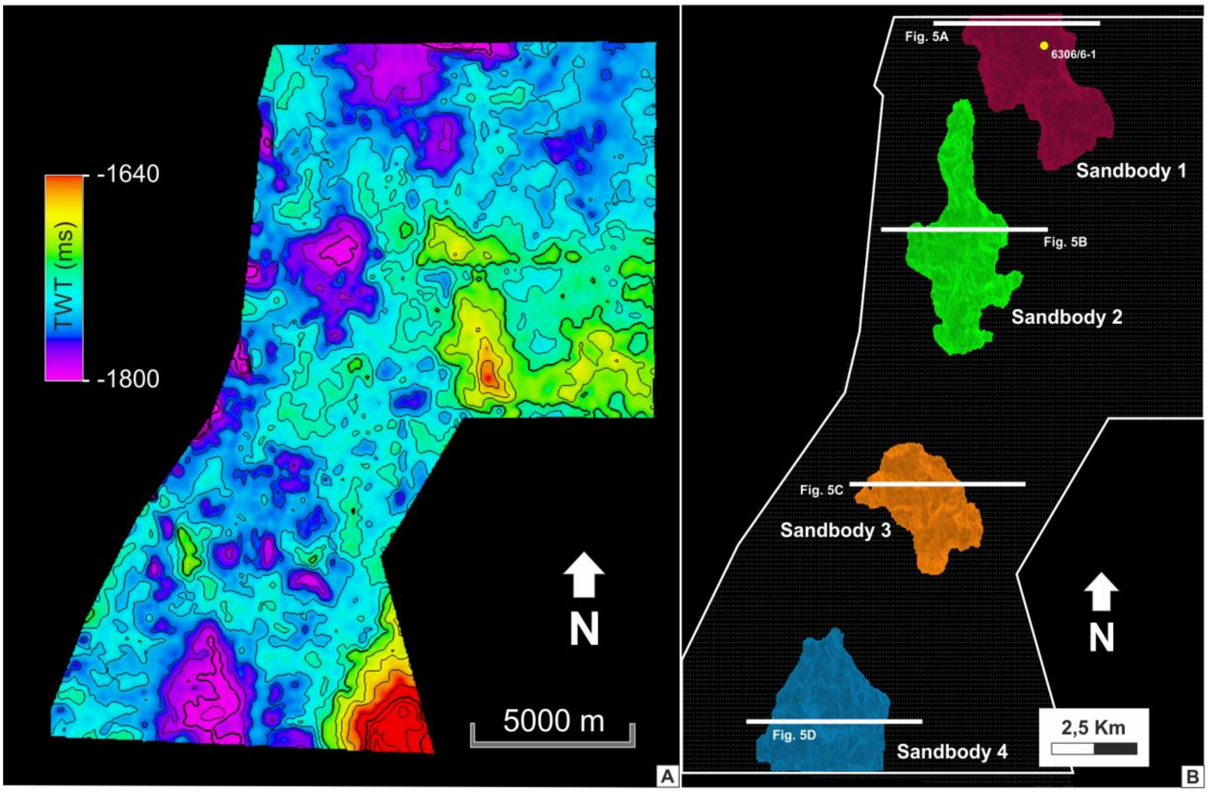

Figure 2 – A) Structure map of the Callovian Unconformity east of the Frøya High. B) 2D map of the four sandbodies recognised in the Frøya High area showing their plan view shape and maximum extension as mapped in seismic. Important to note that bedform 1 and bedform 2 extend outside the available seismic survey. (see Fig. 2C for location).

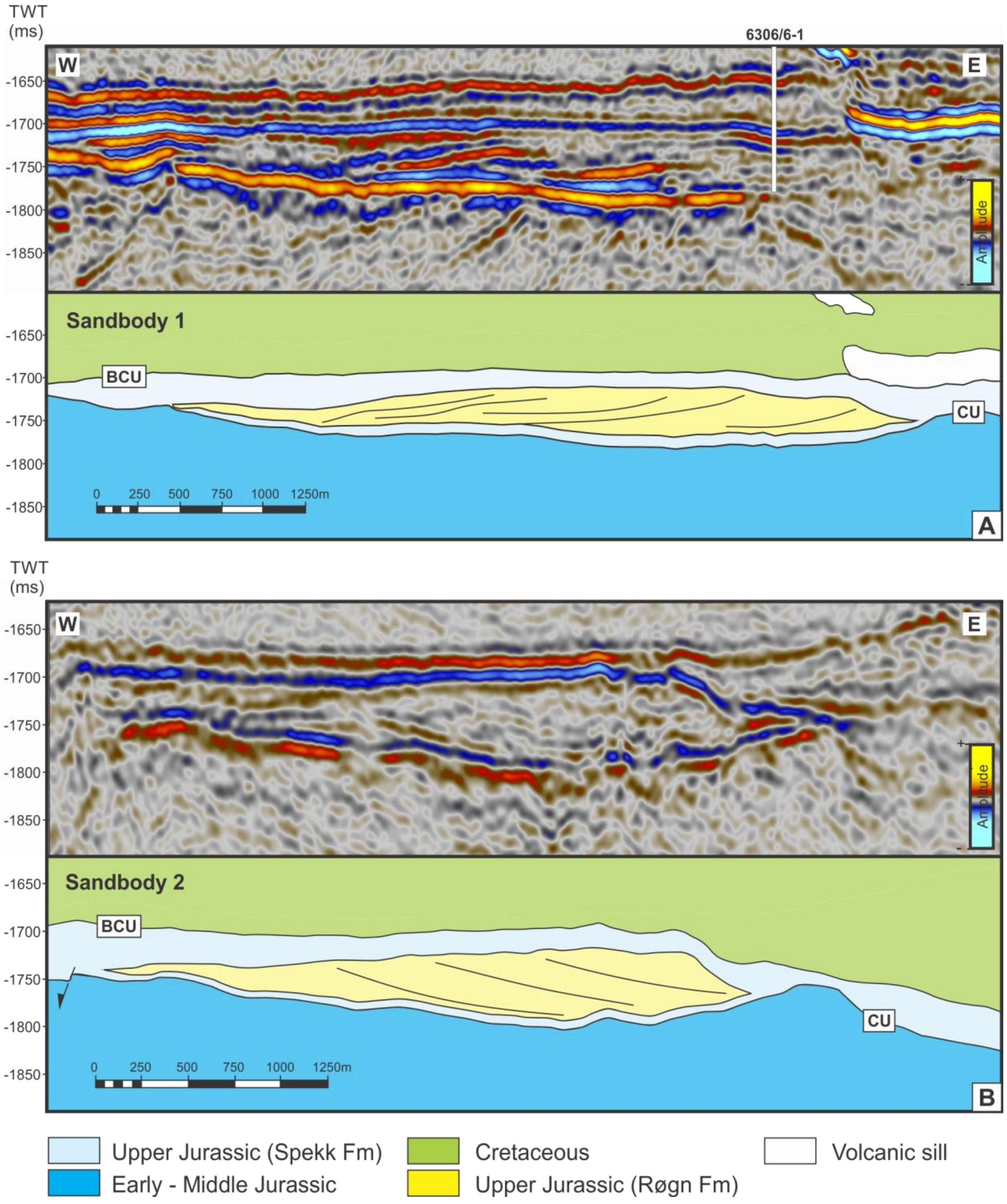

Figure 3 – Cross-sections of the recognised Upper Jurassic Rogn Fm sandbody showing their external lenticular shape encased within the Spekk Fm deposits. Sandbodies are internally characterised by westward (A) or eastward (B, C, and D) dipping reflectors indicating the lateral migration of the sand ridges during their evolution.

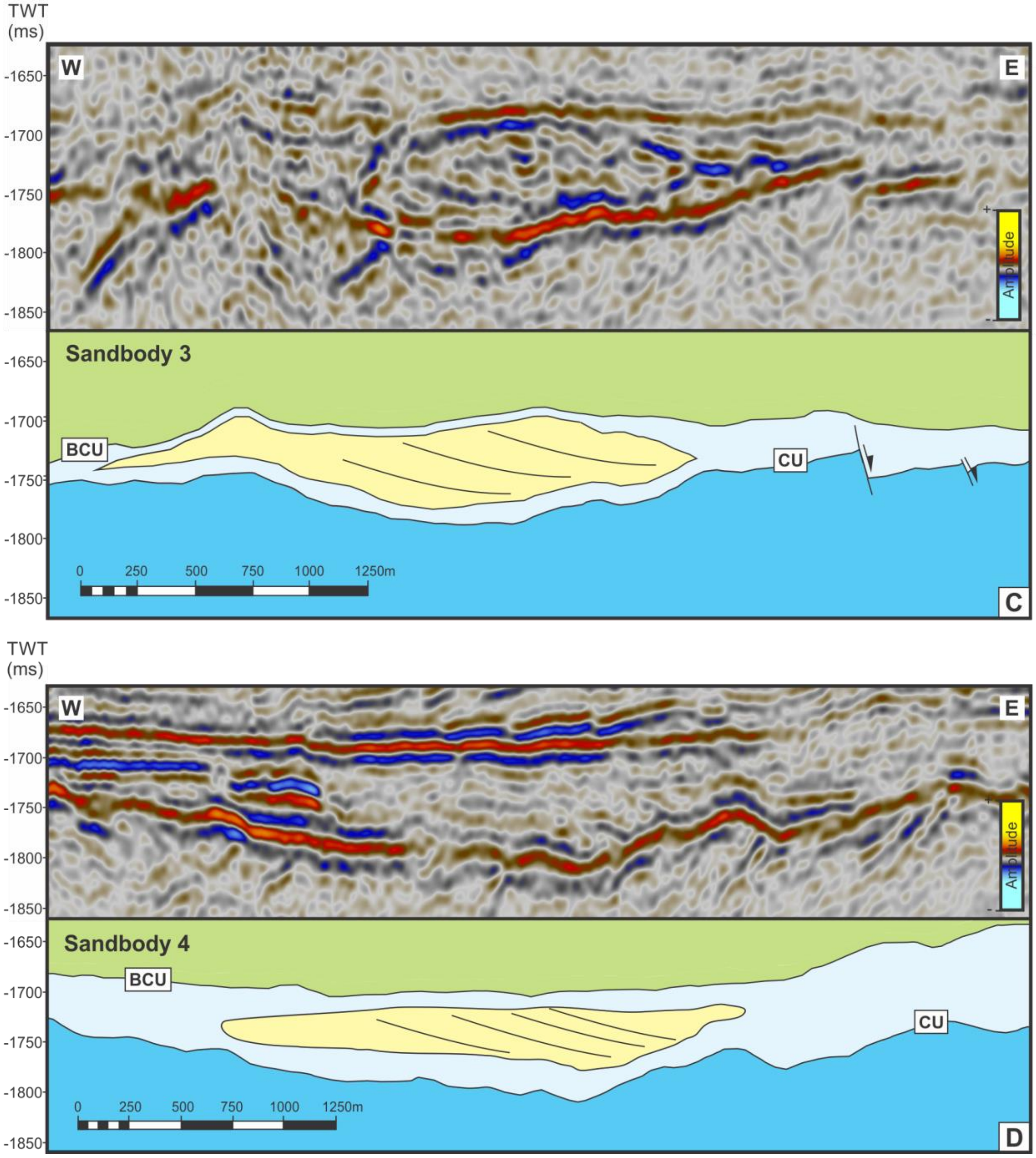

Figure 5 – Continued

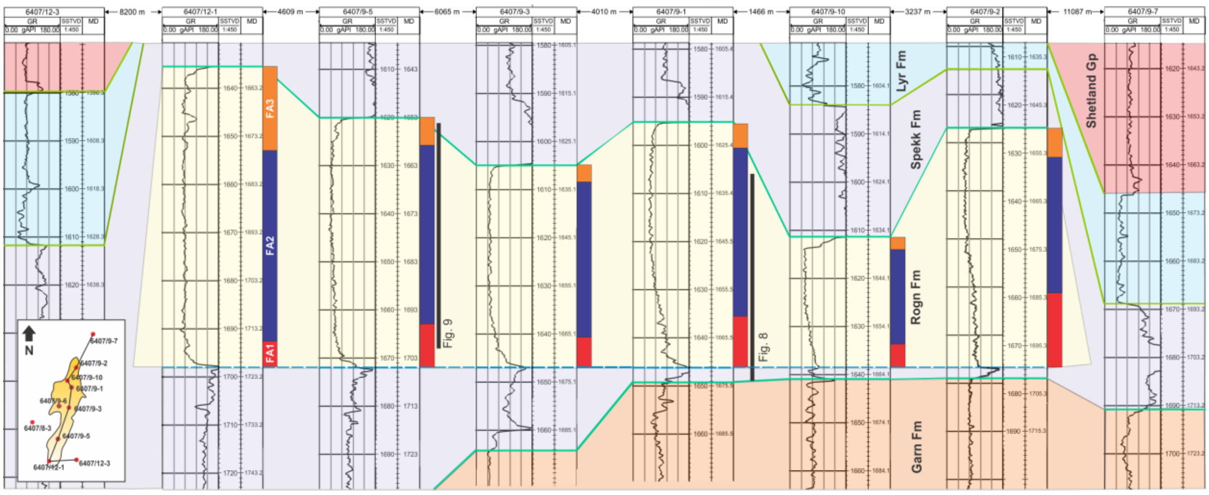

Figure 4A – Correlation panel over the Draugen Field (Froan Basin) with north-south (A) and east-west (B) orientations. Black bars indicate the extent of core intervals

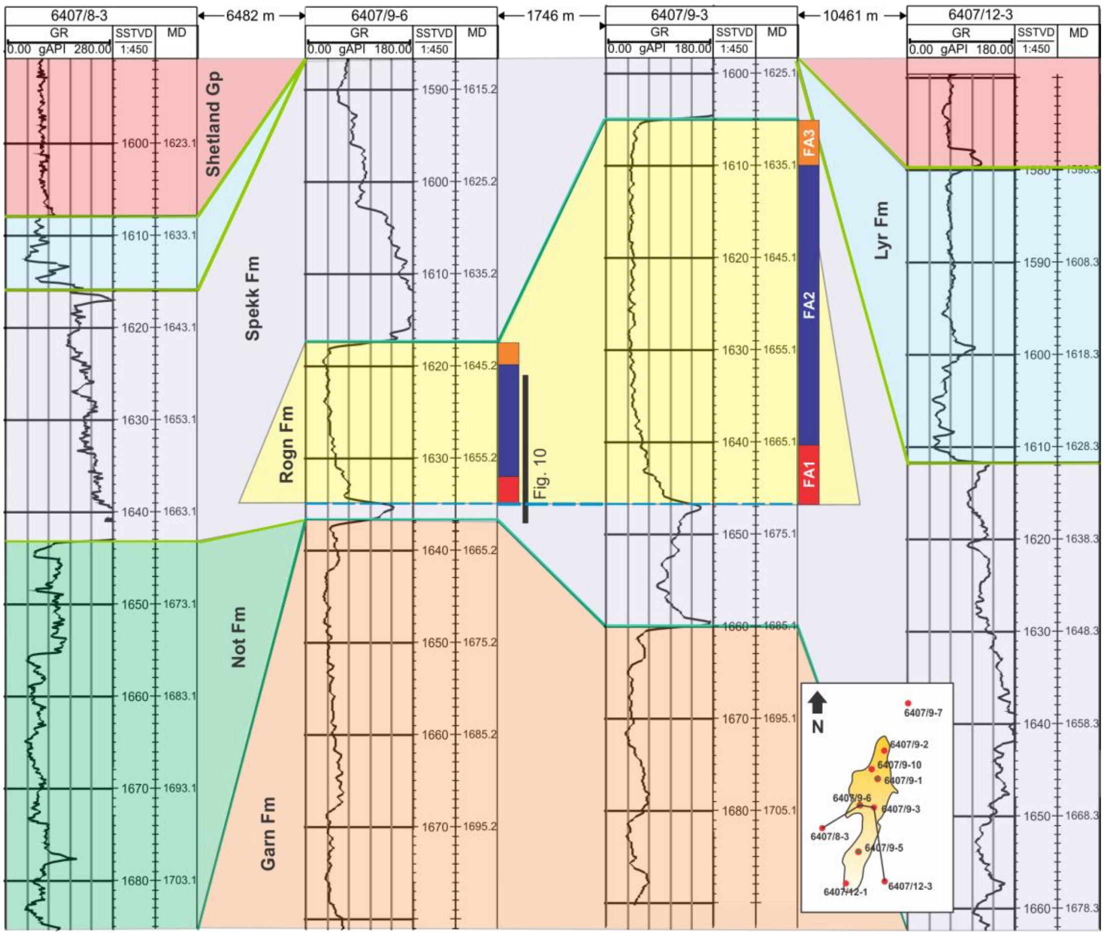

Figure 6B – Continued.

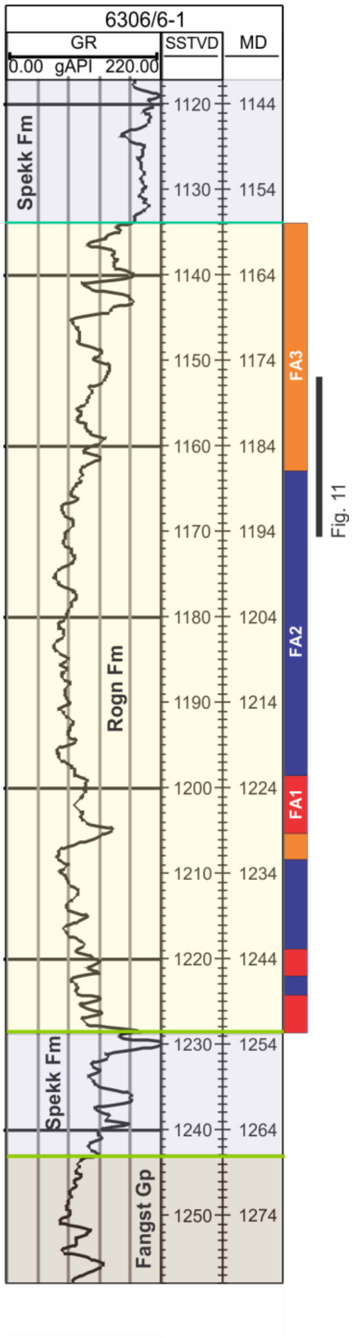

Figure 7 – Wireline log of the well 6306/6-1 located in the Froya High. (Fig. for location see).

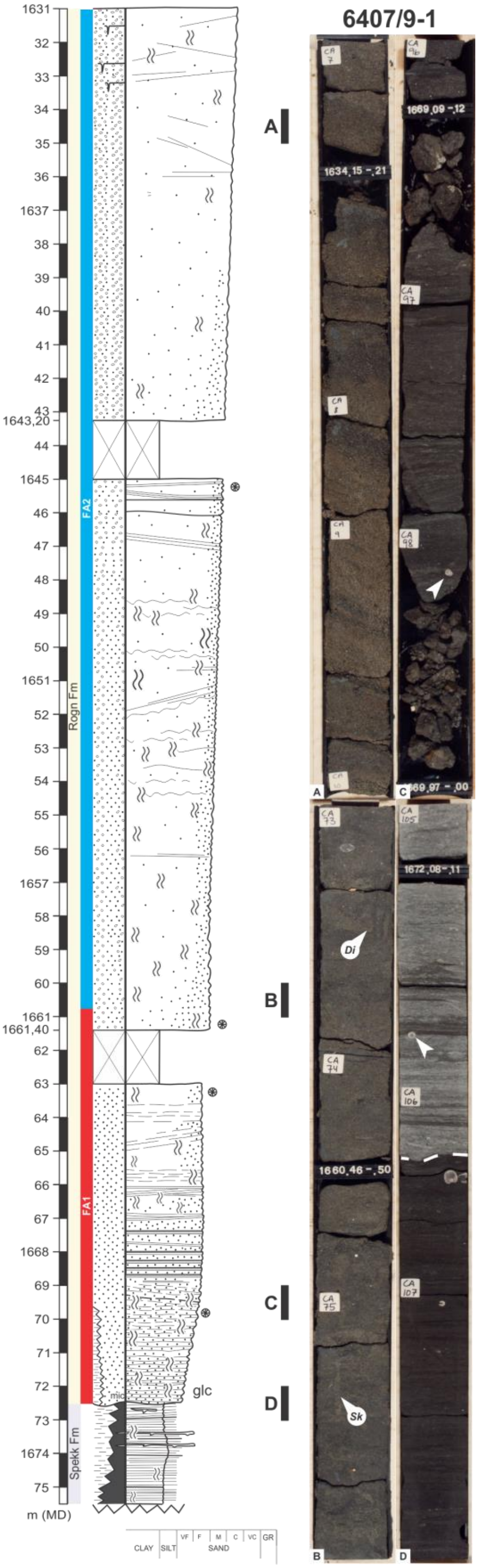

Figure 8 – Core log of the Rogn Fm from well 6407/9-1. A) Cross-strata in coarse-grained-sandstone. B) Fine- to medium-grained sandstones with Diplocraterion (Di) and Skolithos (Sk) traces. C) Fine-grained sandstones showing a faint plane-parallel lamination, Belemnite rostrum are present. D) Stratigraphic contact between the Spekk Fm and the Rogn Fm. Rogn Fm characterised by fine-grained laminae producing a rhythmic alternation. See figure 1 for location and Fig. 11 for the key.

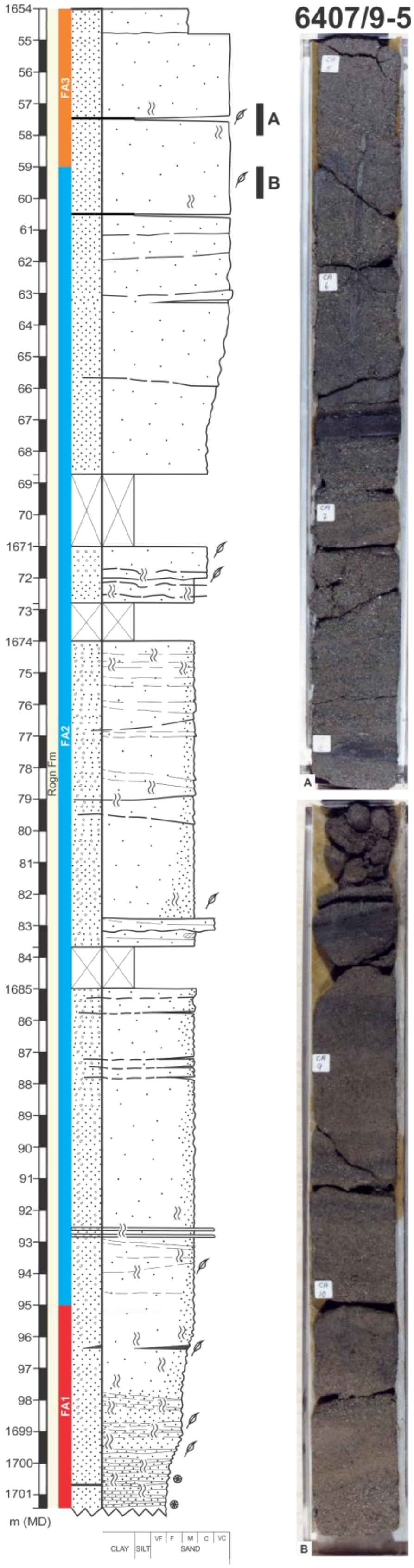

Figure 9 - Core log of the Rogn Fm from well 6407/9-5. Coarse-grained sandstone characterised by the presence of coal layers and leaves fragments. Vertical trace fossil (Skolithos) presents in the upper part of the core. See figure 1 for location and Fig. 11 for the key.

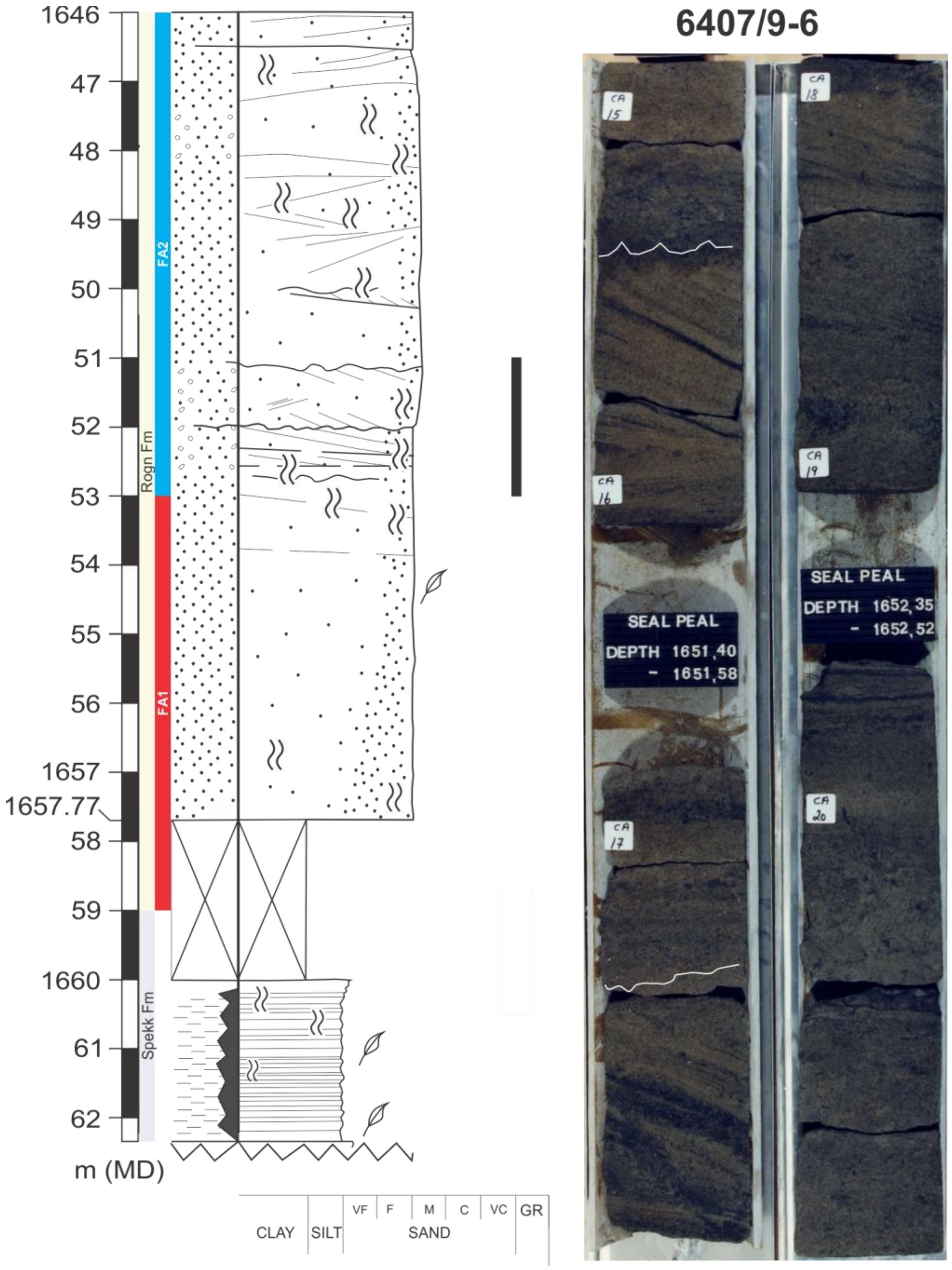

Figure 10 - Core log of the Rogn Fm from well 6407/9-6 showing medium- to coarse-grained sandstones organised into cross-strata. See figure 1 for location and Fig. 11 for the key.

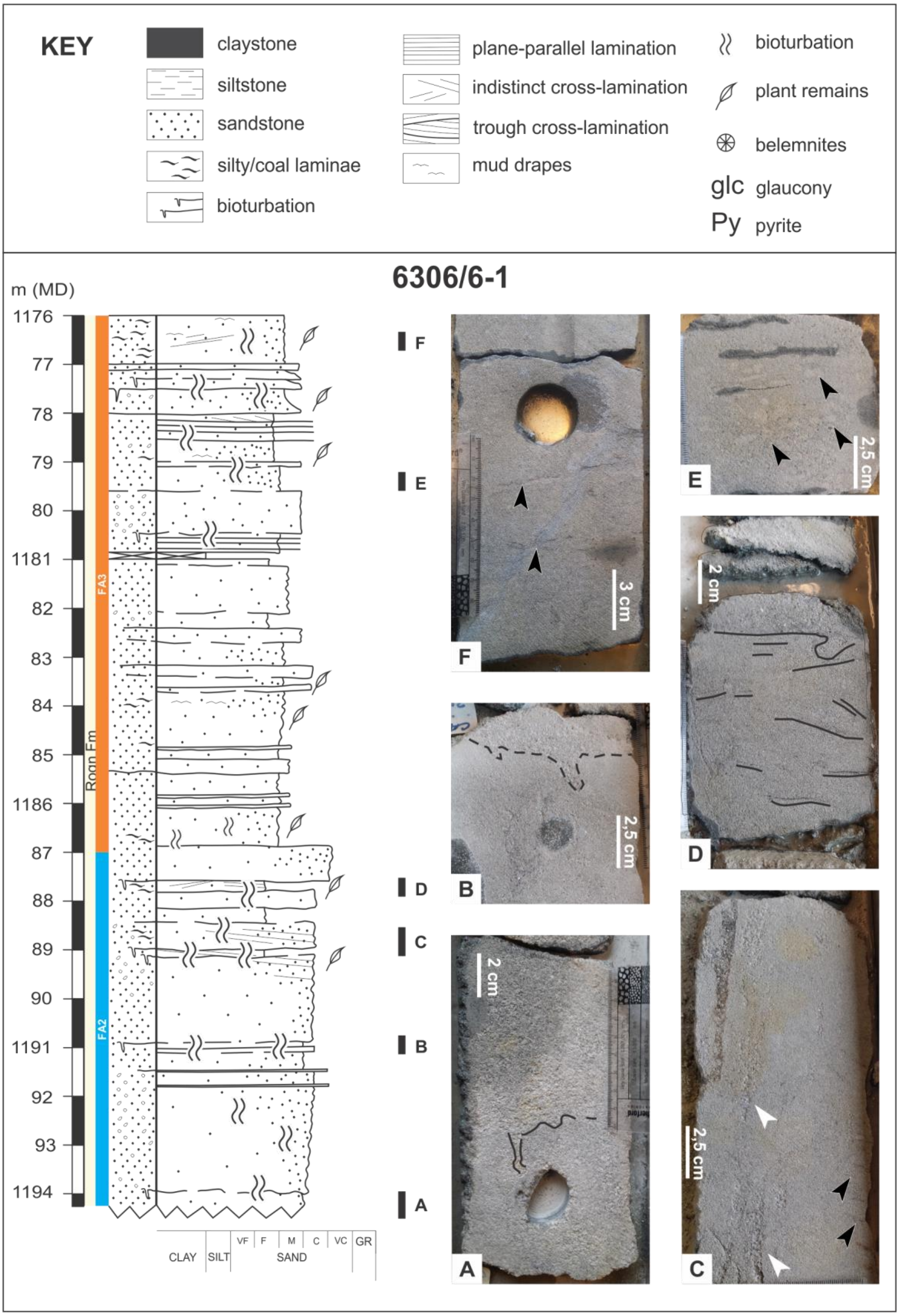

Figure 11 - Core log of the Rogn Fm from well 6306/6-1. A, B and D) Sharp contact between medium-grained and coarse-grained sandstone. The boundary is characterised by the presence of vertical bioturbations. C) Coarse-grained sandstones showing indistinct inclined cross-lamination highlighted by silty laminae (black arrows) and vertical trace-fossils. E) Fine- to medium-grained sandstones showing horizontal trace-fossils. F) Fine- to medium-grained sandstones with indistinct inclined lamination highlighted by silty laminae (black arrows). See Fig. 1 for location.

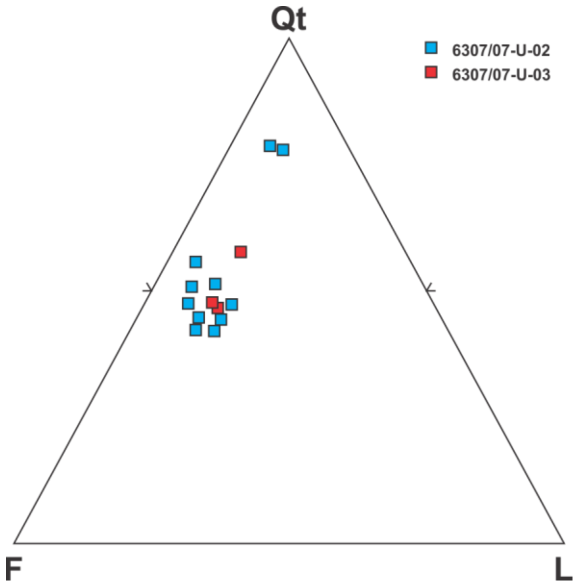

Figure 12 – Ternary diagram showing the petrographic composition of the Rogn Fm in the wells 6307/07-U-02 and 6307/07-U-03. Results show a general quartz-feldspatic composition.

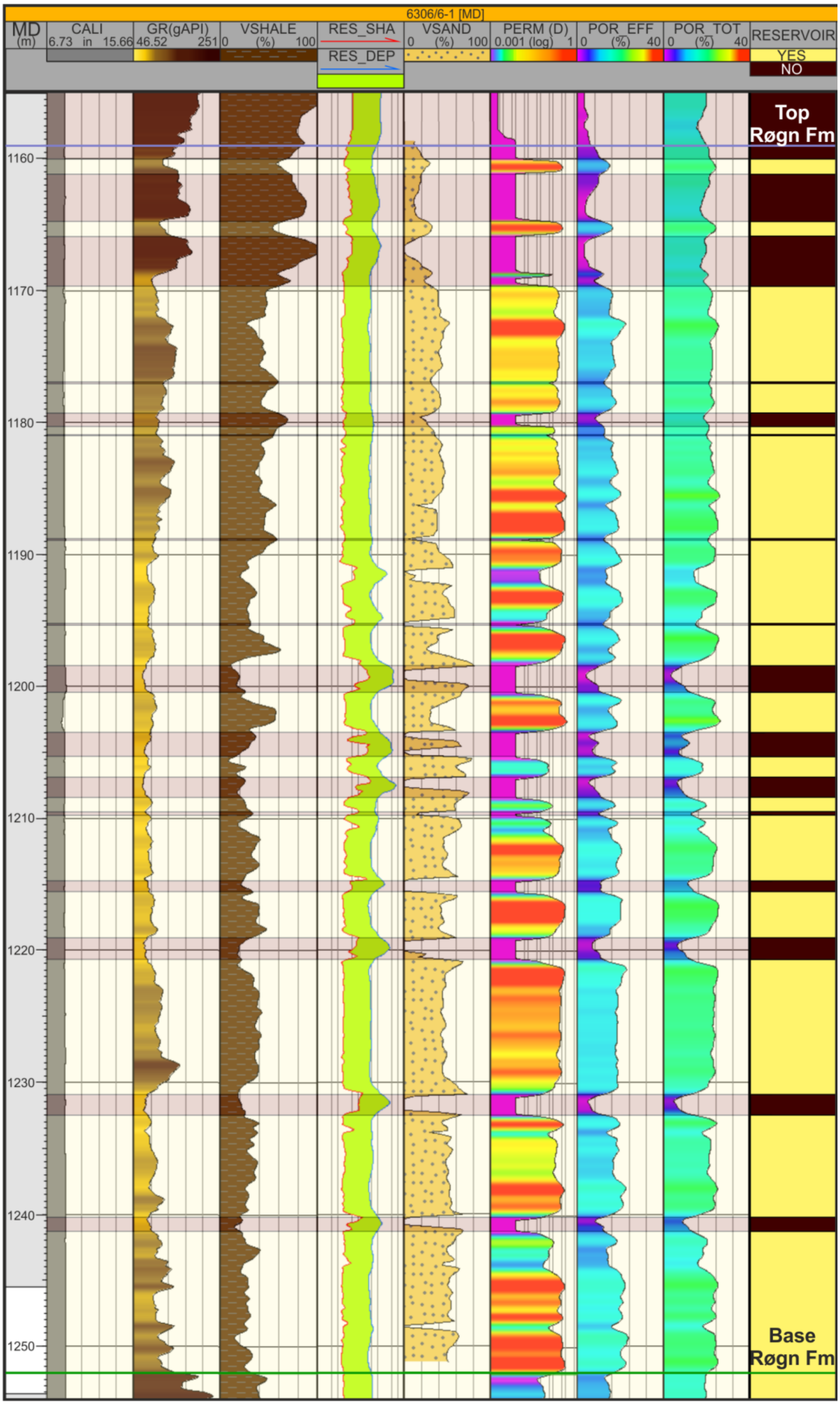

Figure 13 – Set of wireline logs for the well 6306/6-1 showing the main properties and patterns in the Rogn Fm interval (Frøya High).

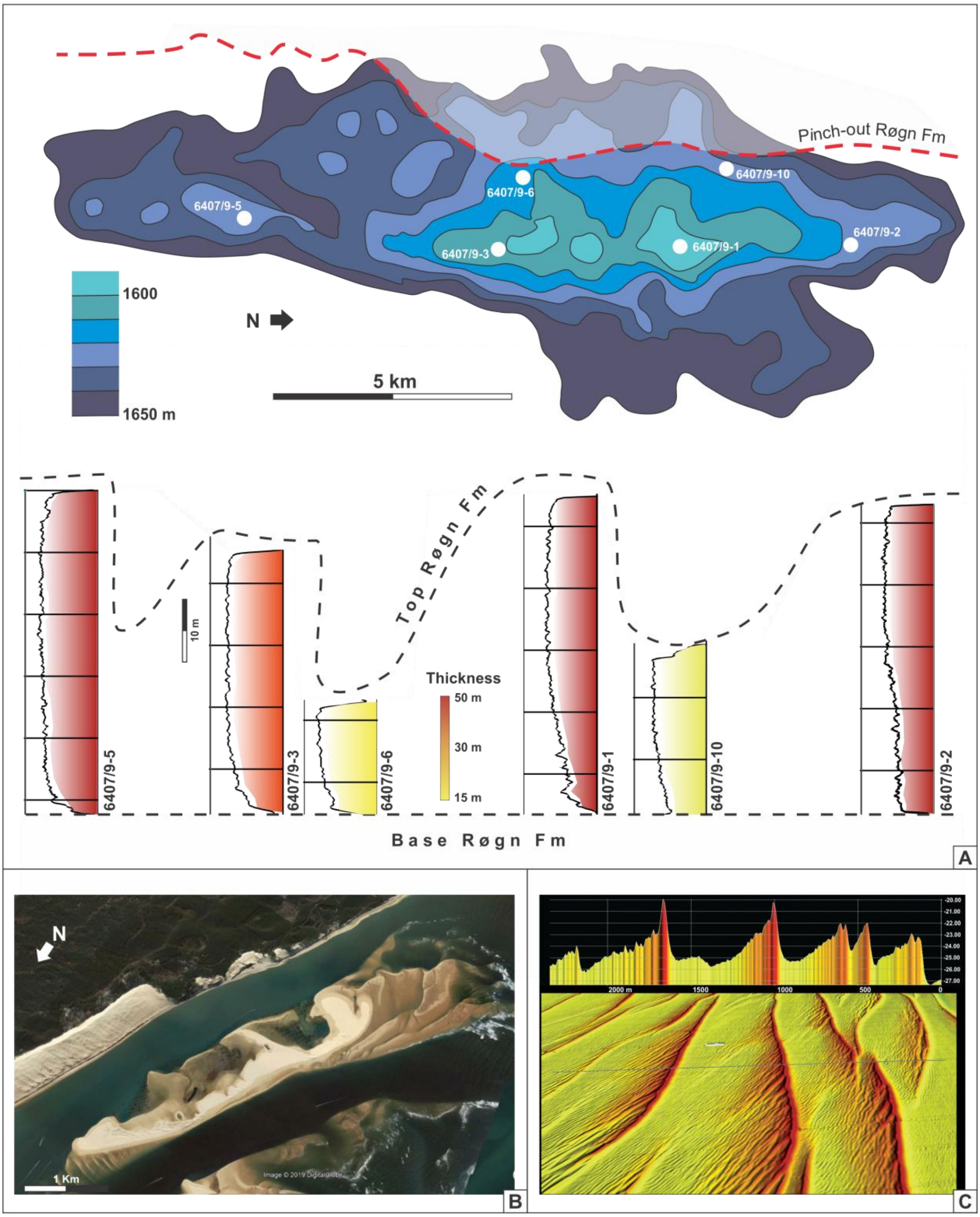

Figure 14 –A) Depth map of the Top Rogn reservoir (Draugen Field) highlighting the lenticular shape of the sandbody as recognized in the Frøya High area (see Fig. 5), and N-S profile along the Draugen sand ridge. B) Satellite image of a modern sand ridge (Banc d`Arquin, France) showing plan view geometry comparable with what recognized in the Draugen Field and bedforms 1-4. C) Bathymetric profile and multibeam echosounder bathymetry of tidal bedforms (Breaksea Shoa, Australia) showing the typical vertical profile along a sand ridge. 3D image of a 150 m long nuclear submarine is shown for scale (Image courtesy of Ron Boyd).