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Research paper

Burrowed matrix powering dual porosity systems – A case study from the Maastrichtian chalk of the Gullfaks Field, Norwegian North Sea

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ABSTRACT

Chalk reservoirs are commonly modelled as dual-porosity systems, in which a very porous but low permeable matrix is intersected by highly permeable vugs and fractures from which oil and gas can be produced. The Gullfaks Field in the Norwegian North Sea contains such a reservoir, which is producing from Maastrichtian chalk in addition to the conventional Triassic and Jurassic siliciclastic reservoirs. However, in comparison to the prolific chalk fields in the southern North Sea (e.g. Ekofisk, Valhall), chalk reservoirs in the northern part (e.g. Oseberg and Gullfaks fields) experience challenged production due to reservoir presence and quality related to depositional facies and structural conditions. Analyses of cores from three wells in the Maastrichtian Shetland Group of the Gullfaks Field reveal that this interval is completely bioturbated during several stages, e.g. mottling with diffuse bioturbated texture in an early softground stage that became subsequently overprinted by more discrete burrows with active and passive fill and different rock properties during the stiffground and firmground stages of the ooze. A rich and moderately diverse trace-fossil assemblage consists of abundant *Zoophycos*, common *Chondrites*, *Taenidium*, *Thalassinoides* and *Virgaichnus*, and rare *Nereites*, *Planolites*, *Spirophyton* and *Teichichnus*. Ichnological features allow the differentiation of five recurrent ichnofabrics (*Thalassinoides*, *Zoophycos*, *Chondrites*, *Nereites* and *Zoophycos-Taenidium* ichnofabrics) with variable influence on porosity and permeability. The *Thalassinoides* ichnofabric in chalk has the highest impact on improving reservoir quality, whereas *Zoophycos* and partly *Chondrites* ichnofabrics, in marly chalk and chalky marlstone respectively, contribute to creating potential reservoir zones if burrow density is high enough. Thin-section analysis of the different ichnofabrics illustrates the negative or positive effect of burrows on porosity distribution, whereas micro-CT imaging reveals an intriguing system of partly open micro-burrows (e.g. *Virgaichnus*) within the matrix, which serves as source for porosity. This burrow porosity provides a connection in the matrix that hosts open vugs and fractures, thus improving oil production.

1. Introduction

Dual porosity models refer to rocks showing two contrasting porosity regimes, such as primary porosity within the matrix and secondary porosity such as fractures or vugs (Warren and Root, 1963; Gingras et al., 2012). Chalk reservoirs can be conceptualised as dual-porosity systems with fluid flow occurring mainly in the large-scale, high-permeability part of the pore system (e.g. large open burrows, fractures and vugs), which drains the fluids stored in the low-permeability but highly porous matrix. Other factors, such as tortuosity of the micro-porosity system and surface tension, may inhibit the fluid flow in chalk as well.

In contrast to the highly productive chalk fields in the southern part of the North Sea (e.g. Ekofisk and Valhall fields), chalky reservoirs in the northern North Sea experience production challenges, partly due to structural control (e.g. Oseberg Field) and partly because of facies variation (e.g. Gullfaks Field). The Shetland Group (Maastrichtian, Upper Cretaceous) of the Gullfaks Field mainly consists of argillaceous chalks to silty calcareous mudstones that alternate with or grade into cleaner, either cemented (i.e. carbonate concretions) or porous chalk beds (Fig. 1). Potential oil production is supported by open fractures (Wennberg et al., 2018); however, heterogeneity within the matrix holds the main part of porosity and remains poorly understood (Dale et al., 2018). In general, small-scale heterogeneities influencing the reservoir quality consist of a combination of sedimentary, ichnological, diagenetic and structural features (Fig. 2). Unlike cases where chalk porosity is controlled by depositional processes (e.g. autochthonous

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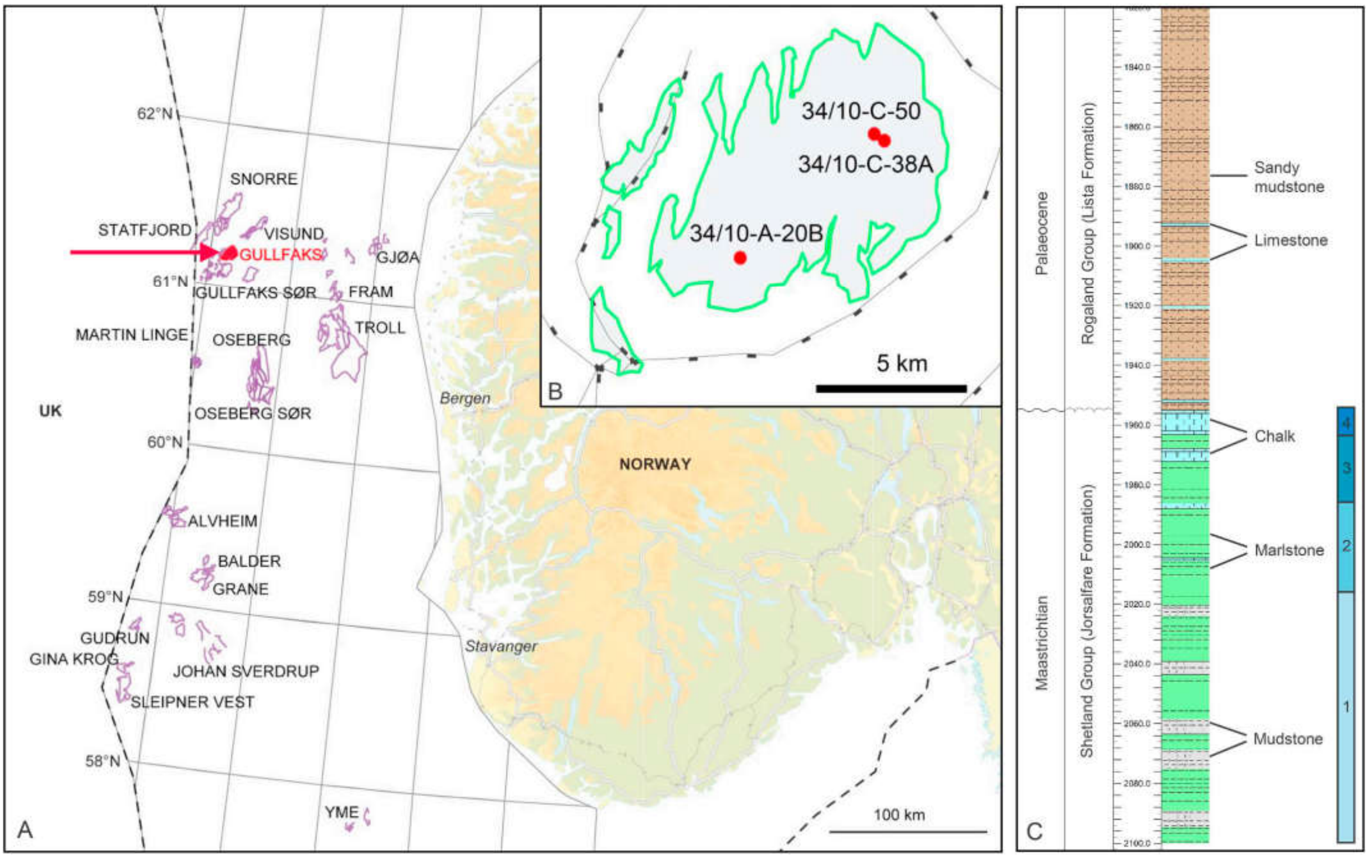

Fig. 1. Location and stratigraphy. **A:** Map of the Norwegian northern North Sea with main oil and gas fields and the Gullfaks Field highlighted (arrow). **B:** Outline of the Gullfaks Field with major faults and studied wells. **C:** Stratigraphy of the studied interval and lithology log based on well 34/10-C-50, with Reservoir Zones 1–4 (right). Main reservoir is in Zone 4 in the chalk interval at the top of the Jorsalfare Formation. The base of the Jorsalfare Formation was not cored and thus is not shown.

versus allochthonous chalk; see Anderskouv and Surlyk, 2012 for an overview), the matrix of almost the entire interval of the studied Maastrichtian part of the Shetland Group was completely bioturbated in different stages, and no primary sedimentary structures are preserved. Therefore, diffuse bioturbated texture and discrete burrows are the main heterogeneities of the matrix controlling the distribution of porosity for oil accumulation. Depending on the kind of trace fossil (including ichnological features such as shape, size and orientation) and the timing of origin of such burrows, various scenarios can be recognised, in which the impact on reservoir quality and performance can vary from open conduits to completely tight rocks (Fig. 3).

The main aims of this study can be summarised as (1) ichnological reservoir characterisation, including features such as bioturbation intensity, trace-fossils assemblages (burrow types, shapes, configuration, fill and orientation), ichnofabric definition and distribution; (2) analysis of the impact of bioturbation on reservoir quality, particularly with respect to porosity and connectivity induced by burrows; (3) identification of potential reservoir zones according to the ichnological signature and available property measurements (e.g. porosity, permeability and composition); and (4) understanding the relationship between burrows and faults and fractures. The purpose of this study is to work towards a better understanding of the impact of bioturbation and resulting burrows on the reservoir quality in the Jorsalfare Formation of the Shetland Group of the Gullfaks Field. The approach is a continuation of research that emphasises the advancement of our understanding of how bioturbation improves and degrades reservoir quality (e.g. Knaust, 2009, 2014).

2. Geological setting and the studied section

The Gullfaks Field is located in the Norwegian North Sea, where it was discovered in 1978 in Block 34/10 (Fig. 1). Since 1986, it primarily produces oil and gas from Upper Triassic to Middle Jurassic fluvial and shallow-marine reservoirs. A secondary reservoir occurs in fractured carbonates and mudstone of the Upper Cretaceous Shetland Group and the Palaeogene Lista Formation, which has contributed to production since 2012 by depletion with pressure support by water injection (Dale et al., 2018; Fig. 1). The Maastrichtian Jorsalfare Formation (Shetland Group) in the studied wells 34/10-A-20B, 34/10-C-38A and 34/10-C-50 contains an up to 165 m thick succession of mudstone with marlstone and chalk, whereas the overlaying Palaeocene Lista Formation (Rogaland Group) is up to 360 m thick and consists of sandy mudstone with thin limestone beds.

Overall, the lower part of the Jorsalfare Formation is more mudstone-dominated, whereas its top consists of chalk acting as main reservoir zone. A change from agglutinated foraminifer assemblage in the lower part to calcareous benthonic components is reflecting a change in deposition from upper bathyal conditions to an outer shelf setting. Continuous development from mudstone through marlstone and chalk (bottom to top) occurs repeatedly in a cyclic manner and gave reason for a reservoir zonation of Zone 1 (bottom) through Zone 4 (top) (Fig. 1). Aside of top Zone 4, chalk reservoir is also developed on top of Zone 3. The chalk layer on top of the Shetland Group (Zone 4) is about 8–10 m thick and developed above the underlying chalky marlstone (Zone 3) into a marly chalk and into porous and tight chalk above it. The top of the chalk is either brecciated or riddled by deeply penetrating cracks and neptunian dykes filled with material introduced from the overlying Lista Formation. This boundary is a widespread omission surface corresponding to a considerably hiatus (ca. 0.7–1.0 Ma) and marks the Cretaceous/Palaeogene (K/Pg) boundary.

The omission surface is overlain by the Lista Formation, in some areas preserving a thin layer of clotted accretionary structures of

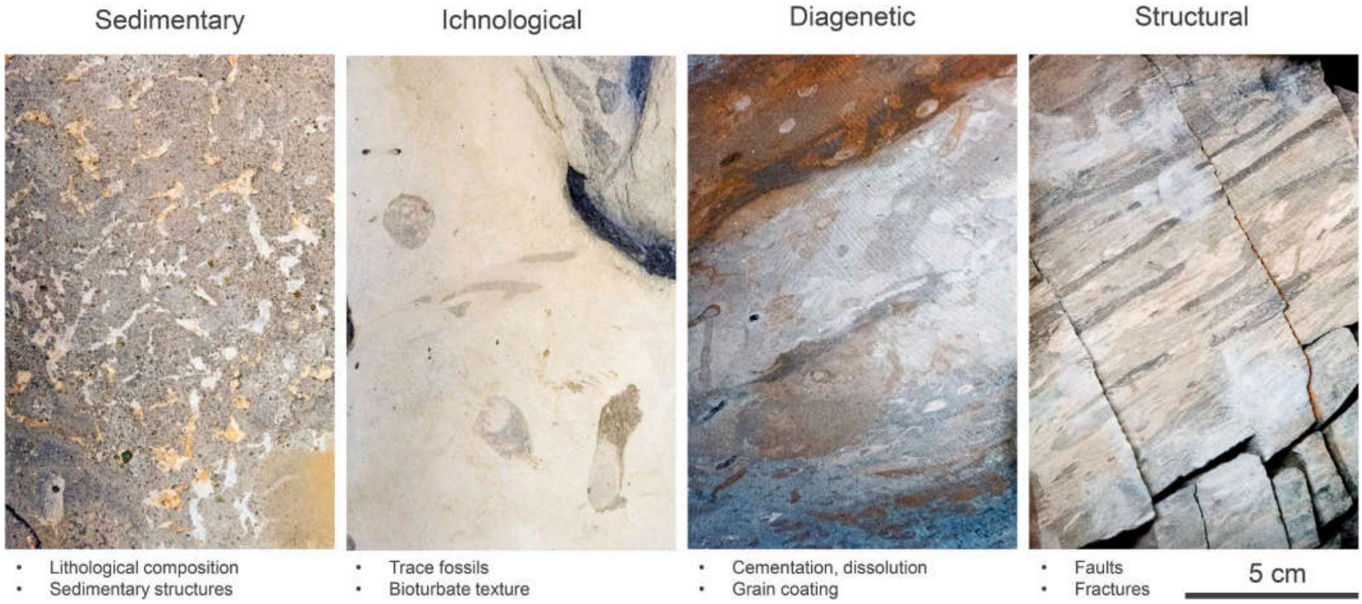

Fig. 2. Major categories of small-scale heterogeneities with impact on rock properties and resulting reservoir quality, illustrated with examples from the studied sections in the Gullfaks Field. Although rarely preserved due to bioturbation, sedimentary structures such as the figured thrombolite just above the Cretaceous/Palaeogene boundary have a primary impact, before different stages of bioturbation modify the sediment. Later, these inhomogeneities guide various fluid flows and mineral precipitation during diagenesis, and the resulting lithology acts ductile or brittle with respect to structural deformation. Modified after Knaust (2013, 2017).

microbial communities (thrombolite, Fig. 2). The Lista Formation is a relatively homogeneous succession of bioturbated mudstone of brownish and greenish colour, containing thin layers of sandstone and limestone.

3. Material and methods

The Jorsalfare Formation was studied based on slabbed core samples of the A-cut (ca. 1/3 of the core slab) and the B-cut (slice from the middle of the core) of wells 34/10-A-20B, 34/10-C-38A and 34/10-C-50 (Fig. 1B). A diverse dataset was available, including well core samples, wireline logs, core images (white and UV light), thin sections, QEMSCAN data, petrophysical data and computed tomography (CT) data. A total of ca. 383 m of core samples, wireline logs and core images were used for sedimentological core description, whereas 156 thin sections and QEMSCAN data were studied to analyse the influence of

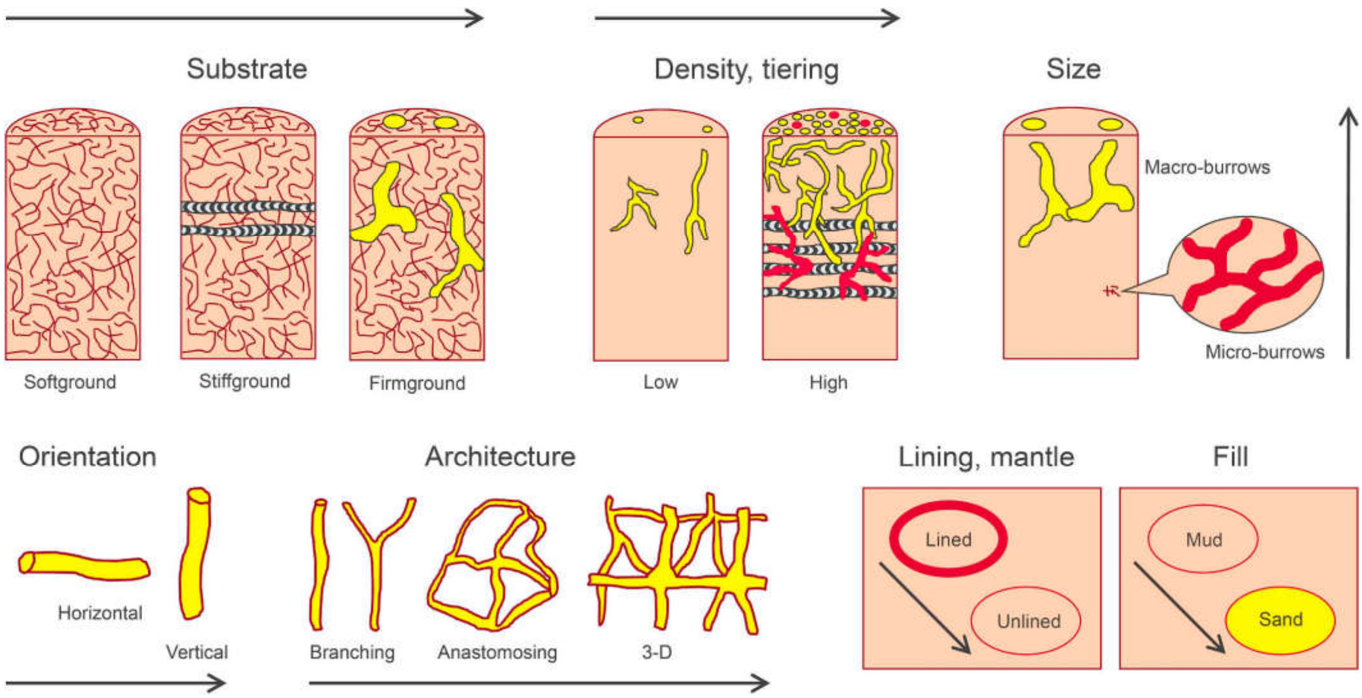

Fig. 3. Impact of architectural elements and characteristics of burrows (i.e. ichnotaxobases) on rock properties and reservoir quality. Although generalised and dependant from case to case, the arrows indicate the overall increase in reservoir property (e.g. porosity and permeability) for each category. Modified after Knaust (2013, 2017).

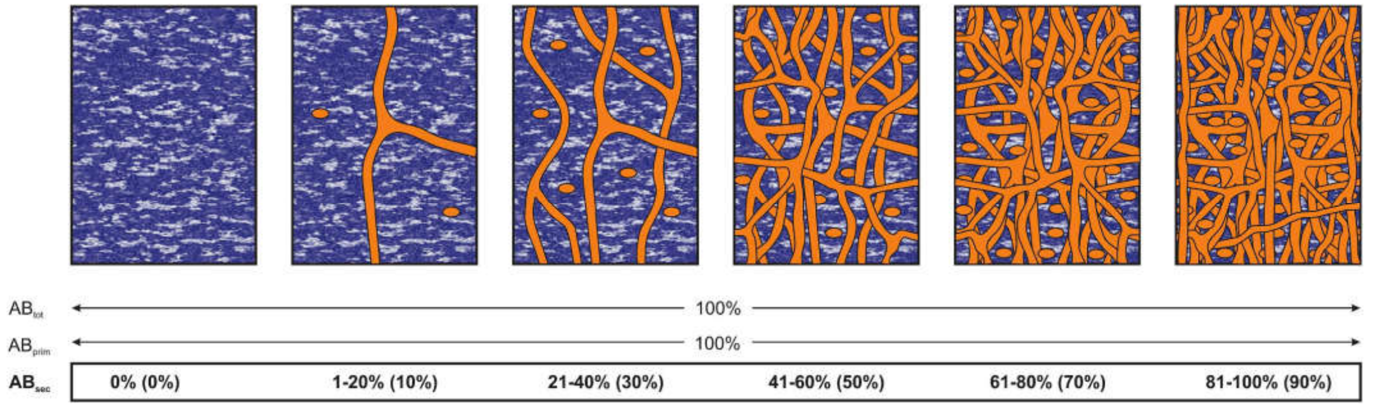

Fig. 4. Amount of bioturbation (AB) in percent schematically expressed by a range for the entire ichnofabric (AB_{tot}) and distinguished between primary softground bioturbation (AB_{prim}) and secondary stiffground and firmground bioturbation (AB_{sec}), the latter which is quantified by a mean (in brackets) and is applied in this study. Modified from Knaust (2019).

burrows on the porosity distribution and composition. Petrophysical values were used to recognise variations of some parameters, such as porosity and permeability, and some micro-tomography images were analysed to characterise the 3D distribution of trace fossils and the linking of burrows and fractures.

The ichnological characterisation, including ichnofabric differentiation, was performed on the A-cut of the core, together with core images from A-cut and B-cut. Results were supported by additional data, such as sedimentological core descriptions and UV core images. Ichnogenera characterisation was developed based on the recognition of ichnotaxobases included in Knaust (2012, 2017). The ichnofabric approach consists of the definition of ichnofabrics based on lithological (lithology, colour and sedimentary structures) and ichnological features (trace-fossil assemblages, amount of bioturbation, cross-cutting relationships and tiering) (Bromley and Ekdale, 1986; Ekdale et al., 2012; Knaust, 2019).

Since the entire sedimentary rock was completely bioturbated during several phases of colonisation (AB_{tot} = 100%), a differentiated method for logging the amount of bioturbation became necessary. While the primary bioturbation AB_{prim} (i.e. mottled background) constantly remains 100% (i.e. total bioturbation produced in soft sediment), the secondary bioturbation AB_{sec} (i.e. well-defined and conspicuous burrows produced later in a stiff and firm substrate) matters with respect to the resulting rock properties and thus was logged separately (Fig. 4). The percentage of these discrete burrows overlapping a completely bioturbated mottled background was quantified using linear growth intervals with an increment of 20% (i.e. 0%, 1–20%, 21–40%, 41–60%, 61–80%, 81–100%; for methodology see Knaust, 2017, 2019). In some ichnofabrics with clear relationships of the original substrate consistency, percentage values were measured by distinguishing different phases of colonisation (i.e. softground, stiffground and firmground). Ichnofabric distribution and abundance were analysed in detail throughout the Jorsalfare Formation in well 34/10-C-50, considering 10 cm-thick intervals in the entire cored interval.

Porosity distribution was analysed using available core-plug data from the Conventional Core Analysis (CCA), supplemented by a visual analysis of all existing thin sections. In addition, quantitative analysis of bioturbation and porosity by image treatment was applied to estimate the porosity in different parts of selected thin sections (Dorador and Rodríguez-Tovar, 2014, 2018; Dorador et al., 2014a, b; Miguez-Salas et al., 2019; Rodríguez-Tovar et al., in press). Finally, the relationship between burrows and fractures was observed and characterised at different scales. Various core samples (mainly from the chalk intervals) were used for micro-CT scanning (see Wennberg and Rennan, 2018) and the converted images were processed (3D rendering and volume segmentation) using PerGeos® and 3D Slicer® for 3D visualization (Kikinis et al., 2014).

4. Ichnological analysis

4.1. Trace fossils

No primary sedimentary structures can be recognised with certainty throughout all cores due to complete bioturbation of the sediment. A moderately diverse trace-fossil assemblage, composed of nine ichnogenera, was documented in the studied cores. *Zoophycos* is the most abundant ichnotaxon, and *Chondrites*, *Taenidium*, *Thalassinoides* and *Virgaichnus* are common (Table 1). *Planolites*, *Nereites, Spirophyton* and *Teichichnus* are rare and not regarded to be relevant in the context of this study.

Different kinds of sediment were identified as filling the burrows, which is important for resulting reservoir properties. Two main

Table 1
Ichnogenera as identified in the studied cores.

Abundance	Ichnogenus	Appearance	Approx. size	Fill
Abundant	*Zoophycos*	Horizontal spreiten burrows with dark and light lamellae, spreite may be obliterated	3–10 mm wide, commonly extending core width	Active (spreiten)
Common	*Chondrites*	Small spots and tubes, sometimes branched	Less than 1–3 mm wide, ca. 3–50 mm long	Active
	Taenidium	Sub-horizontal tubular meniscate burrows	8–19 mm wide, 20–80 mm long	Active (meniscate)
	Thalassinoides	Large vertical and horizontal tubular burrows, branched	10–25 mm wide, 8 to > 20 cm long (outside core scale)	Passive (open or cemented)
	Virgaichnus	Pinch-and-swell-like burrows with branching	Ca. 1 mm or smaller (mainly visible in thin sections and micro-CT images)	Passive (open or cemented)
Rare	*Nereites*	Grouped tubular sections with lined wall	5–7 mm in diameter	Active
	Planolites	Unbranched tubular sections	7–12 mm in diameter	Active
	Spirophyton	Christmas tree-like burrows	10–15 mm wide, 10–25 mm long	Active
	Teichichnus	Horizontal burrow with vertical spreiten	13 mm wide, 20 mm long	Active (spreiten)

Table 2
Different types of burrow fill within the recognised ichnogenera and their impact on the reservoir quality.

Fill		Ichnotaxa	Description	Impact on reservoir quality
Passive	Open	Tiny burrows (e.g. *Virgaichnus*), partially open *Thalassinoides*	Burrows remain open, in some cases connecting fractures	Increased connectivity
	Muddy	*Thalassinoides*	Burrows created in stiffground, filled with porous material	Enhanced porosity
	Bioclasts	*Thalassinoides*	Burrows filled with foraminifera and shell fragments	Increased porosity in chalky marls
Active	Meniscate	*Taenidium*	Some meniscate burrows are filled with porous material	Porosity modified in a positive or negative way
	Spreiten	*Zoophycos*	Different types of spreiten burrows with alternating laminae material	Enhanced or reduced porosity, depending on fill
	Cement	*Chondrites*, *Virgaichnus*	Fill material consists of diagenetic cement (e.g. calcite)	Decreased porosity and connectivity
Reburrowed traces		Mainly *Thalassinoides*	*Chondrites* (younger) reworking the fill material of *Thalassinoides*	Partly decreasing properties of the reworked *Thalassinoides*

scenarios of burrow fill are common, (1) active fill (the burrow fill is introduced by the trace-making organism simultaneously during burrowing), and (2) passive fill (an abandoned burrow becomes subsequently and passively filled with sediment, it remains open, or it becomes subject to cementation). Additionally, (3) some burrow fills (mainly *Thalassinoides*) are occasionally reworked with *Chondrites* that modifies the original fill sediment. Thus, depending on the resulting rocks, several types of burrow fill can be distinguished within the three groups of burrow fill (Table 2).

4.2. Amount of bioturbation (AB)

Considering the total amount of bioturbation (AB_{tot}, including diffuse bioturbate texture and discrete burrows), the studied sedimentary rocks are completely bioturbated (100%) and primary sedimentary structures are not preserved. Organisms reworked the original sediment and produced a diffuse mottling. However, in most cases discrete burrows, resulting from the subsequent activity of various trace makers that introduced contrasting material, overprinted this mottled background and consequently modified the host rock. Therefore, only the secondary amount of bioturbation (AB_{sec}) was estimated by considering stiffground and firmground burrows (Fig. 4).

The secondary amount of bioturbation (AB_{sec}) average of the total interval of all studied cores is around 25% (moderate to low) but increases to 40% if only intervals with secondary bioturbation present are considered. This average is, however, quite variable depending on the interval and ichnofabric. The amount of bioturbation varies with depth as reflected by the calculated values for each reservoir zone (i.e. Zones 1 to 4, Fig. 1C). Zones 1 and 4 (lower and upper part of the Jorsalfare Formation) show relatively low AB_{sec} values of 20–22%. Zone 3 has on average 28% and Zone 2 is characterised by the highest value of 30%. Calculations that exclude non-bioturbated intervals result 49% in Zone 2 and 39% in Zone 3.

4.3. Ichnofabrics

Five ichnofabrics were defined and named according to their main constituents, which are (from clay-rich to chalky substrate): *Zoophycos-Taenidium*, *Nereites*, *Chondrites*, *Zoophycos* and *Thalassinoides* ichnofabric (Figs. 5 and 6). The ichnofabrics are related to specific lithofacies and the ichnofabrics influenced the distribution of porosity.

4.3.1. Description

The *Zoophycos-Taenidium* ichnofabric consists of green mottled mudstone with common discrete burrows. The background has a mottled texture and is completely bioturbated (AB_{prim} = 100%) by primary burrowing and overprinted by discrete secondary burrows ranging from AB_{sec} = 40–80% (moderate to very high bioturbation). *Zoophycos*, *Taenidium* and mud-filled *Thalassinoides* are abundant, and some rare *Chondrites* are also present. Under UV light, this ichnofabric is completely dark, thus providing no evidence for oil staining.

The *Nereites* ichnofabric comprises argillaceous marlstone with complete bioturbation (mottling) and scattered carbonate concretions. Discrete burrows are commonly absent (AB_{sec} = 0%), although in some parts burrows with a muddy core and a thick sandy mantle are tentatively assigned to *Nereites*. In addition, *Chondrites* can be recognised, particularly in thin sections. This ichnofabric is completely dark under UV light.

The *Chondrites* ichnofabric consists of marlstone with a common presence of chalk-filled burrows. *Taenidium*, *Thalassinoides* and *Zoophycos* are abundant, whereas *Nereites*, *Planolites*, *Spirophyton* are rarely identified. *Chondrites* is quite abundant and best recognised in thin sections. The bioturbation intensity is moderate in average but ranges from low to very high (AB_{sec} = 20–80%). The host sediment from these intervals looks dark under UV light, but chalky traces appear yellowish due to oil staining.

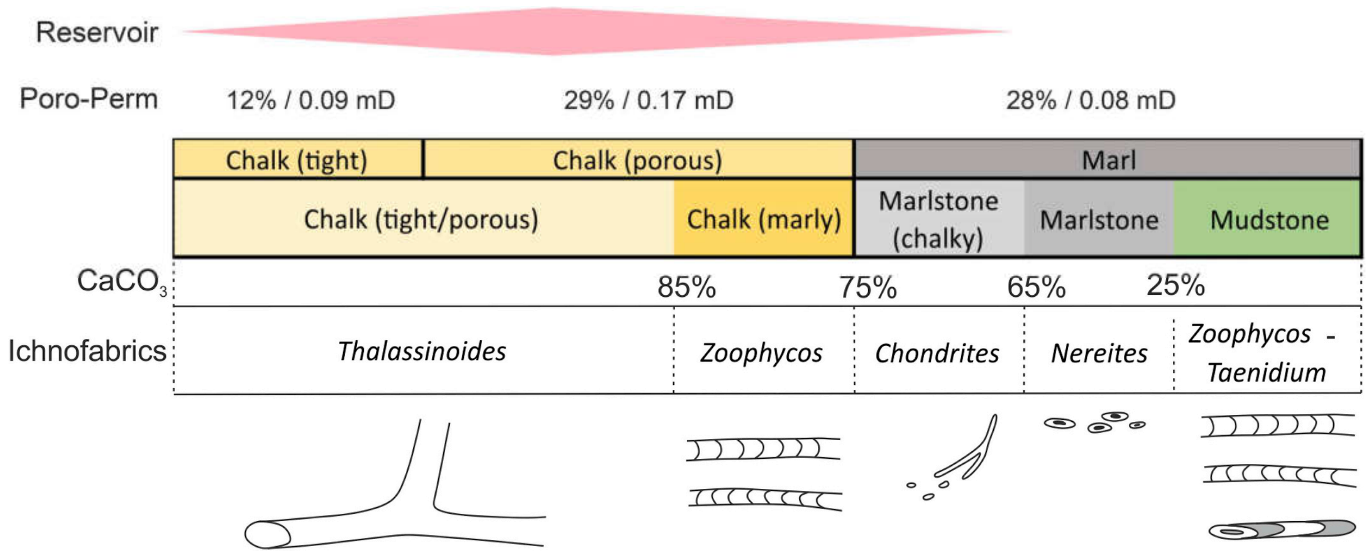

Fig. 5. Summary of common lithofacies types and associated ichnofabrics in the Jorsalfare Formation of the Gullfaks Field, as well as mean porosity and permeability and the main reservoir units.

The *Zoophycos* ichnofabric consist of porous chalk, which contains abundant marl-filled burrows with low to high amount of bioturbation (AB_{sec} = 20–60%). *Chondrites*, *Taenidium*, *Thalassinoides* and *Zoophycos* are commonly identified, particularly in thin sections, while *Planolites* remains rare. Intervals characterised by this ichnofabric look yellowish under UV light.

The *Thalassinoides* ichnofabric occurs in both porous and tight chalks with a mottled texture in the background, overlapped by two generations of discrete burrows. The first generation is represented by abundant *Chondrites*, *Taenidium, Virgaichnus* (the last ichnogenus is mainly observed in CT images) and *Zoophycos*, accompanied by rare *Planolites* and *Thalassinoides*. This generation occurs with a moderate bioturbation intensity (AB_{sec} = 20–40%) and was produced in a stiffground. Burrows are mostly filled with marl and incorporate porous material. Later, another generation was developed in a more consolidated substrate (i.e. firmground), mostly consisting of *Thalassinoides* filled with porous sediment and variable amount of bioturbation (AB_{sec} = 20–60%). This ichnofabric is clearly affected by fractures and open burrows, both considerably increasing porosity and connectivity. The fractures and burrows appear yellowish under UV light and are partly oil stained.

4.3.2. *Ichnofabric development through time and in response to substrate cohesiveness*

Ichnofabrics are complex systems recording ichnological fidelity in a taphonomic window (e.g. Knaust, 2019). The factors time and substrate consistency were proven to be most relevant for the resulting rock properties, and an attempt to reconstruct major stages of colonisation and substrate consistency was made. Some scenarios of overlapping discrete burrows were observed throughout the cores; particularly in chalky intervals where cross-cutting relationships are well pronounced. This evidence reveals favourable long-time conditions for colonisation, the development of different tiers (i.e. infaunal colonisation of different depth horizons from shallow to deep substrate) and changing substrate consistency. The different styles of bioturbation took place during changing stages of sediment consistency as recognised by the appearance of bioturbate texture (i.e. mottled background) and different discrete burrows (Fig. 7).

Stage 1: In an early phase, the benthic trace makers disturbed the soft sediment in the uppermost part of the substrate and developed a mottled fabric which now is recognised as a completely homogenised sedimentary rock without containing any recognisable trace fossils.

Stage 2: Subsequent colonisation in a more consolidated and stiff sediment resulted in discrete burrows that can be recognised by their shape and fill; in some cases, subsequent compaction led to subtle deformation.

Stage 3: During a late phase, more consolidated, firm sediment was penetrated by the trace makers, which created conspicuous, open burrow systems subject to subsequent fill with sediment or cement.

These different stages are reflected in their ichnofabrics and result in ichnological features which strongly impact, in a variable degree, the reservoir properties within the Jorsalfare Formation.

5. Petrophysical properties related to ichnofabrics

5.1. *Porosity and permeability measurements*

Porosity and permeability measurements from the Jorsalfare Formation in cores from well 34/10-C-50 were analysed for the different ichnofabrics. In general, the average poro-perm data for all ichnofabrics do not show significant differences and remain low reflecting the relatively tight nature of the reservoir (Fig. 5). Highest average permeability occurs in the *Thalassinoides* ichnofabric and could be related to the connectivity between open or passively filled burrows and fractures in an otherwise tight matrix.

A thin-section analysis was performed in order to evaluate porosity trends in connection with particular burrow types on a millimetre scale. The analysis reveals that porosity is heterogeneously distributed in samples and commonly influenced by trace fossils. Burrows can induce changes in porosity, increase or decrease it, all depending on the abundance, size and the nature of the fill material of relevant burrows. For example, *Chondrites* is a dichotomously branching burrow system with burrow diameters around 1–2 mm and can either be filled with tight mud or porous grainy sediment, with contrasting effects on the resulting reservoir rock.

Porosity was measured in some thin sections using two different methods, pixel counting by image treatment (see Dorador et al., 2014) and QEMSCAN analysis (Fig. 8). Both methods show some differences in the obtained values. Measurements obtained by pixel counting using image treatment produced rather unrealistic absolute values, whereas their relative values seem to be reliable. In all examples, burrows have higher values compared with the surrounding matrix. For instance, the

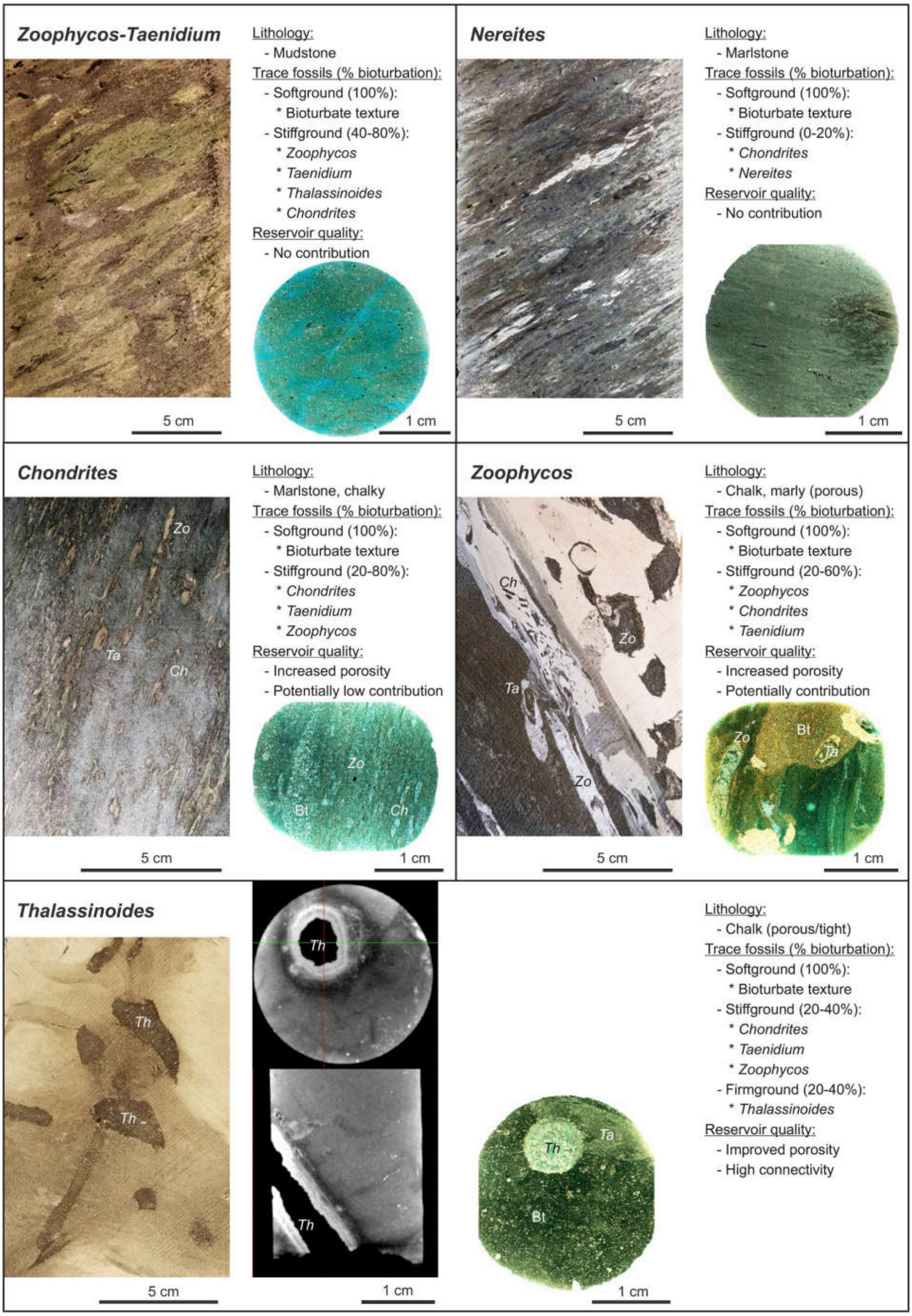

Fig. 6. Summary of the observed ichnofabrics with core image, microphotograph (thin section), description and CT scan (*Thalassinoides* ichnofabric). Bt, Bioturbate texture; *Ch*, *Chondrites*; *Ta*, *Taenidium*; *Th*, *Thalassinoides*; *Zo*, *Zoophycos*. Core images and microphotographs were slightly adjusted in grey scale, contrast and sharpness.

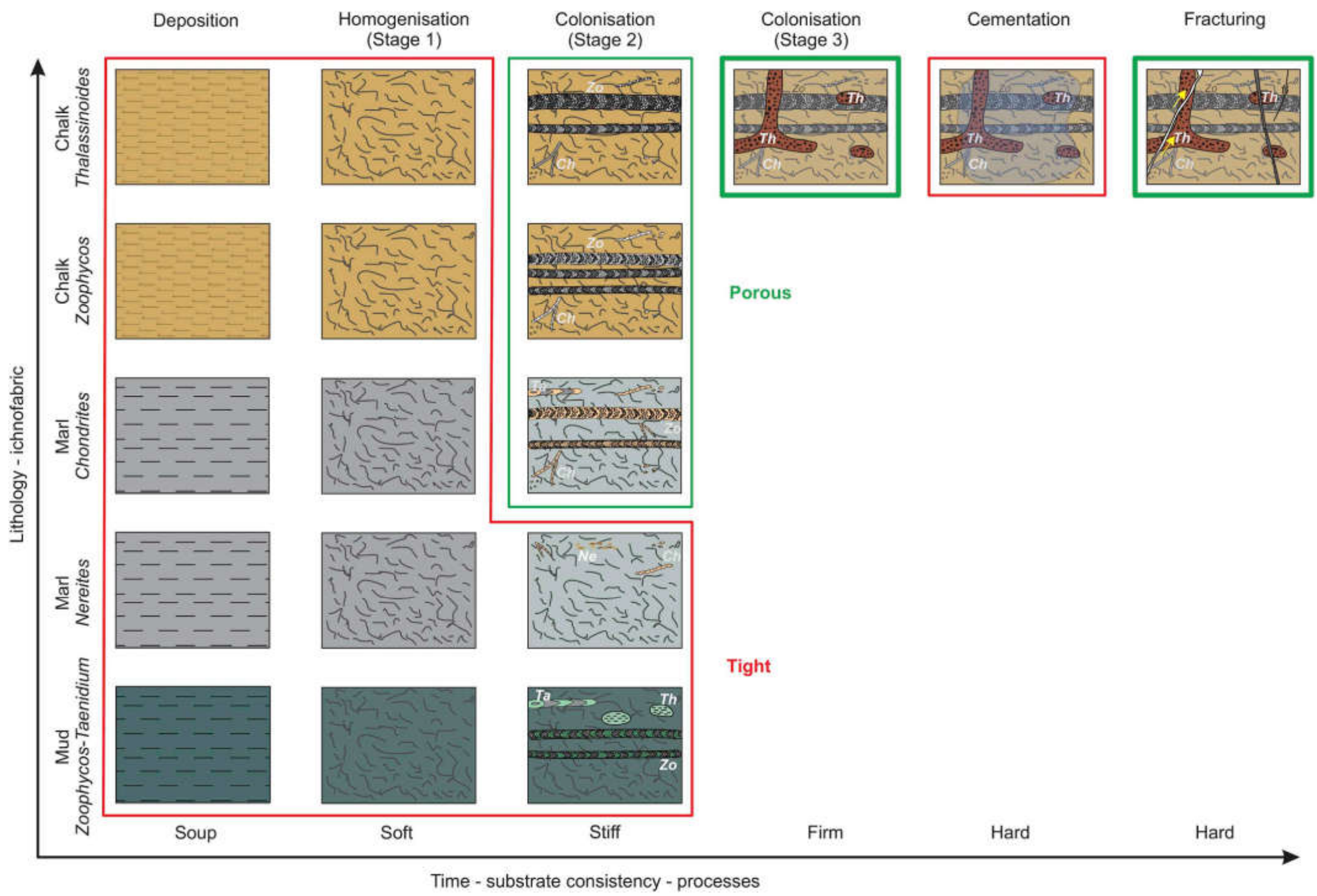

Fig. 7. Diagram illustrating the development of recognised ichnofabrics in response to lithology and stages of colonisation, substrate consistency and the resulting impact on porosity. *Ch, Chondrites; Ne, Nereites; Ta, Taenidium; Th, Thalassinoides; Zo, Zoophycos.*

fill of *Zoophycos* shows the highest porosity values of all measurements (11–18%), while the surrounded matrix with bioturbated texture has low porosity (1–5%). Another example contains a *Thalassinoides* burrow in cross section, which is filled with much more grainy and porous material (9% porosity) than its tight host rock (0.1% porosity).

5.2. Ichnofabric distribution within the reservoir

The distribution of individual ichnofabrics within reservoir Zones 1–4 of the Jorsalfare Formation was semi-quantified based on core observations from well 34/10-C-50 (Fig. 3C).

Zone 1: This lowermost zone is less relevant for reservoir quality because of the dominance of the *Nereites* and *Chondrites* ichnofabrics (combined 89%), the latter which may marginally enhance the reservoir quality if the *Chondrites* burrows are sand-filled.

Zone 2: In Zone 2, the *Nereites* ichnofabric is most abundant (43%), followed by the *Thalassinoides* and *Zoophycos* ichnofabrics (combined 33%), while the *Chondrites* ichnofabric remains subordinate (23%). Enhanced reservoir quality due to these ichnofabrics only plays a minor role in this zone.

Zone 3: In Zone 3, the *Nereites* ichnofabric is dominant (55%) but does not have a positive effect on the reservoir quality. It is followed by the *Chondrites* ichnofabric (25%), which again has comparatively little impact on reservoir performance. The *Thalassinoides* and *Zoophycos* ichnofabrics together are minor (19%) but probably with the strongest impact on reservoir properties.

Zone 4: This uppermost zone is the chalkiest interval and is dominated by the *Thalassinoides* ichnofabric (79%), which in turn is considered the most characteristic ichnofabric of higher reservoir quality rock (main reservoir zone).

With respect to an evaluation of existing and potential reservoir units, Zone 4 remains outstanding because of the overall presence of the *Thalassinoides* ichnofabric. Additional potential intervals with a relatively high presence of *Thalassinoides* ichnofabric occur in Zones 2 and 3, both intervals characterised by favourable reservoir properties. The second most promising ichnofabric is represented by the *Zoophycos* ichnofabric, which is also present in these intervals.

The *Thalassinoides* ichnofabric is the most contributing ichnofabric in terms of reservoir quality and – beside its occurrence in Zone 4 – is also present in Zone 2 where it provides a potential reservoir zone. Moreover, some micro-faults affect the burrows, thus enhancing the conectivity between burrows and fractures. A potential reservoir interval in Zone 3 is similar to the previous one regarding its ichnofabric characterisation. It is dominated by a *Thalassinoides* ichnofabric composed of chalky sediment with *Thalassinoides* containing a relatively porous fill.

6. Burrows linked to fractures and faults in the dual porosity system

Structural elements such as fractures, faults and dissolution seams play an important role in chalky reservoirs and are recognised as such within the reservoirs of the Jorsalfare Formation, in particular within Zones 1 and 4. These heterogeneities are believed to act as main conduits for fluid flow; however, the results of this study indicate that there is a close relationship between such fractures and faults and the hosting

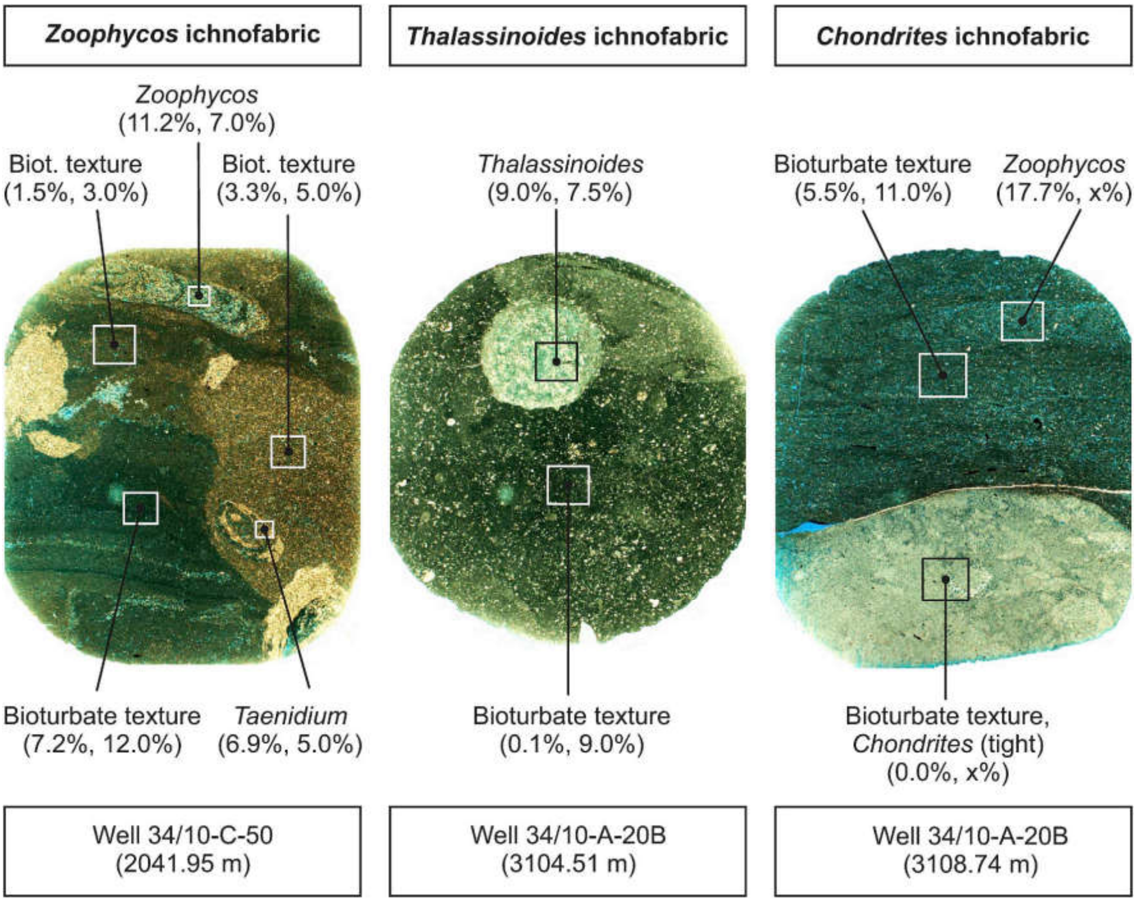

Fig. 8. Examples of porosity estimation based on thin-section analysis of sidewall cores by applying image treatment (first value) and QEMSCAN analysis (second value) in selected areas of thin sections (squares) from the Jorsalfare Formation, and their relationship to recognised trace fossils. Thin sections are ca. 2.5 cm in diagonal direction and were slightly adjusted in grey scale, contrast and sharpness. Light blue colour refers to increased porosity. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

matrix they are penetrating. While ichnofabrics resulting from primary bioturbation in an early softground stage are commonly tight, secondary bioturbation in stiffground and firmground created burrows with a more complex structure. These relatively late burrows may also act as conduits and are commonly penetrated by fractures and faults. In this way they contribute to a network (or better 3D boxwork) of interconnected conduits and help in the production of hydrocarbon from the bioturbated matrix via fractures and faults.

In this study, some examples of possible relationships between fractures/faults and burrows were observed from the three cores. Micro-CT images from some of these samples were processed to produce a 3D reconstruction of burrows and fractures. They reveal interesting features on a millimetre scale, which may be applicable at a larger scale as well. Fig. 9 shows some common interrelationships between micro-burrows and fractures. Different types of burrows can be observed in the processed images, such as partially open *Thalassinoides* and tiny open and cemented burrows assigned to *Virgaichnus*, all of them are affected by and, consequently connected to, fractures (Fig. 10).

7. Conclusions

An ichnological analysis of three wells (34/10-C-50, 34/10-A-20B and 34/10-C-38A) from the Jorsalfare Formation (Shetland Group) in the Gullfaks Field reveals the existence of an abundant and moderately diverse trace-fossil assemblage, composed of nine ichnogenera (*Chondrites*, *Nereites*, *Planolites*, *Spirophyton*, *Taenidium*, *Teichichnus*, *Thalassinoides*, *Virgaichnus* and *Zoophycos*). *Zoophycos* is the most abundant trace fossil; *Chondrites*, *Taenidium*, *Thalassinoides* and *Virgaichnus* are common, while the remaining trace fossils are rare. Trace-fossils assemblage and other ichnological features, such as the amount of bioturbation and tiering, allow the outlining of five ichnofabrics: *Zoophycos-Taenidium*, *Nereites*, *Chondrites*, *Zoophycos* and *Thalassinoides* ichnofabrics.

The *Thalassinoides* ichnofabric in chalk with firmground colonisation performs best in terms of reservoir quality. Marly chalk and chalky marlstone with *Zoophycos* and partly *Chondrites* ichnofabrics may contribute as potential reservoir zones if burrow density is sufficiently high. Ichnofabrics distribution and relative abundance define the reservoir zonation, with Zone 4 (upper part of the Shetland Group) as the best-performing reservoir unit, followed by additional potential intervals in Zones 2 and 3. The study of thin sections shows that burrows have a high impact on porosity distribution and are a control of the reservoir quality, whereas the analysis of selected micro-CT images has revealed a high connectivity between some burrows and fractures.

Overall, good reservoir quality is associated with chalky intervals, whereas clay-rich lithofacies appears with rather tight properties. Although a more detailed and comprehensive analyses and the inclusion of more wells would be necessary for a widespread evaluation, this investigation shows a strong impact of bioturbation on the porosity distribution within the matrix of this dual-porosity system, and the importance of bioturbation for reservoir quality and producibility in chalk reservoirs.

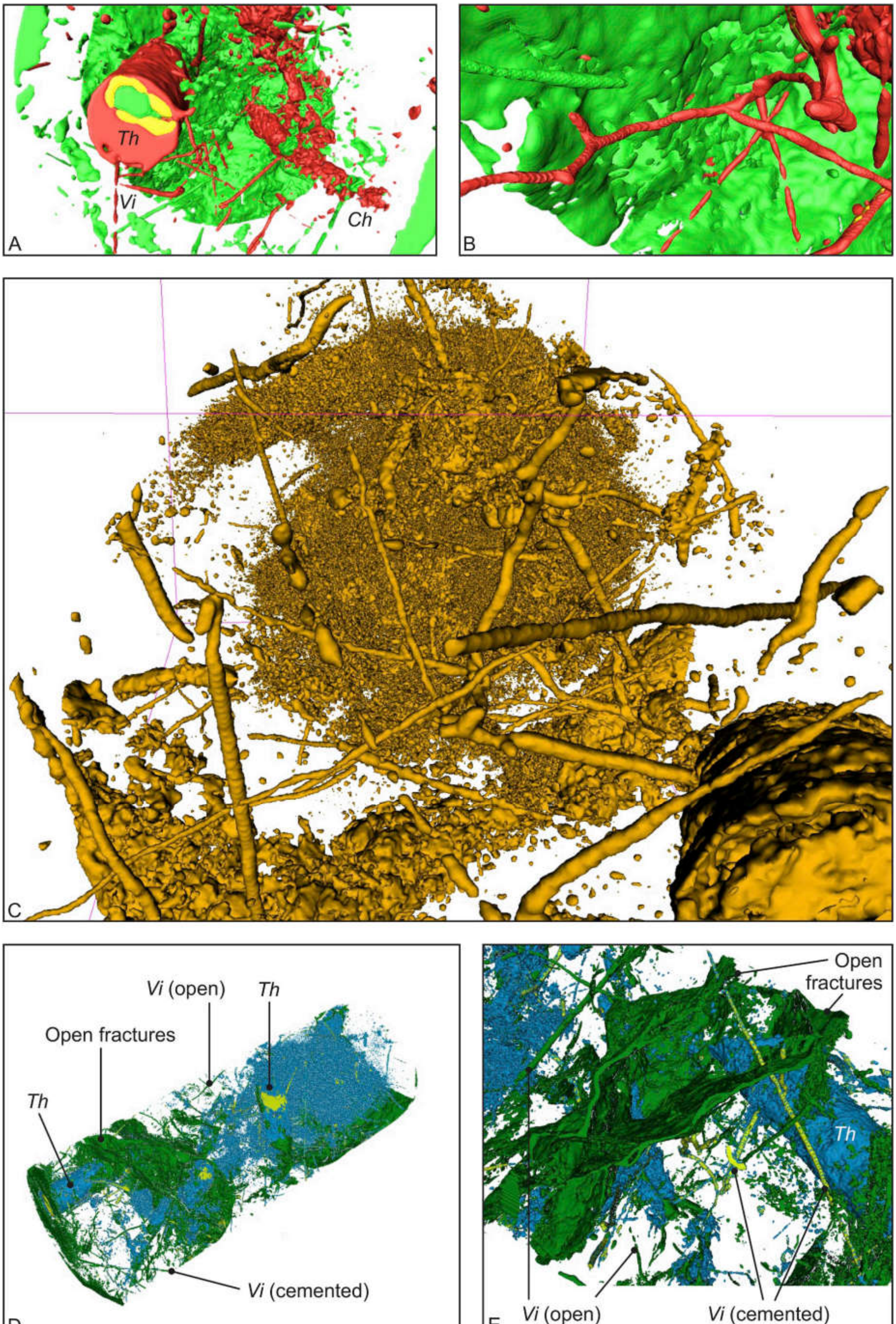

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Fig. 9. Representative chalk samples from cylindrical core plugs processed by 3D micro-CT scanning, illustrating their ichnological content and burrow interaction with fractures. **A:** Ichnofabric containing *Thalassinoides* (*Th*); *Chondrites* (*Ch*) and *Virgaichnus* (*Vi*). Circular outline in the front and the back of the image is ca. 2.5 cm in diameter. **B:** Close-up view from A displaying a three-dimensional burrow system of *Virgaichnus* with the characteristic branching pattern and undulating burrow outline. Burrow diameter ca. 0.2–0.8 mm. **C:** Dense system of tiny burrows (*Virgaichnus*) connecting with *Thalasinoides* (lower right). All burrows are observed to be open within the matrix, thus contributing to the (micro-) porosity within this otherwise tight reservoir rock. **D:** Same sample as in C, showing tiny open and cemented burrows (green and yellow, respectively) assignable to *Virgaichnus* (*Vi*), *Thalassinoides* (*Th*, blue), and open fractures (green). Note that non-eliminated "noise" in the background appears in spotted blue. Plug diameter ca. 2.5 cm. **E:** Close-up image of D revealing the intimate cross-cutting relationship of burrows such as *Thalassinoides* (*Th*) and *Virgaichnus* (*Vi*) with open fractures. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

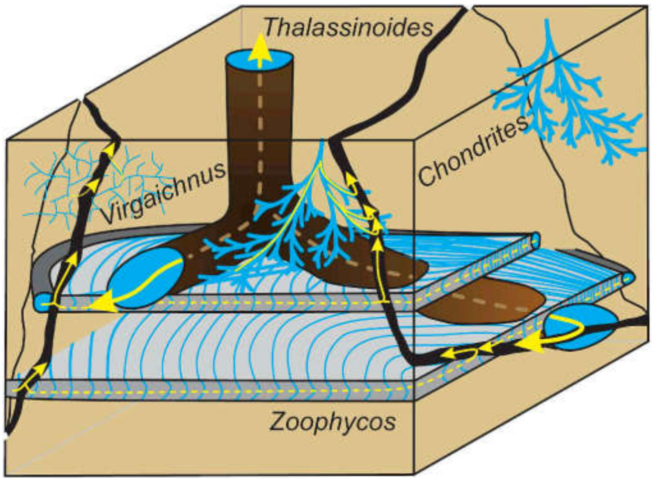

Fig. 10. Idealised block diagram illustrating various stiffground and firmground burrows (secondary bioturbation) overprinting completely bioturbated softground (primary bioturbation, beige). If enough porous portions of the burrows (blue) are intersected with fractures, the oil in the burrowed chalk matrix can be produced (yellow arrows). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Author contribution statement

Dirk Knaust: Conceptualization, Writing - original draft, Visualization, Project administration, Javier Dorador: Methodology, Investigation, Data curation, Writing - review & editing, Visualization, Francisco J. Rodríguez-Tovar: Validation, Writing - review & editing, Supervision.

Declaration of interest statement

No conflict of interest exists.

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