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

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Abstract

Chalk reservoirs are often 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, 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 three wells in the Maastrichtian Shetland Group of the Gullfaks Field reveal that this interval is completely bioturbated during several staged, e.g. mottling with diffuse bioturbated texture in an early soft-ground stage that became subsequently overprinted by more discrete burrows with active and passive fill and different properties during the stiff-ground and firm-ground 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 (*Zoophycos-Taenidium*, *Nereites*, *Chondrites*, *Zoophycos* and *Thalassinoides* ichnofabrics) with variable influence on rock properties. The *Thalassinoides* ichnofabric in chalk has the highest impact on good reservoir quality, while *Zoophycos* and partly *Chondrites* ichnofabrics, in marly chalk and chalky marlstone respectively, contribute as potential reservoir zones if burrow density is high enough. Thin-section analysis of the different ichnofabrics illustrates the 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. In connection with open vugs and fractures, these open burrows seem to have a main contribution for oil production.

Key words: Bioturbation, burrow, chalk, reservoir, porosity, Shetland Group, Cretaceous

1. Introduction

Dual porosity models refer to rocks consisting of two contrasting porosity regimes, such as primary porosity within the matrix and secondary porosity introduced in form of fractures or vugs (Warren and Root, 1963, Gingras et al., 2012). Chalk reservoirs are an example of dual porosity systems, in which high-porosity and low-permeability within the matrix interacts with highly permeable natural fractures. They commonly store a waste amount of hydrocarbon (up to 99%) within the poorly connected micro-pores, whereas macroscopic heterogeneities (e.g. large open burrows, fractures and vugs) become necessary for producing such hydrocarbons.

In contrast to the well-producing chalk fields in the southern part of the North Sea (e.g. Ekofisk Field), chalky reservoirs in the northern North Sea experience production challenges, partly due to structural control (e.g. Oseberg Field) and partly because of facies development (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 pass gradually into cleaner, either cemented or porous chalk beds and concretions. Potential oil production is supported by open fractures (Wennberg et al., 2018); however, heterogeneity within the matrix holds the main part of porosity but 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. 1). Unlike than in chalk porosity controlled by depositional processes (e.g. autochthonous versus allochthonous chalk; see Anderskouv and Surlyk, 2012 for an overview), the matrix of almost the entire interval of the studied Shetland Group was completely bioturbated in different stages, and no primary sedimentary structures are preserved. Therefore, diffuse bioturbated texture and discrete burrows (i.e. trace fossils) 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, orientation, etc.) and the timing of origin of such burrows (Fig. 2), various scenarios can be recognised, in which the impact on reservoir quality and performance can vary from open conduits to completely tight rocks. The main 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 Shetland Group of the Gullfaks Field. This approach is a continuation of previous research with emphasis on bioturbation in carbonate reservoirs (e.g. Knaust, 2009, 2014).

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, orientation, etc.), 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) approaching the relationship between burrows and fractures/faults.

2. Geological setting and the studied section

The Gullfaks Field is located in the Norwegian North Sea (Fig. 3), where it was discovered in 1978 in Block 34/10. Since 1986, it primarily produces oil and gas from Upper Triassic to Middle Jurassic shallow-marine and fluvial reservoirs. A secondary reservoir occurs in fractured carbonates and shale of the Upper Cretaceous Shetland Group and the Palaeogene Lista Formation (Fig. 3), which has contributed to production since 2012 by depletion with pressure support by water injection (Dale et al., 2018). The Maastrichtian Jorsalfare Formation (Shetland Group) in the studied wells 34/10-A-20, 34/10-C-38 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 Shetland Group is more mudstone-dominated, whereas its top consists of chalk acting as main reservoir zone, 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). Aside of top Zone 4, chalk reservoir is also developed on top of Zone 3. The chalk layer on top of the Shetland Group is about 8-10 m thick and developed from the underlaying chalky marlstone into a marly chalk and eventually into porous and tight chalk. Its top is 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 with a considerable time gap (ca. 0.7-1.0 Ma) and marks the K/Pg (Cretaceous/Palaeogene) boundary.

Above that unconformity starts the Lista Formation, in some areas preserving a thin layer of clotted accretionary structures of microbial communities (thrombolite). 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 Shetland Group was studied based on slabbed core samples of the A-cut (ca. 1/3 slab) and the B-cut (slice from the middle of the core) of wells 34/10-A-20, 34/10-C-38 and 34/10-C-50. 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. Core samples, wireline logs and core images were used for sedimentological core description; whereas thin sections and Qemscan data were studied to analyse the influence of burrows on the porosity distribution and composition. Moreover, 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 (facies, colour, sedimentary structures, etc.), 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 is completely bioturbated during several phases of colonisation, a differentiated method for logging the amount of bioturbation became necessary. While the primary bioturbation (i.e. mottled background) constantly remains 100% (i.e. total bioturbation produced in soft sediment), the secondary bioturbation (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. soft-, stiff- and firm-ground). Ichnofabric distribution and abundance were analysed in detail throughout the Shetland Group 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 treated with micro-CT scanning (see Wennberg and Rennan, 2018) and the resulting images were processed using PerGeos® and 3D Slicer® (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 relative moderately diverse trace fossil assemblage, composed of nine recognised ichnogenera, is 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. Those trace fossils that were only occasionally observed (rare in Table 1) are not further regarded in this research.

Different kinds of sediment were identified as filling material of the burrows, which is important for resulting reservoir properties (e.g. porosity and permeability of the final rock). Two main 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 of cementation). Additionally, some burrows (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 both groups (Table 2).

Table 1. Ichnogenera as identified in the studied cores.

Abundance	Ichnogenus	Appearance	Approximate size	Fill
Abundant	*Zoophycos*	Horizontal spreiten burrows with dark and light lamellae, spreite may be obliterated	3 to 10 mm wide, commonly extending core width	Active (spreiten)
Common	*Chondrites*	Small spots and tubes, sometimes branched	Less than 1 to 3 mm wide, ca. 3 to 50 mm long	Active
	Taenidium	Sub-horizontal tubular meniscate burrows	8 to 19 mm wide, 20 to 80 mm long	Active (meniscate)
	Thalassinoides	Large vertical and horizontal tubular burrows, branched	10 to 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 to 7 mm in diameter	Active
	Planolites	Unbranched tubular sections	7 to 12 mm in diameter	Active
	Spirophyton	Christmas tree-like burrows	10 to 15 mm wide, 10 to 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, sometimes connecting fractures	Increased connectivity
	Muddy	*Thalassinoides*	Burrows created in stiff-ground, 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*

4.2. Amount of bioturbation

Considering the total amount of bioturbation (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 has been estimated by considering stiff- and firm-ground burrows.

The secondary amount of bioturbation (AB_{sec}) average of all studied cores is around 25% (moderate to low) but increases to 40% if non-bioturbated intervals are excluded. 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). Zones 1 and 4 (upper and lower part of the Shetland Group) 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 have been defined and named according to their main constituents, which are (from muddy to chalky substrate) *Zoophycos-Taenidium*, *Nereites*, *Chondrites*, *Zoophycos* and *Thalassinoides* ichnofabric (Figs. 5, 6). They are related to particular lithofacies types and influence the distribution of porosity.

4.3.1. *Zoophycos-Taenidium* ichnofabric

This ichnofabric consists of green mottled mudstone with common discrete burrows. The background is completely bioturbated (mottled background) and overprinted by discrete burrows in a variety of percentages (AB_{sec}=40-80%), being moderately to very highly bioturbated. *Zoophycos*, *Taenidium* and mud-filled *Thalassinoides* are abundant, and some rare *Chondrites* can be also identified. Under UV light, this ichnofabric looks completely dark, thus they are not oil stained.

4.3.2. *Nereites* ichnofabric

This 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.

4.3.3. *Chondrites* ichnofabric

This 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. Furthermore, *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.

4.3.4. *Zoophycos* ichnofabric

This 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.

4.3.5. *Thalassinoides* ichnofabric

This 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* (mainly observed in CT images) and *Zoophycos*, accompanied with rare *Planolites* and *Thalassinoides*. This generation occurs with a moderate bioturbation intensity (AB_{sec}=20-40%) and was produced in a stiff-ground. Burrows are mostly filled with marl and incorporate porous material. Later, another generation was developed in a more consolidated substrate (i.e. firm-ground), 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. They look yellowish under UV light and are partly oil stained.

4.3.6. 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). In the performed study, the factors time and substrate consistency have proven to be most relevant for the outcoming rock properties, and an attempt to reconstruct major stages has been 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, allowing 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).

Phase 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.

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

Phase 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 phases and the repeated colonisation stages are reflected in their ichnofabrics and result in ichnological features which strongly impact, in a variable degree, the reservoir properties (e.g. porosity, permeability) within the Shetland Group.

5. Petrophysical properties related to ichnofabrics

5.1. Porosity and permeability measurements

Porosity and permeability measurements from the Shetland Group in cores from well 34/10-C-50 were analysed with respect to the evaluation of different ichnofabrics. In general, the average poro-perm data for all ichnofabrics does not show significant differences and remains 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 has been performed in order to evaluate porosity trends in connection with particular burrow types on a millimetre scale. The conducted analysis reveals that porosity is heterogeneously distributed in samples and frequently influenced by trace fossils. Burrows can induce changes in porosity, increase or decrease it, all depending on the frequency, size and fill material of relevant burrows. For example, *Chondrites* is a dichotomously branching burrow system with burrow diameters around 1 to 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, pixels counting by image treatment (see Dorador et al., 2014) and Qemscan analysis (Fig. 8). Both methods show some differences in the obtained values. Those measurements obtained by pixels counting using image treatment, absolute values seem not to be realistic, but relative values are reliable. In all examples, highest values are associated with burrows. For instance, the fill of *Zoophycos* shows the highest porosity values of all measurements (11-18%), while the surrounded matrix has low porosity values around 5% (Fig. 8A, C). Another example contains a *Thalassinoides* burrow in cross section (Fig. 8B), 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 predefined reservoir zone of the Shetland Group (i.e. Zone 1 to 4) was semi-quantified based on core observations from well 34/10-C-50.

Zone 1: This zone is the chalkiest interval and is dominated by the *Thalassinoides* ichnofabric (79%), which in turn is considered the most appropriate ichnofabric in terms of reservoir quality (main reservoir zone).

Zone 2: In this interval, 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 3: In this zone the *Nereites* ichnofabric is most abundant (43%), followed by the *Thalassinoides* and *Zoophycos* ichnofabrics (combined 33%), while the *Chondrites* ichnofabric remains subordinate (23%).

Zone 4: This 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.

With respect to an evaluation of existing and potential reservoir units, Zone 1 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.

A potential reservoir interval in Zone 2 corresponds to the *Thalassinoides* ichnofabric, the most contributing ichnofabric in terms of reservoir quality. 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 by 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 Shetland Group, 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 those structural elements and the hosting matrix they are penetrating. While ichnofabrics resulting from primary bioturbation in an early soft-ground stage are commonly tight, secondary bioturbation in stiff- and firm-ground (maybe also partly in hard-ground) created burrows (and partly borings) with a more complex structure. These relatively late burrows may also act as conduits and are frequently penetrated by fractures and faults. In this way they contribute to a network (or better 3D boxwork) of interconnected conduits and help producing hydrocarbon from the bioturbated matrix via fractures and faults.

In this study, some examples of possible relationships between fractures/faults and burrows have been observed from core. 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. Figure 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.

7. Conclusions

An ichnological analysis of three wells (34/10-C-50, 34/10-A-20 and 34/10-C-38) from the 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 firm-ground 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 high enough. Ichnofabrics distribution and relative abundance define the reservoir zonation, with Zone 1 (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 control the reservoir quality, whereas the analysis of selected micro-CT images has revealed a high connectivity between some burrows and fractures.

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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References

Anderskouv, K., Surlyk, F., 2012. The influence of depositional processes on the porosity of chalk. Journal of the Geological Society, London 169, 311–325.

Bromley, R.G., Ekdale, A.A., 1986. Composite ichnofabrics and tiering of burrows. Geological Magazine 123, 59–65.

Dale, E.I., Eikeberg, O., Haugen, Å., Irondelle, M., Jonoud, S., Aase, S.A., 2018. Developing Gullfaks Shetland/Lista fractured carbonate reservoir – from hope and pray to trial and error. SPE-191329-MS.

Dorador, J., Rodríguez-Tovar, F.J., 2014. A novel application of digital image treatment by quantitative pixel analysis to trace fossil research in marine cores. Palaios 29, 533–538.

Dorador, J., Rodríguez-Tovar, F.J., 2018. High-resolution image treatment in ichnological core analysis: initial steps, advances and prospects. Earth-Science Reviews 177, 226–237.

Dorador, J., Rodríguez-Tovar, F.J., IODP Expedition 339 Scientists, 2014a. Digital image treatment applied to ichnological analysis of marine core sediments. Facies 60, 39–44.

Dorador, J., Rodríguez-Tovar, F.J., IODP Expedition 339 Scientists, 2014b. Quantitative estimation of bioturbation based on digital image analysis. Marine Geology 349, 55–60.

Ekdale, A.A., Bromley, R.G., Knaust, D., 2012. The ichnofabric concept. In: Knaust, D., Bromley, R.G. (eds.), Trace Fossils as Indicators of Sedimentary Environments. Developments in Sedimentology 64. Elsevier, Amsterdam, pp. 139–155.

Gingras, M.K., Baniak, G., Gordon, J., Hovikoski, J., Konhauser, K.O., La Croix, A., Lemiski, R., Mendoza, C., Pemberton, S.G., Polo, C., Zonneveld, J-P., 2012. Porosity and Permeability in Bioturbated Sediments. In: Knaust, D., Bromley, R.G. (eds.), Trace Fossils as Indicators of Sedimentary Environments. Developments in Sedimentology 64. Elsevier, Amsterdam, pp. 837–868.

Kikinis, R., Pieper, S.D., Vosburgh, K., 2014. 3D Slicer: a platform for subject-specific image analysis, visualization, and clinical support. In: Jolesz, F.A., (ed.), Intraoperative Imaging and Image-Guided Therapy. Springer, New York, pp. 277–289.

Knaust, D., 2009. Ichnology as a tool in carbonate reservoir characterization: A case study from the Permian – Triassic Khuff Formation in the Middle East. GeoArabia 14, 17–38, enclosed poster.

Knaust, D., 2012. Trace-fossil systematics. In: Knaust, D., Bromley, R.G. (eds.), Trace Fossils as Indicators of Sedimentary Environments. Developments in Sedimentology 64. Elsevier, Amsterdam, pp. 79–101.

Knaust, D., 2013. Bioturbation and reservoir quality: towards a genetic approach. Search and Discovery Article #50900.

Knaust, D., 2014. Classification of bioturbation-related reservoir quality in the Khuff Formation (Middle East): towards a genetic approach. In: Pöppelreiter, M.C. (Ed.), Permo-Triassic Sequence of the Arabian Plate. EAGE, pp. 247–267.

Knaust, D., 2017. Atlas of Trace Fossils in Well Core: Appearance, Taxonomy and Interpretation. Springer, Dordrecht, xv + 209 pp.

Knaust, D., 2019. Ichnofabric. In: Alderton, D., Elias, S. (Eds.), Encyclopedia of Geology, 2nd edition. Elsevier, Amsterdam, 11 pp.

Miguez-Salas, O., Dorador, J., Rodríguez-Tovar, F.J., 2019. Introducing Fiji and ICY image processing techniques in ichnological research as a tool for sedimentary basin analysis. Marine Geology 413, 1–9.

Rodríguez-Tovar, F.J., Miguez-Salas, O., Dorador, J., in press. Image processing techniques to improve characterization of composite ichnofabrics. Ichnos.

Warren, J.E., Root, P.J., 1963. The behavior of naturally fractured reservoirs. SPE-426-PA, 245–255.

Wennberg, O.P., Graham Wall, B., Sæther, E., Jonoud, S., Rozhko, A., Naumann, M., 2018. Fractures in chalks and marls of the Shetland Group in the Gullfaks Field, North Sea. 80th EAGE Conference & Exhibition 2018, 11-14 June 2018, Copenhagen, Denmark, 5 pp.

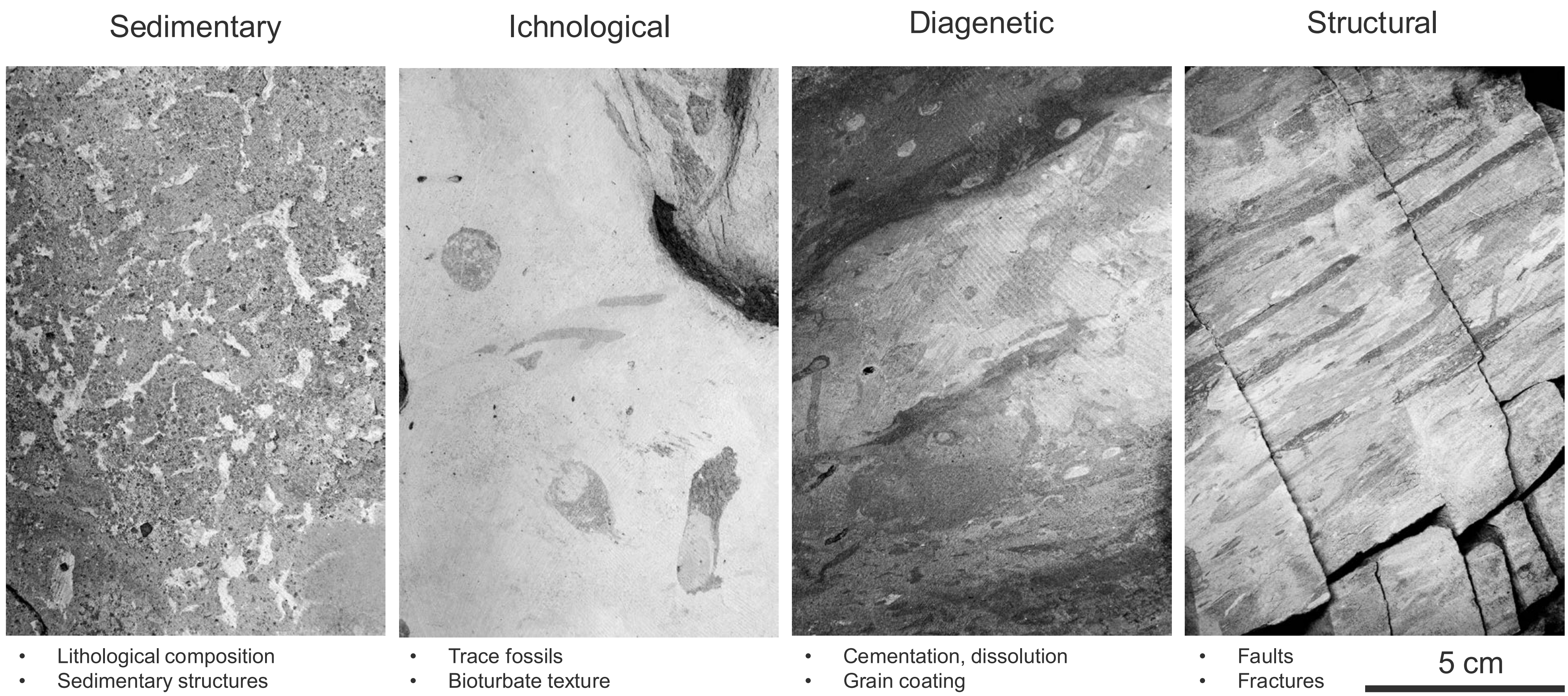
Figure captions

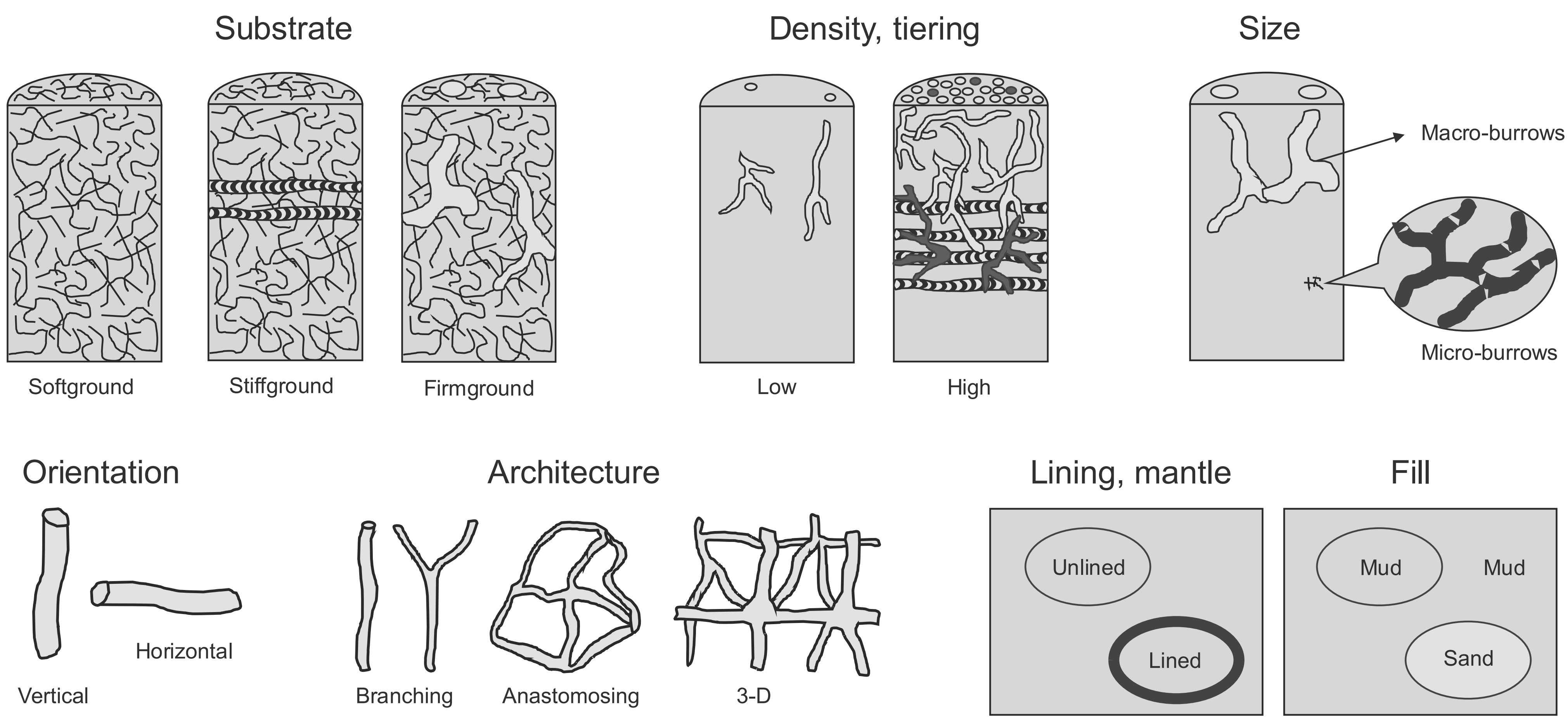
1. Major categories of small-scale heterogeneities with impact on rock properties and resulting reservoir quality, illustrated with examples from the studied sections in the Gullfaks Field. Modified after Knaust (2013, 2017).
2. Impact of architectural elements and characteristics of burrows (i.e. ichnotaxobases) on rock properties and reservoir quality. Modified after Knaust (2013, 2017).
3. Location and stratigraphy. **A:** Map of the Norwegian North Sea with main oil and gas fields and the Gullfaks Field highlighted. **B:** Stratigraphy of the studied interval and lithology log based on well 34/10-C-50, with the reservoir in the chalk interval at the top of the Shetland Group.
4. Amount of bioturbation (AB) schematically expressed by a range (and mean) for the entire ichnofabric (AB_{tot}) and distinguished between primary soft-ground bioturbation (AB_{prim}) and secondary stiff- and firm-ground bioturbation (AB_{sec}), the latter which is regarded in this study. Modified from Knaust (2019).
5. Summary of common lithofacies types and associated ichnofabrics in the Shetland Group of the Gullfaks Field, as well as mean porosity and permeability and the main reservoir units.
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*.

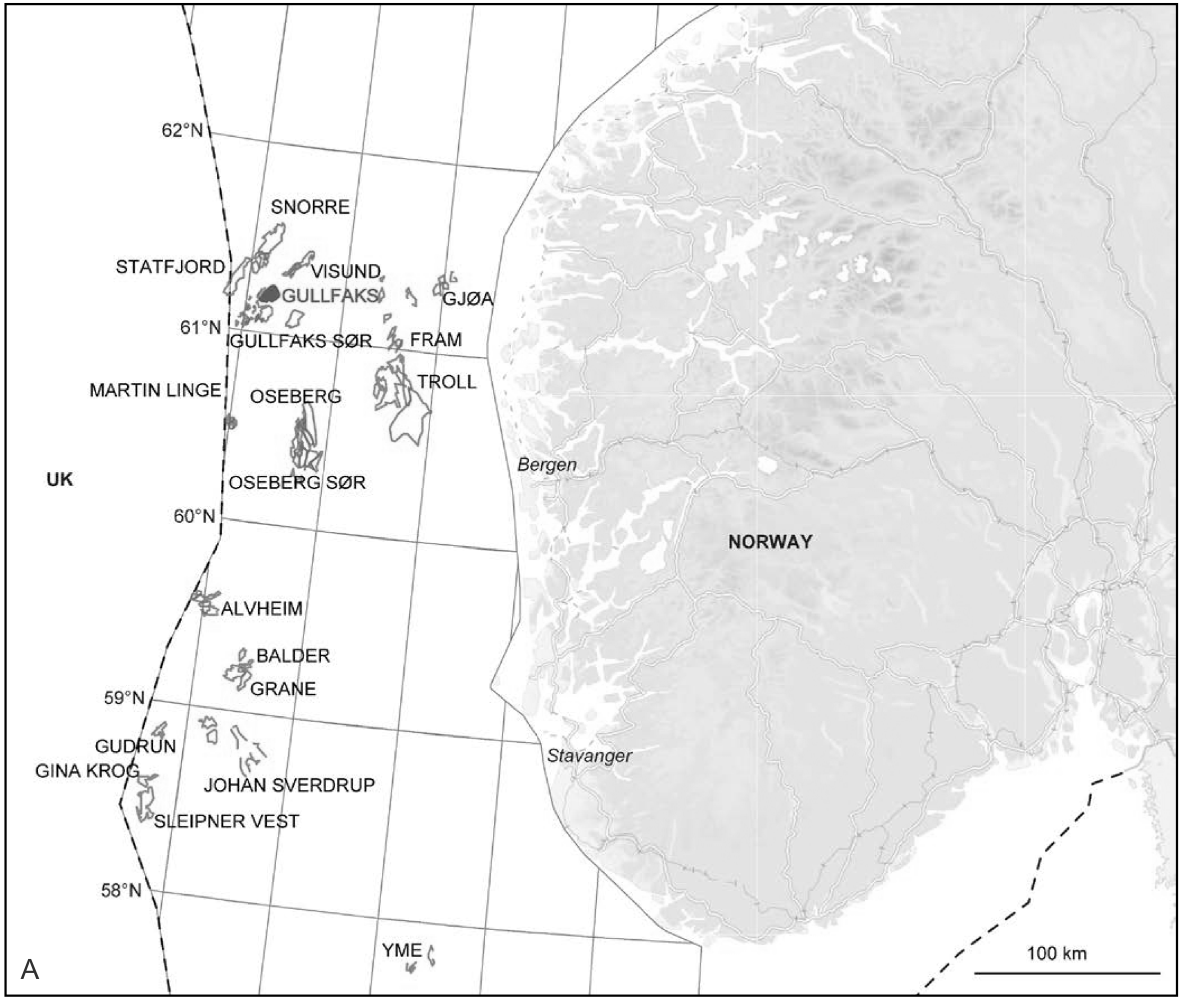
7. Diagram illustrating the development of recognised ichnofabrics in response to lithology and substrate consistency and the resulting impact on porosity. *Ch*, *Chondrites*; *Ne*, *Nereites*; *Ta*, *Taenidium*; *Th*, *Thalassinoides*; *Zo*, *Zoophycos*.

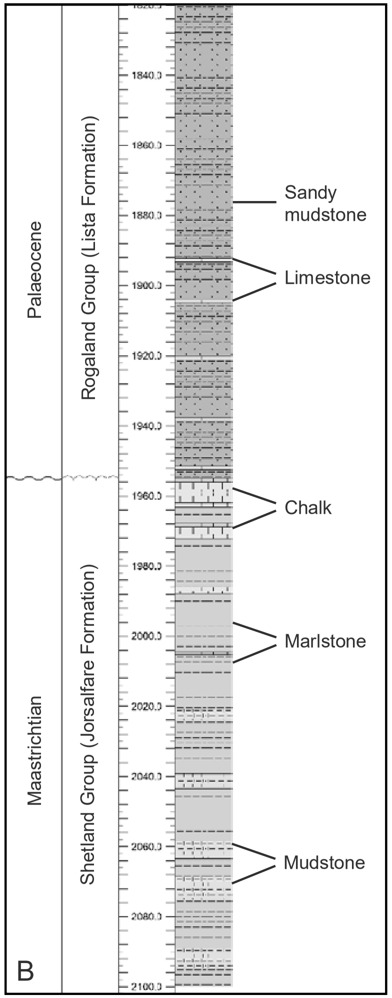
8. Porosity estimation based on thin-section analysis of sidewall cores from two wells by applying image treatment (results in white boxes) and Qemscan analysis (values in white font) in selected areas of thin sections (red squares) from the Shetland Group, and their relationship to recognised trace fossils. Thin sections are ca. 2.5 cm in diagonal direction. *Ta*, *Taenidium*; *Th*, *Thalassinoides*; *Zo*, *Zoophycos*. **A:** *Zoophycos* ichnofabric. **B:** *Thalassinoides* ichnofabric. **C:** *Chondrites* ichnofabric.

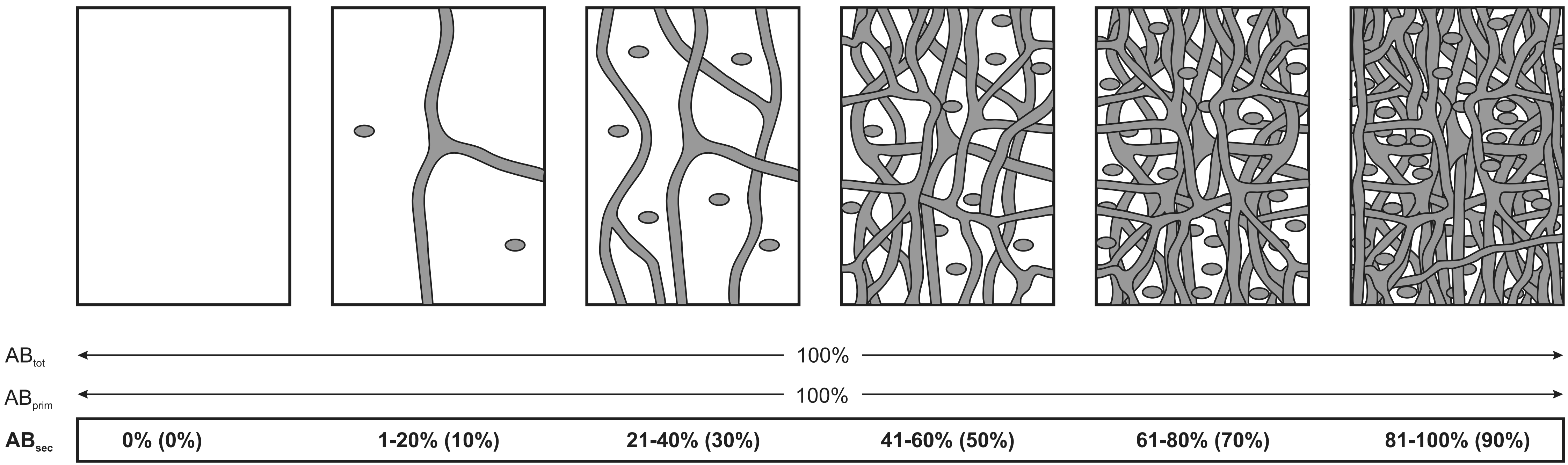
9. Representative chalk samples from cylindrical core plugs processed by 3D micro-CT scanning, illustrating their ichnological content and burrow interaction with fractures. **A:** Ichnofabric containing *Thalassinoides (Th)*; *Chondrites (Ch)* and *Virgaichnus (Vi)*. Circular outline in the front and the back of the image 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 (yellow and green, respectively) assignable to *Virgaichnus*, *Thalassinoides* (*Th*, blue), and open fractures (green). Note that non-eliminated “noise” in the background also appears in blue. Plug diameter ca. 2.5 cm. **E:** Close-up image of D revealing the intimate cross-cutting relationship of burrows with open fractures.


Sedimentary
Ichnological
Diagenetic
Structural
• Lithological composition
• Sedimentary structures
• Trace fossils
• Bioturbate texture
• Cementation, dissolution
• Grain coating
• Faults
• Fractures
5 cm

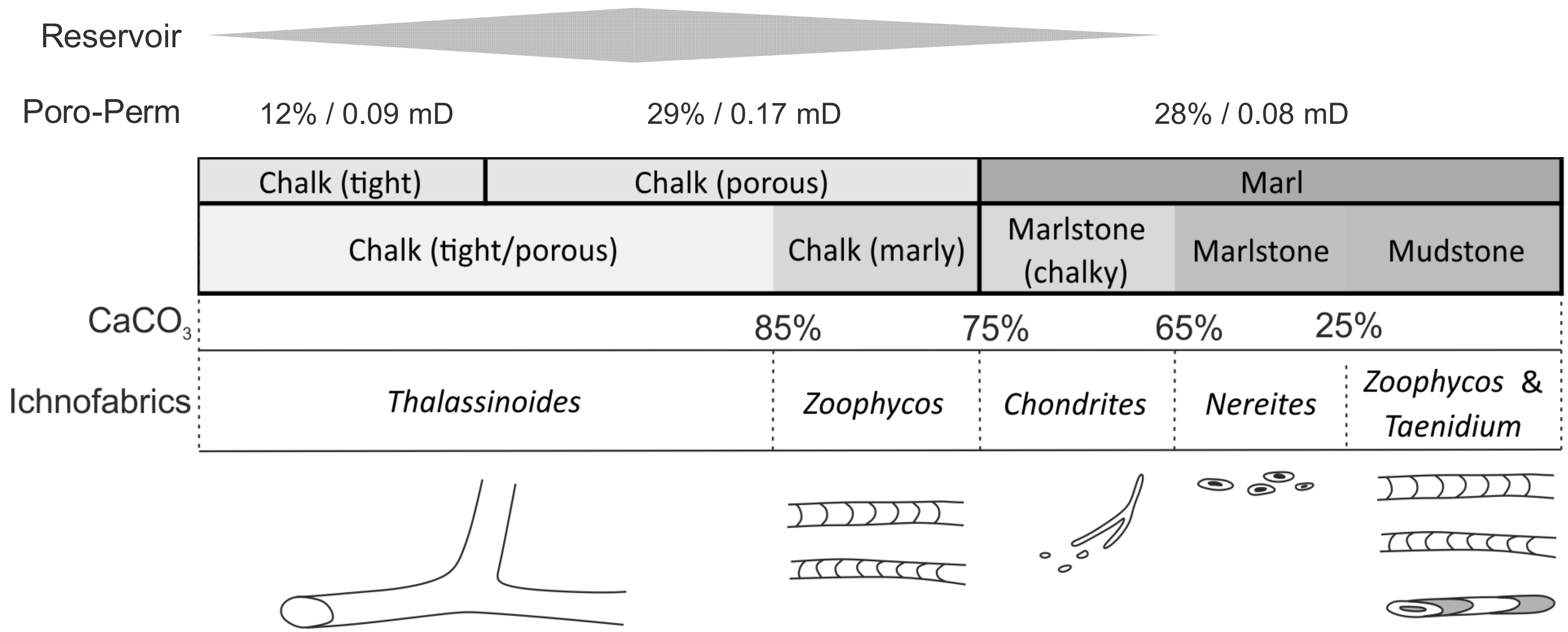

Substrate
Softground
Stiffground
Firmground
Density, tiering
Low
High
Size
Macro-burrows
Micro-burrows
Orientation
Vertical
Horizontal
Architecture
Branching
Anastomosing
3-D
Lining, mantle
Unlined
Lined
Fill
Mud
Mud
Sand


A
62°N
61°N
60°N
59°N
58°N
UK
NORWAY
SNORRE
STATFJORD
VISUND
GULLFAKS
GJØA
GULLFAKS SØR
FRAM
TROLL
MARTIN LINGE
OSEBERG
OSEBERG SØR
Bergen
ALVHEIM
BALDER
GRANE
GUDRUN
GINA KROG
JOHAN SVERDRUP
SLEIPNER VEST
Stavanger
YME
100 km


B
Palaeocene
Maastrichtian
Rogaland Group (Lista Formation)
Shetland Group (Jorsalfare Formation)
1840.0
1860.0
1880.0
1900.0
1920.0
1940.0
1960.0
1980.0
2000.0
2020.0
2040.0
2060.0
2080.0
2100.0
Sandy mudstone
Limestone
Chalk
Marlstone
Mudstone



AB_{tot}
100%
AB_{prim}
100%
AB_{sec}
0% (0%)
1-20% (10%)
21-40% (30%)
41-60% (50%)
61-80% (70%)
81-100% (90%)

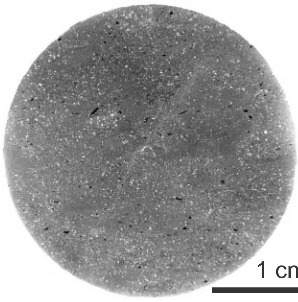

Reservoir
Poro-Perm
12% / 0.09 mD
29% / 0.17 mD
28% / 0.08 mD
Chalk (tight)
Chalk (porous)
Marl
Chalk (tight/porous)
Chalk (marly)
Marlstone (chalky)
Marlstone
Mudstone
CaCO3
85%
75%
65%
25%
Ichnofabrics
Thalassinoides
Zoophycos
Chondrites
Nereites
Zoophycos & Taenidium

Zoophycos-Taenidium

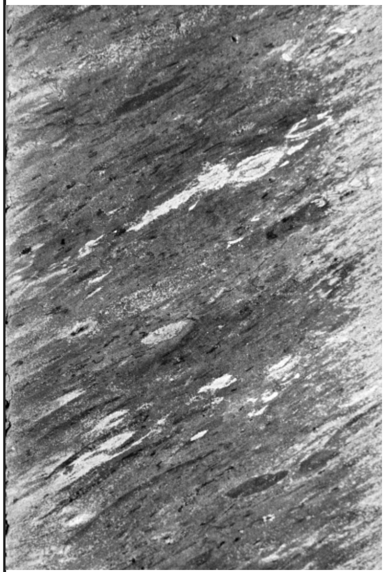
Lithology:
- Mudstone

Trace fossils (% bioturbation):
- Softground (100%):
  * Bioturbate texture
- Stiffground (40-80%):
  * *Zoophycos*
  * *Taenidium*
  * *Thalassinoides*
  * *Chondrites*

Reservoir quality:
- No contribution



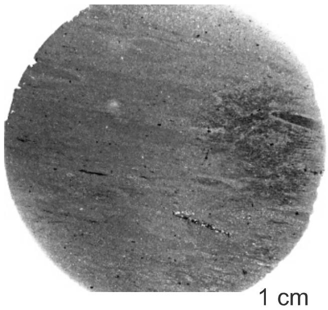
Nereites



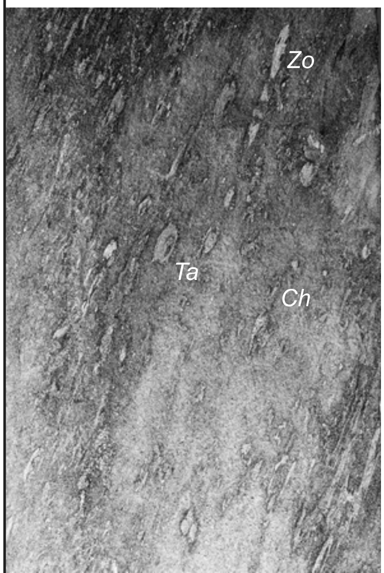
Lithology:
- Marlstone

Trace fossils (% bioturbation):
- Softground (100%):
  * Bioturbate texture
- Stiffground (0-20%):
  * *Chondrites*
  * *Nereites*

Reservoir quality:
- No contribution



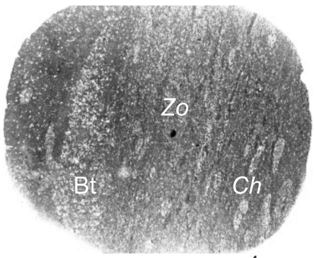
Chondrites



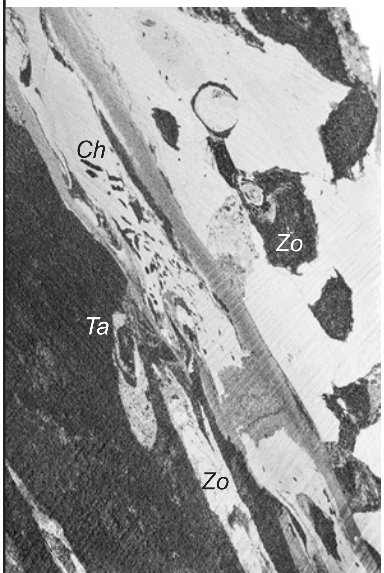
Lithology:
- Marlstone, chalky

Trace fossils (% bioturbation):
- Softground (100%):
  * Bioturbate texture
- Stiffground (20-80%):
  * *Chondrites*
  * *Taenidium*
  * *Zoophycos*

Reservoir quality:
- Increased porosity
- Potentially low contribution



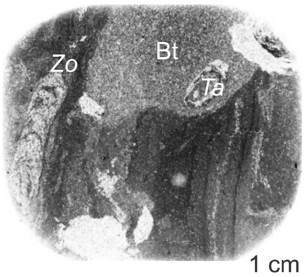
Zoophycos



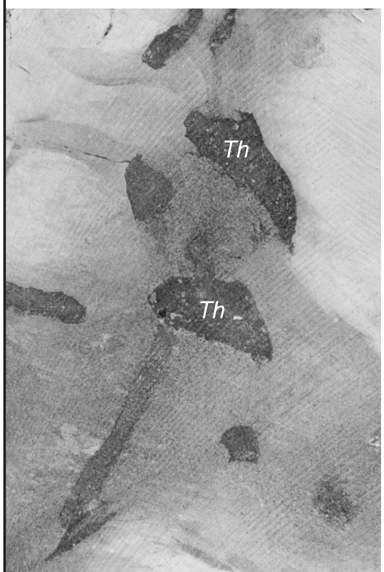
Lithology:
- Chalk, marly (porous)

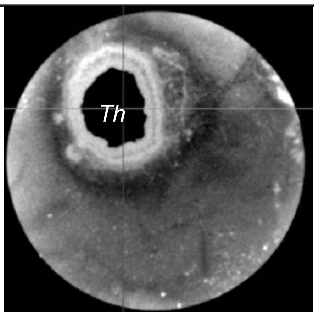
Trace fossils (% bioturbation):
- Softground (100%):
  * Bioturbate texture
- Stiffground (20-60%):
  * *Zoophycos*
  * *Chondrites*
  * *Taenidium*

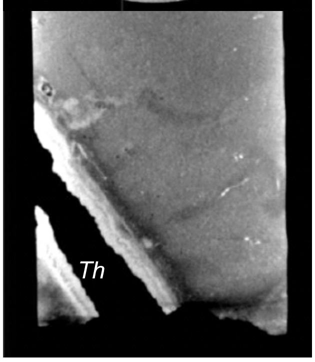
Reservoir quality:
- Increased porosity
- Potentially contribution

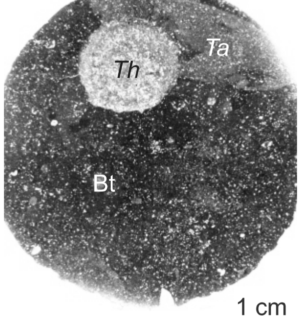


Thalassinoides





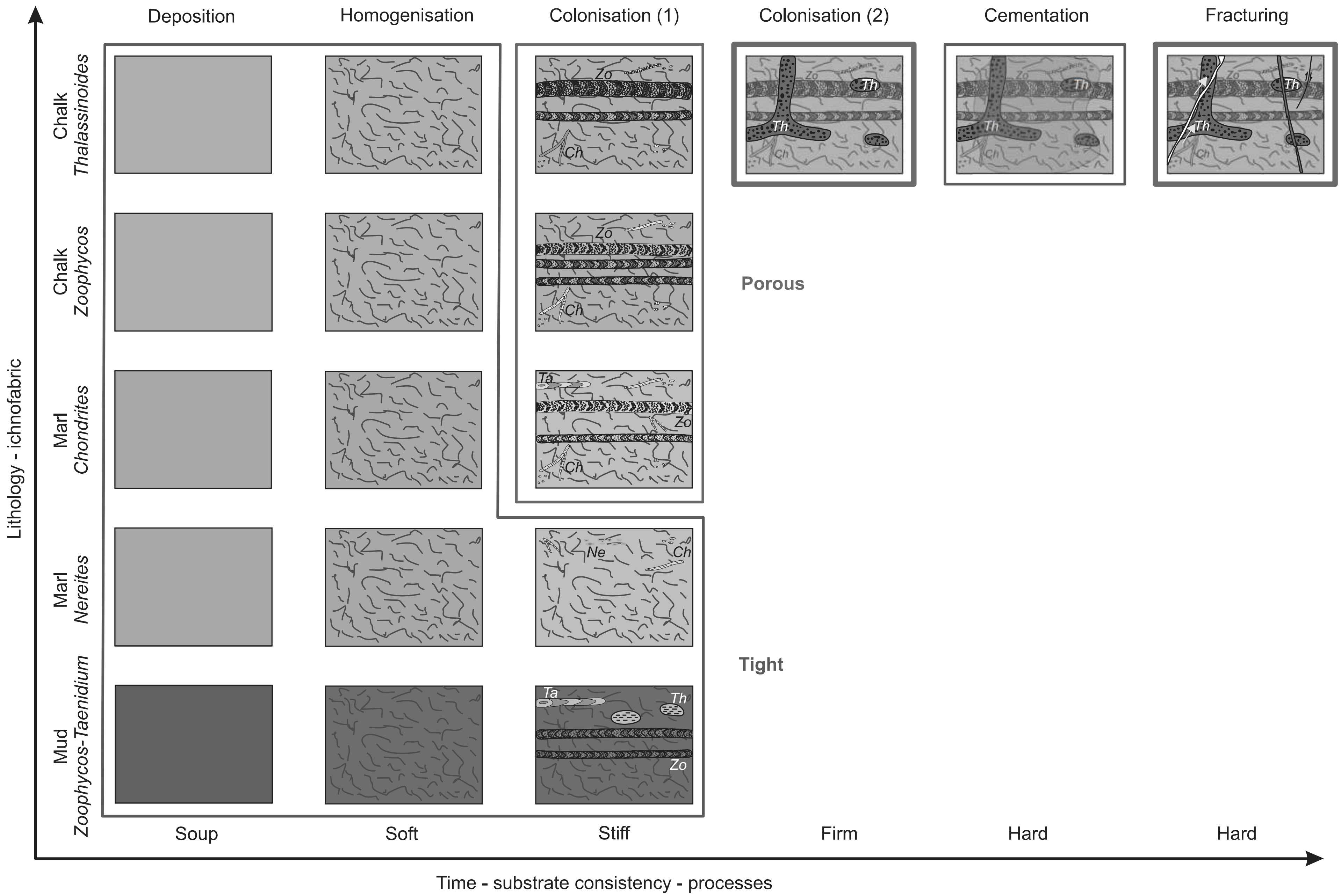


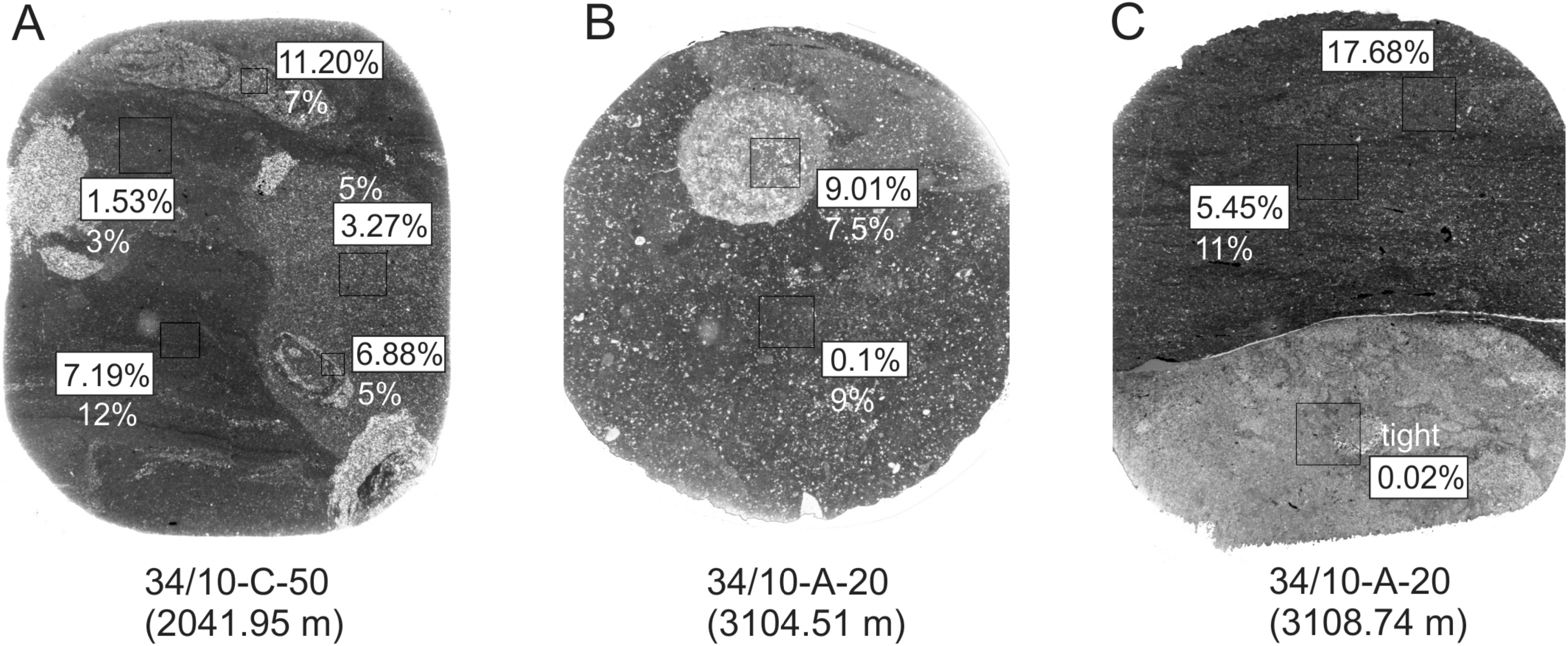


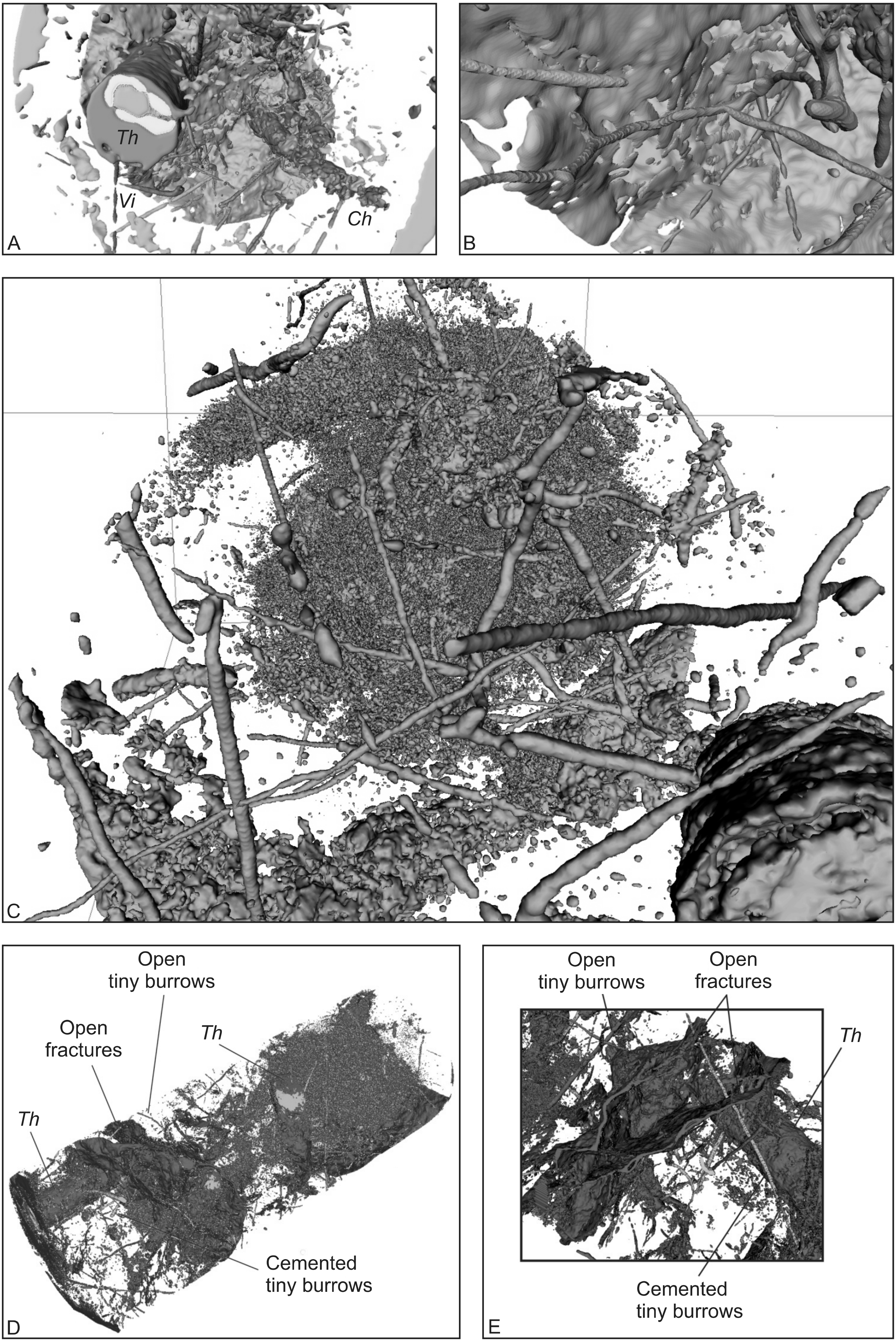
Lithology:
- Chalk (porous/tight)

Trace fossils (% bioturbation):
- Softground (100%):
  * Bioturbate texture
- Stiffground (20-40%):
  * *Chondrites*
  * *Taenidium*
  * *Zoophycos*
- Firmground (20-40%):
  * *Thalassinoides*

Reservoir quality:
- Improved porosity
- High connectivity


Deposition
Homogenisation
Colonisation (1)
Colonisation (2)
Cementation
Fracturing
Chalk
Thalassinoides
Chalk
Zoophycos
Marl
Chondrites
Marl
Nereites
Mud
Zoophycos-Taenidium
Zo
Ch
Ta
Ne
Th
Porous
Tight
Soup
Soft
Stiff
Firm
Hard
Hard
Lithology - ichnofabric
Time - substrate consistency - processes


A
11.20%
7%
1.53%
3%
5%
3.27%
7.19%
12%
6.88%
5%
34/10-C-50
(2041.95 m)
B
9.01%
7.5%
0.1%
9%
34/10-A-20
(3104.51 m)
C
17.68%
5.45%
11%
tight
0.02%
34/10-A-20
(3108.74 m)



Th
Vi
Ch
A
B
C
Open
tiny burrows
Open
fractures
Th
Th
Cemented
tiny burrows
D
Open
tiny burrows
Open
fractures
Th
Cemented
tiny burrows
E