DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE **RAPPORT 2020/42**

Capture, Storage and Use of CO_2 (CCUS)

Sedimentological description of Gassum and Fjerritslev Formations from cores in the Stenlille area, with interpretations of depositional environments (Part of Work package 6 in the CCUS project)

Jussi Hovikoski & Gunver Pedersen

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Preface

Late 2019, GEUS was asked to lead research initiatives in 2020 related to technical barriers for Carbon Capture, Storage and Usage (CCUS) in Denmark and to contribute to establishment of a technical basis for opportunities for CCUS in Denmark. The task encompasses (1) the technical potential for the development of cost-effective CO2 capture technologies, (2) the potentials for both temporary and permanent storage of CO2 in the Danish subsurface, (3) mapping of transport options between point sources and usage locations or storage sites, and (4) the CO2 usage potentials, including business case for converting CO2 to synthetic fuel production (PtX). The overall aim of the research is to contribute to the establishment of a Danish CCUS research centre and the basis for 1-2 large-scale demonstration plants in Denmark.

The present report forms part of Work package 6 and focuses on sedimentological characteristics of the Gassum and Fjerritslev Formations in the Stenlille area.

Contents

CCUS project – part of work package 6.

Dansk sammendrag

Gassum Formationen består af sandsten, mellem lejret af tyndere muddersten. Formationen forekommer i størstedelen af Danmark, og dens sedimenter blev i Stenlille området aflejret i den seneste del af Trias, ca. 200 mio. år før nu. I Stenlille-området ligger toppen af formationen på dybder fra ca. 1500 m til ca. 1600 m (Nielsen & Japsen 1991), se også rapporter indenfor dette projekt (Vosgerau et al. 2020, Gregersen et al. 2020). I Stenlille området er der boret 20 dybe boringer helt eller delvis igennem Gassum Formationen (St-1 til St-19 er lokaliseret på Fig. 1). Der er taget borekerner i adskillige af boringerne. Kernerne repræsenterer forskellige niveauer af formationen, og nogle kerner indeholder også den nederste del af Fjerritslev Formation, som overlejrer Gassum Formationen. Endvidere foreligger der petrofysiske målinger fra alle boringerne.

Denne rapport beskriver resultaterne af en sedimentologisk undersøgelse af borekerner fra St-1 til St-19 (se Tabel 1). Formationen er inddelt i syv sekvenser (SQ1–SQ7), hvor den nederste og øverste sekvens også indeholder aflejringer fra henholdsvis den underliggende og overliggende formation. Tilsammen dækker de tolkede kerner Gassum Formationen fra den øverste del af Sekvens 3 og op til formations top samt den allernederste del af den overliggende Fjerritslev Formation. Målet med undersøgelsen er ud fra kernebeskrivelser at identificere og beskrive aflejringsenheder, og at tolke deres aflejringsmiljø. Dette er et bidrag til etablering af en geologisk model, der kan fungere som en analogi for Gassum Formationen i Havnsø strukturen, f.eks. til at vurdere fordelingen af sand- og lersten og reservoir-egenskaberne af sandstenene i denne struktur.

De kernede dele af Gassum Formationen og Fjerritslev Formationen er inddelt i fem faciesassociationer (FA1 til FA5) som spænder over aflejringsmiljøer fra dybt hav til marsk og flodslette. FA1–FA4 er underopdelt, og der skelnes i alt mellem ni aflejringsmiljøer.

To stratigrafiske niveauer er så godt dokumenteret, at det er muligt at vise laterale variationer. Sekvens 4 (mellem sekvensgrænserne SB4 og SB5) er opmålt i St-14, St-15, St-18 og St-19. Kernerne fra St-15, som er den boring, der ligger længst mod sydvest, indeholder ikke de tykke sandsten (FA4), som ses i de øvrige boringer, og toppen af sekvens 4 er mere præget af terrestriske miljøer end i de samtidige aflejringer fra de andre boringer.

Boringen St-6 dokumenterer aflejringerne (mellem den transgressive flade TS5 og sekvensgrænsen SB8) nordøst for Stenlille strukturen (Fig. 1). Dette interval er også kernet i St-1, som den nærmeste boring til St-6. St-1 er boret på strukturen. På denne er Intervallet TS5 til SB8 ligeledes kernet i St-2, St-4, St-5, St-14 og St-17. Korrelation mellem disse boringer viser laterale forskelle på flere niveauer mellem TS5 (øvre del af sekvens 5) og SB8 (nedre grænse for sekvens 8 beliggende i Fjerritslev Formationen). Generelt synes St-6 at dokumentere aflejringer på større vanddybde end de øvrige boringer.

Fremtidige undersøgelser

Denne rapport omtaler de resultater, som foreligger primo oktober 2020. Dokumentationen for en del af tolkningerne foreligger i form af sedimentologiske logs, som det, på grund af tidspres, ikke har været muligt at færdiggøre endnu. Alle logs bliver færdiggjort senere på året, og vil styrke tolkningerne af de laterale faciesvariationer.

Antallet af borekerner, som er blevet beskrevet, er mindre end forudsat ved studiets påbegyndelse på grund af covid-19 restriktioner. Nogle få, kritiske kerneintervaller mangler stadig at blive føjet til datasættet. Dette gælder dele af St-1 og af St-15.

Facies association 4, foreløbigt tolket som fluvial til æstuarin, kræver nærmere undersøgelse (se tolkningen af FA4a). Endvidere forestår en bedre sammenkædning mellem de palynologiske data (Lindström, S. 2020, report, this project) og de sedimentologiske observationer. Dette er særlig vigtigt for at kunne identificere om (og i hvor høj grad) aflejringsmiljøerne er marint påvirkede – et vigtigt input til at forstå det overordnede aflejringssystem og udbredelsen af sandstensenhederne.

Summary

As a part of the CCUS project, a set of cores (Table 1) penetrating the main part of the Gassum Formation and the basal part of the Fjerritslev Formation in the Stenlille structure were described sedimentologically, with emphasis on sedimentary facies associations and depositional environments. The results are expected to provide a crucial input to the prediction of facies of the Gassum and Fjerritslev formations in the neighboring Havnsø structure.

The studied interval is divided into 5 facies associations and 8 sub-associations. These include: 1) offshore-shelf environments (FA1a and b), including potentially pro-deltaic variants; 2) shoreface complex (FA2a and b); 3) lagoonal complex (FA3a and b); 4) fluvial/deltaic-estuarine (FA4) deposits; and root-bearing intervals (FA5), which includes a number of sub-environments such as backshore, supratidal lagoon margin and marsh. At the time of writing this report, full integration with other data sets such as palynology and 3D seismic data remain to be done, and therefore this scheme must be considered as tentative. The main remaining challenge is to delineate depositional processes (marine vs. terrestrial) of FA4 intervals.

In two intervals, stratigraphic overlap of the studied set of cores allows to distinguish lateral (distal-proximal) facies trends:

1) Between SB4 and SB5, the deposits in the SE corner of the study area (St-15) appear more terrestrially dominated than correlative intervals towards the west (e.g., St-14 and St-18). While St-15 shows the development of three root-bearing intervals intercalated with lagoonal deposits, the correlative deposits consists entirely of lagoonal complex sediments. In St-18 the interval between SB4 and TS4 is dominated by FA4a, and the interval between TS4 and SB5 is characterized by heterolithic sandstone FA3b and sand-streaked mudstone (FA1a/FA3a). Small proportions of marine dinocysts indicate marine connections, though not fully marine environments. Similarly, the thick sandstone package (FA4) formed by SB4 related regression, which is present in Stenlille-structure, is not developed similarly in St-15, possibly pointing to differences in mechanism of forced regression and/or sediment routing.

2) St-6 is located NE of the Stenlille structure, and the closest well to this in the Stenlille structure is St-1.The upper part of SQ5, SQ6–SQ8 is cored in both wells, but differ distinctly particularly in SQ7. St-6 is characterized by a much larger proportion of shoreface to offshore facies than St-1, and SB7 is nearly reduced to a correlative conformity. The comparison between St-1 and St-6 above TS5 suggests that St-6 represents deposition in a deeper water (more marine?) palaeogeographic position than St-1.

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Future studies

- At the time of writing this report, only a set of sedimentological logs have been finalized by GEUS drawing personel due to lack of time. All logs will be finalized later this year to allow the broader documentation particularly of lateral trends of the depositional system.
- The number of described cores was more limited than anticipated due to covid-19 restrictions. Thus, a few critical core intervals still need to be studied to complete the data set. These include St-1 and remaining part of St-15.
- Facies association 4, tentatively interpreted as fluvial, deltaic and estuarine, needs more study (see FA4a interpretation above). In addition to the description of the afore mentioned yet to be studied core intervals, the sedimentological data need closer integration with palynofacies data. In particular, this is expected to contribute to the recognition of marine-influenced facies.

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Introduction

As a part of the CCUS project, a set of cores (Table 1) penetrating the main part of the Gassum Formation and the basal part of the Fjerritslev Formation in the Stenlille structure were described sedimentologically, with emphasis on sedimentary facies associations and depositional environments. The Stenlille structure has a high number of wells, many of them cored, through the Gassum Formation, which allows interpretations of the lateral continuity of the facies associations. The study may therefore serve as a model for the Gassum Formation in the eastern part of the Danish Basin. Further, the study provides crucial input to the prediction of facies of the Gassum and Fjerritslev formations in the neighboring Havnsø structure.

Database

The studied core intervals are shown in the Table 1. These cover upper part of the Sequence 3 (SQ3), and sequences above until the lowermost part the Fjerritslev Formation. It is anticipated that the data set will be supplemented with selected core intervals from St-1 and St-15 to complete the data set. Location of the wells is indicated in Figure 1 and well logs of the studied cores are shown in Figure 2.

Core	**Depth**	**Sequences/Key surfaces**
Stenlille-1	1486-1505m, 1506.70-1512.8 m	Above MFS 7 Upper part of SQ6
Stenlille-2	1548.4-1475m	Upper half of SQ5-SB9?
Stenlille-4	1490-1512 m 1512-1520 m 1520-1550 m	MFS 7, SQ8, lower part of SQ9 SQ7 to MFS7 Top of SQ5 and SQ6
Stenlille-5	1535-1588 m	Upper part of SQ5, SQ6-SB8
Stenlille-6	1536-1611 m	Upper part of SQ5, SQ6-lower part of SB9
Stenlille-14	1729.4-1629.5m	Top of SQ3 - lower part of SQ6
Stenlille-15	so far 1614.5-1600m	SQ4 including SB5
Stenlille-17	1607-1688.1 m	SQ5,SQ6, and lower part of SB7
Stenlille-18	1596-1678.0 m	SQ4 and most of SQ5

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Stenlille-19	1661-~1640m	Upper part of SQ3 (not including SB3), lower part of SQ4

***Table 1**: Described core intervals included in this report. Note that the depth here are depth below reference level (different from mean sea level; see Nielsen & Japsen 1991). The sequence stratigraphy in the Stenlille area is discussed by Vosgerau et al. (2020).*

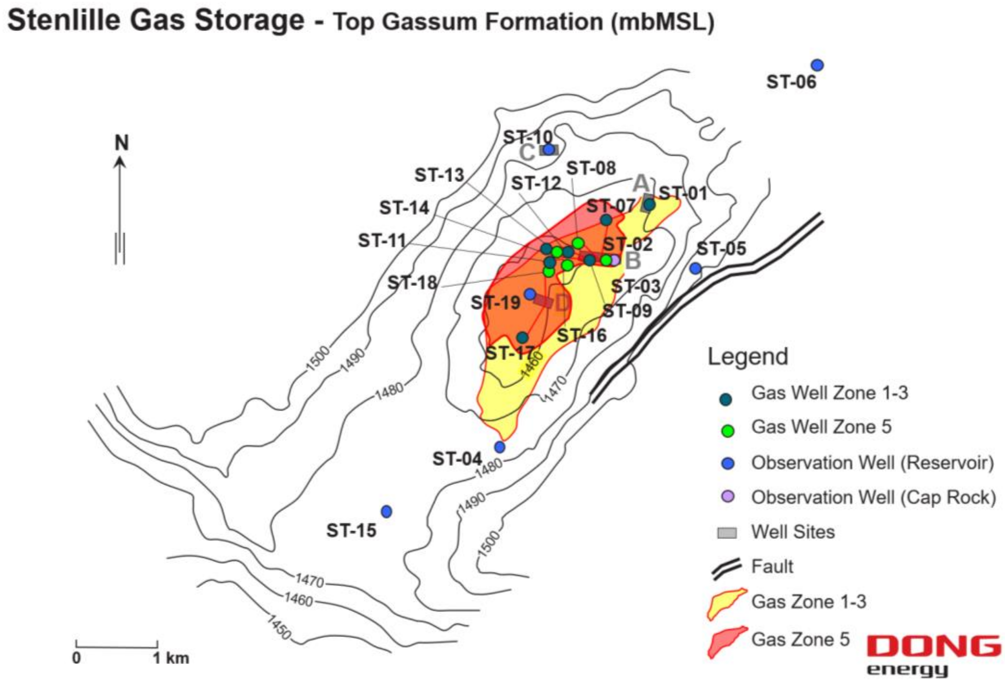

***Figure 1**: Stenlille Structure. Well locations and a simplified top Gassum Formation depth structure map. The closed depth contours outline the Stenlille structure. Note that the depth here are depths below sea level. Figure provided by DONG Energy. Reused from report by Kristensen (2020).*

Facies Associations

The studied deposits are divided into 5 facies associations (FA1-5) and 8 sub-associations and presented below broadly following a distal – proximal gradient. Figure 3 illustrates a set of cores that cover the studied stratigraphic interval. Facies plates and examples of sedimentological logs are shown in the end of the report.

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FA1: Offshore-shelf

Description: FA1 is a broad FA-type dominated by dark grey to black mudstones and storm generated sand-mud heteroliths. The facies range from black laminated claystone (a rare facies), through grey, weakly laminated or structureless mudstone, to dark grey mudstone with streaks of coarse silt to very fine-grained sand (Fig. 4). The proximal examples, gradational to FA2 (shoreface), are characterized by sand-dominated tempestites (Fig. 5). The mudstones of FA1 normally contain marine palynomorphs; however, some intervals are strongly dominated by terrestrial microfossils (spores and pollen; e.g., lower part of Fjerritslev Fm; Lindström, 2020). The marine conditions in the Fjerritslev Formation has been also documented in biostratigraphic studies of ostracods (Michelsen 1975) and palynomorphs (Dybkjær 1991, and Lindström et al. 2012).

Subdivision: FA1 is divided into two sub-associations: FA1a: Lower offshore-shelf, and FA1b: Upper offshore. These tentative divisions are broad and include potentially deltaic and embayment variants.

Occurrence: Facies association 1a is inferred to be a common FA type in the Fjerritslev Formation particularly above TS9, but it is rarely documented in cores (Pedersen 1985; see e.g., St-2, St-5 and St-6 for exception in Fig. 2). It forms up to several meters thick, aggradational to upward coarsening successions. Its appearance is distinguishable from the GR log as an abrupt change to steadily high values (above TS9), or basal part of large-scale funnel shaped GR signature upwards from the formation boundary (MFS7).

A variant of FA1a occurs also in the upper part of the Gassum Fm (e.g., MFS5, MFS6). There, it forms gradationally based, rarely more than 2–3 m thick successions above upper offshore (FA1b) deposits, and are interpreted to include maximum flooding surfaces. The deposits are commonly erosionally truncated by FA4. In the GR log, FA1a is visible as maximum GR values in the top of bell-shaped successions (e.g., MFS5 in Fig. 2).

Sub-association FA1b is a recurring FA-type in Sequence 5. It comprises sharp-based, upward fining (below FA1a) or coarsening successions (below FA2: shoreface/barrier). Thus, the GR-response can be varied ranging from bell-shaped successions below maximum GR-values, to base of funnel-shaped successions that terminate in minimum GR-values (zone of maximum progradation).

FA1a: Lower offshore-shelf

Description: FA1a includes dark grey to black mudstones, locally laminated, but mostly with weak lamination or without recognizable structures. Pyrite may occur as small nodules (1–5 mm in diameter), or is detectable as jarosite staining. Commonly, the dark grey mudstone is silt-streaked with thin (0.5–3 mm thick) streaks of coarse silt. The laminae are often normally graded, and may be planar or show miniature ripples that may show internal structures reminiscent of hummocky cross-lamination. The silt-streaks enhance the burrows that may be present. Distal examples comprise bioturbated, fossiliferous mudstone containing bivalve shells and rare ammonites. Recognized trace fossils include *Chondrites* isp. and *Phycosiphon/Helmintopsis* isp. (Fig. 4A, 4B) particularly above TS9.

Interpretation: FA1a is dominated by mud carried in suspension. The silt-streaks with graded bedding/lamination suggest deposition from currents, and the miniature-scale HCS and wave ripple cross lamination indicate that the currents may be storm-generated, and that deposition occurred near maximum storm wave-base, representing lower offshore water depth (sensu Pemberton et al., 2012). Unbioturbated examples with synaereis cracks may represent a pro-deltaic variant (Fig. 4C); this interpretation will be tested with closer integration with palynofacies data. The distal examples that lack tempestites (particularly above TS 9) and contain marine trace fossils and body fossils are interpreted to represent an open marine shelf (sensu Pemberton et al., 2012) generally below maximum storm wave base. Monogeneric occurrences of *Chondrites* and locally common pyrite/jarosite suggest that, at times, the setting was oxygen restricted.

Similarly, the sedimentary facies and stratigraphic position (gradationally below upper offshore deposits) indicate that FA1A occurrences were deposited close to maximum storm wave base in the Gassum Formation. However, unlike the occurrences in Fjerritslev Formation, FA1A develops only a few meter thick occurrences, lack fully marine trace fossils and body fossils, but contain marine microfossils (MFS6; Lindström, 2020). Further, considering rapid gradation to the bounding facies associations, FA1A is interpreted to represent offshore regions in an embayment or a similar semi-restricted marine basin. FA1A represents maximum flooding intervals in both formations.

FA1b: Upper offshore

Description: FA1b comprises sand-mud heteroliths and show normally graded event laminae/beds, comprising basal hummocky or wave ripple cross lamination overlain by a mud-drape (Fig. 5). Synaeresis cracks are locally common in mud-dominated intervals. FA1b may be devoid of burrows or bioturbated. Observed trace fossils include *Planolites, fugichnia*, and *Arenicolites*-like U-shaped burrows. Proximal examples (gradational to lower shoreface) are locally burrowed with *Teichichnus-Planolites* suite. In a few intervals, *Diplocraterion, Siphonichnus, ?Scalichnus, Chondrites* and/or *Nereites*-like traces are present.

Heterolithic mudstones also occur in FA3 (lagoonal complex; Fig. 8) and intergradational examples exist. FA1b and FA3 differ with respect to trace fossil assemblage and wave- vs. current-generated structures.

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Interpretation: Distribution of wave-generated structures indicate an environment above storm wave base, but below fair weather wave base. Storm-generated structures dominate, whereas fair weather offshore processes are subordinate, pointing to an upper offshore environment (sensu Pemberton et al., 2012). Common presence of synaeresis cracks may indicate fluctuating salinity. Similarly, the common lack of bioturbation can be due to elevated depositional rate and/or salinity stress. The locally occurring *Teichichnus-Planolites* suite is characteristic for brackish settings (e.g., Buatois et al., 2011), whereas fully marine assemblages are absent or rare. Therefore, despite evidence for powerful storm-wave climate (common hummocky cross-lamination), the environment may differ from open shoreline upper offshore settings by restricted or fluctuating salinity. Corresponding environments include embayments or distal delta front environments (Fig. 5A, 5B).

FA2: Shoreface

Description: FA2 is characterized by heterolithic sandstones grading into clean sandstones (Figs. 6–7). The sandstones are generally well-sorted and range from very fine-grained to medium-grained sand. They contain wave-generated structures, which may be partly obliterated by bioturbation. The sandstone beds are interbedded with relatively thin mudstone beds or contain mudstone drapes. FA2 contains marine palynomorphs as well as coalified debris of terrestrial plants.

Subdivision: FA2 is subdivided into FA2a: lower shoreface, and FA2b: middle- to upper shoreface.

Occurrence: The sandstones of FA2 form sharp-based, aggradational or generally upward coarsening several meter thick successions that dominate sandstone intervals from upper half of Sequence 5 (above TS5) to the top of Sequence 6. In the top of the Gassum Formation, the shoreface successions become thinner. The sharp-based occurrences often overlie FA1 (offshore). Top of FA2 occurrences can be root-bearing (FA5) or fine upwards into bioturbated heteroliths FA3/FA1b (e.g., St-2 1537 m, 1511.6 m).

FA2a: Lower shoreface

Description: The deposits consist dominantly of very fine- to upper fine-grained, 5–10 cm thick sandstone beds; mud-laminae occur frequently in the lower part of UC successions at the gradation to FA1b (upper offshore). Main facies include hummocky cross-stratification, low angle-cross lamination, wave ripple cross lamination and parallel lamination. Both sand- and mud-lithologies may be strongly bioturbated (Fig. 6B, 6C) leading to muddy sandstone. The trace fossil assemblage is dominated by deposit feeders but may include suspension feeders. The trace fossil assemblage includes *Teichichnus, Siphonichnus, Diplocraterion,*

?Parahantzschelinia, Rhizocorallium, Planolites, ?Scalichnus, fugichnia, and cryptobioturbation (Fig. 6). Marine palynomorphs occur in FA2a.

Interpretation: FA2a is interpreted as deposited in a wave-dominated marine environment at depths close to and generally above fair-weather wave-base, corresponding to lower shoreface environment (sensu Pemberton et al., 2012).

FA2b: Middle to upper shoreface

Description: FA2b is characterized by well-sorted fine-grained, locally medium-grained, sandstones, in some cases with comminuted plant debris outlining the sedimentary structures. These include hummocky cross stratification on various scales, parallel lamination, low-angle cross-stratification and through-shaped wave-ripple cross-lamination. Gutter cast-like truncations occur locally (see also Hamberg and Nielsen, 2000). Observations of double mud-drapes are rare. The physical structures are often well preserved, but may alternate with burrowed to mottled sandstones (Fig. 7). Several intervals, particularly near the top of UC successions, appear structureless due to uniform grain size.

Finally, the successions are locally interrupted by up to one m-thick, erosionally-based occurrences of moderately-sorted medium-grained sandstone showing common coal-clasts and plant fragments (e.g., near SB 6).

Interpretation: The well-sorted nature of the deposits, distribution of wave-generated structures as well as the bounding facies associations (e.g., root-bearing deposits of FA5) indicate shallow, middle shoreface-foreshore-like environments continuously above the fair weather wave base. Shoreface occurrences grading directly to root-bearing interval may represent simple strandplain-attached shorefaces, without the backbarrier component. However, those occurrences overlain by wave-dominated lagoonal deposits suggest that some occurrences can represent barrier or spit deposits.

The erosionally-based, coal-rich, moderately sorted beds that locally interrupt FA2b successions are contrasting from the rest of the well-sorted facies generated by waves. Tentatively, these may represent delta front mouth bars, or basal parts of inlets/ebb-tidal deltas formed during storms, when short-lived inlets break through the barrier. Due to overall wave-dominated environments, the inlets would have been short-lived and mainly filled with barrier sediments.

Finally, the scarcity of double mud-drapes suggests that tidal influence was weak, and overprinted by oscillatory processes. However, considering that the progradational shoreface successions show locally minor grain size variability (subdued UC trend), the wave base depth may have been influenced by (micro?) tidal range (Dashtgard et al., 2010).

FA3: Lagoonal complex

Description: FA3 includes a range of heterolithic mudstone and sandstone facies (Figures 8 and 9), which are locally associated with palaeosols, rootlets or coaly mudstone (FA5; See below). These facies represent deposition landwards of a barrier coastline or drowning river-system in lagoonal or other estuarine environments. The term estuarine here refers to a transgressive setting (Boyd et al., 1992; Dalrymple et al., 1992) and covers marine and/or tide-influenced lower reaches of fluvial systems. The term does not imply macrotidal conditions.

Subdivision: FA3 is subdivided into FA3a: central embayment (Fig. 8), FA3b: tidal flats and channels (Fig. 9).

Occurrence: Facies association 3 occurs particularly between TS4 and MFS4. It comprises gradationally- or sharp-based, decimeter to few m thick occurrences of burrow-mottled mud-dominated (FA3a) or sand dominated heteroliths (FA3b).

The sub-association 3a deposits typically overlie FA4b (see below) and are erosionally overlain by FA3b (see below). Thus, the GR-log shows typically rapid increase in GR values immediately above the gradationally upward fining top of the blocky sandstone of FA4.

The sub-association 3b forms sharp-based, either upward fining or coarsening successions up to 4m thick, which overlie mud-dominated heteroliths (FA3a). The characteristic GR-response is therefore bell-shaped (e.g., St-14 1711-1707m) or weakly funnel shaped (e.g., St-15) successions (Fig. 2).

FA3a: Central embayment

Description: FA3a is characterized by heterolithic mudstones (Fig. 8) including heterolithic lamination and lenticular bedding. The deposits show fluctuating bioturbation intensity ranging from unbiotubated to intensively bioturbated intervals (Fig. 8A–B) burrowed with a low diversity trace fossil assemblage dominated by *Planolites* isp. rarely accompanied by *Siphonichnus* isp. (Fig. 8A). The mudstones may also be characterized by silt-streaked mudstones with few thin sandstone beds. Soft-sedimentary deformation and synaresis cracks are common (Fig. 8C–D).

Interpretation: The present sedimentary facies points to a sheltered, shallow brackish setting. The silt-streaked mudstones indicate low-energy environments with deposition of material carried in suspension and deposited below the local wave-base. The trace fossil assemblage, comprising dominantly *Planolites* and indistinct burrow mottling, points to a stressed setting. Common presence of synaeresis-cracks may suggest fluctuating salinity. Considering the stratigraphic occurrence gradationally above transgressive top of estuarine channel or shoreface/barrier sediments (FA4b, FA2) and below tidally dominated strata (FA3b), the deposits are broadly interpreted as lagoonal. Intervals with common synaeresis cracks may represent bay-head delta setting.

FA3b: Tidal flats and channels?

Description: FA3b is a rare sub-association intercalated with FA3a. Base of the succession show mud-clast bearing fine-grained sandstone, or mud-draped, cross-bedded, upper fine to lower medium grained sandstone. Upper part of the successions consists of sand- to mud-dominated heteroliths, which are often contorted. Mud-draped current ripples with sigmoidal forests and double mud drapes are common. Bioturbation (*Planolites*, burrow mottling) is concentrated on mud-drapes (Fig. 9A–B).

Sub-association FA3b is developed particularly in core St-14, which is inclined up to 20–25 degrees. This complicates locally distinction between paleohorizontal heterolithic stratification (HS) and inclined heterolithic stratification (IHS).

Interpretation: Sub-association 3b contains sharp-based successions with upward fining grain size trend, which may point to channel deposition. Common occurrence of double mud-drapes suggests tidal influence. Distribution of bioturbation supports the interpretation as it suggests opening of colonization window during mud-drape formation (semi-diurnal slack water). Despite local challenges in delineating paleohorizontal orientation (St-14), observed contorted bedding and strata inclination in the lower part of UF successions suggest the presence of depositional gradient and IHS typical for tidal creeks and channels. Top of the successions and other occurrences of HS may represent tidal flats/shoals, some of which are also wave influenced (upward coarsening examples).

FA4: Fluvial, delta and estuary

Description: FA4 is dominated by well-sorted, fine- to medium-grained cross-bedded sandstone, forming successions, which are several tens of meters thick. The top of the FA4 occurrences is commonly upward fining and characterized by appearance of mud-draped cross bedding.

Subdivision: FA4a: fluvio-deltaic and FA4b: fluvio-estuarine complexes. The interpretation is very tentative, and requires further work (e.g., palynofacies data).

Occurrence: FA4 is the dominant FA type in the lower half (sequences 4 and 5) of the Gassum Formation above SB4 and SB5. It is readily distinguishable from the GR log by its characteristic blocky signature.

Base of the FA4b successions corresponds to TS4 and TS5. The top shows gradation into root-bearing sandstone (FA5) and/or lagoonal (FA3) heteroliths. Alternatively, roots can be directly overprinted by equilibrium burrows descending from a flooding surface / transgressive surface of erosion (cf. Fig. 12b).

FA4a: Fluvio-deltaic complex?

Description: FA4a dominantly comprises well- to moderately-sorted, fine- to medium-grained cross-bedded sandstone (Fig. 10). Faintly upward fining successions, a few m thick, are recurring, while upward fining successions are less common. Where visible, the foreset termination on the basal set boundary is angular and bottom sets are commonly poorly developed. However, locally occurring bottom sets can be formed by ripple cross-laminated units. Foresets can show grain size contrast, or lack it resulting in structureless-appearing sandstone. Mud clasts, and coal fragments and (gutter cast-like?) erosional truncations are observed locally. Finally, FA4a is unbioturbated.

Interpretation*:* Sub-association 4a lack clear depositional trends and comprises generic facies that can be generated by various processes ranging from fluvial currents to wave-related processes, complicating the interpretation of the setting. Indeed, under wave-dominated regime medium-grained sands could form well-sorted cross-bedding as observed here (see Yoshida et al., 2007). Tentatively, however, limited *in situ* palynofacies data suggest generally terrestrial environment, locally with marine influence (Lindström et al., 2020). Similarly, the deposits are unbioturbated, possibly pointing to terrestrial or low salinity setting; however, that is commonly the case also in similar facies of FA2 interpreted as shoreface sediments. Seismic data point to lack of major channels, but prominent progradation during deposition of SB4 and SB5 (Vosgerau et al., 2020). Potential tidal indicators (sigmoidal cross-bedding, double mud-drapes, reactivation surfaces or bi-polarity) are typically absent in FA4a.

One depositional scenario that is in line with the above mentioned constrains would be a braid plain at sea level. In this setting, the channels (stacked and thin) and upward fining motifs (limited lateral accretion) are not well developed, and the deposits can grade into broad, deltaic near-shore setting. The bulk thickness of these units (up to several tens of meters) suggests that accommodation was generated repeatedly, possibly leading to marine influence on several intervals. The most prominent change would coincide with TS4 and TS5, where the cross-bedded sets become heterolithic, which is interpreted as a drowning and a change to an estuarine setting (FA4b; see below), followed by lagoonal/bayhead delta setting (FA3). The fluvial interpretation would require a well-sorted sediment source. These interpretations will be tested in the future as more palynofacies data become available.

FA4b: Fluvio-estuarine complex

Description: Sub-association FA4b forms a few m-thick upward fining top of the FA4 intervals. It is characterized by heterolithic cross bedding, with well-developed mud-draped foresets (Fig. 11). Locally, cross-bedded sets with well-developed bottom sets (tangential/sigmoidal form) are present. Moreover, some intervals are well sorted and appear as structureless. FA4b is locally bioturbated by *Planolites, Taenidium* and burrow mottling. Sporadic palynofacies data point to marine influence.

Interpretation: The appearance of mud-draped cross strata in the top of FA4 occurrences (Sequences 4 and 5), suggest a process-change and possibly initial transgression. This is supported by gradationally overlying lagoonal sediments, which suggest change to brackish conditions as the transgression proceeds. Thus, FA4b may represent a drowning estuarine system, increasingly influenced by tidal processes. The locally occurring well-sorted facies may suggest superimposed wave influence and, considering the overlying lagoonal sediments, change towards a barrier coast (Boyd et al., 1992).

FA5: Backshore/lake or lagoon margin/marsh

Description*:* Facies association 5 comprises rhizolith-bearing decimeter scale deposits of variable lithology. Some examples are multicolored with matrix cement and un-oriented slickenside. In few cases FA5 can be overprinted by marine trace fossils.

Occurrence: Typically, FA5 occurs at the top of upward coarsening successions and descends into FA2 or FA4. Consequently, although the FA cannot be conclusively recognized from the GR-log alone, it commonly occurs at the top surface of blocky or funnel shaped GR-signature. Alternatively, FA5 develops in laminated coal rich mud (St-15 1612.8m), resulting in higher GR-values. FA5 is particularly common in St-15 in the interval between SB4 and SB5. FA5 occur also at TS5 in St-17 (poorly developed) and at TS6 in St-1 and St-5.

***Interpretation**:* Considering the typical stratigraphic position gradationally above prograding shoreface-foreshore succession (FA2)*,* some FA5 occurrences are interpreted to represent a backshore environment. The occurrences above mudstone or coaly mudstone may represent lake margin, supratidal lagoon margin and/or marsh. The multicolored examples suggest prolonged sub-aerial exposure and increasing influence by soil-forming processes, and thus record gradation towards a paleosoil (St-15, 1603.6m).

Locally, the deposits can represent zone of maximum progradation associated with forced or normal regression.

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Captions to figures

Figure 2: *Correlation panel showing studied core intervals. Main sequence stratigraphic surfaces are shown.*

Figure 3*: Summary sedimentological section through the Gassum formation (based on cores from three wells, located in Fig. 2). The depths of the cored intervals are shown above each log. Sandstone and mudstone are the main lithologies, they are shown in yellow and grey on the logs. The lower part of the cores (between SB4 and TS5) is dominated by sandstone, while the upper part (between TS5 and MFS7) contain more mudstone. The presence of marine microfossils (palynomorphs) is shown, and support the interpretation of the depositional environments. These are shown to the left of the logs with a colour code. The environments range from wetlands (green) to the deep sea (dark blue). For further explanation see sedimentological logs in the end of the documented.*

Figure 4. *Facies examples of lower offshore and shelf deposits (FA1), including potentially prodeltaic sediments. All examples from Fjerritslev Formation. A and B) Examples of shelfal deposits below maximum storm wave base. Ch–Chondrites, Ph/He–Phycosiphon/Helminthopsis. Both pictures are from St-2, ~1488 m. C) Mainly unbioturbated, normally graded storm-wave generated laminae. fu-fugichnia, sy-synaeresis crack (Stenlille-4, 1498 m). D) Silt-streaked mudstone and normally graded distal storm beds. Trace fossil assemblage is characterized by morphologically simple Planolites and Arenicolites-like burrows (Stenlille-4, 1500 m).*

Figure 5. *Facies examples of storm-dominated, potentially deltaic setting in water depth equivalent to upper-offshore - lower shoreface gradation (FA1b/FA2a). All examples from a stratigraphic interval situated above TS5. A) and B) Unbioturbated, normally graded event beds showing basal hummocky cross-stratification and/or wave ripple cross lamination grading upwards to suspension fall-out drape. Synaeresis cracks are common. Mud-drapes do not show significant loading suggesting that initial dewatering took place before next event bed emplacement. Therefore, the event frequency alone does not explain paucity of bioturbation.*

Core depths: A) St-18, Core 1, 1600.8 m. B) St-17, Core 3, 1642.7 m. C) Similar to previous one, but showing Planolites and rare fugichnia. St-2, ~1546.8m. D) Amalgamated tempestites. St-14, ~1656.6m.

Figure 6. *Facies examples of lower shoreface deposits (FA2A). A) Bioturbated sandstone overlain by stratified siltstone. Te–Teichichnus, Si–Siphonichnus, ?Ne–?Nereites, ?Di–?Diplocraterion. St-2, ~1537m. Transgressive interval grading to MFS 5. B–D) Bioturbated tempestites with local remnant mud-drapes. Par-Parahaentzschelinia, Pl–Planolites, eq – equilibrium structure. Figure C is characterized by bivalve generated equilibrium sturctures (Sc–Scalichnus). Core depths: B) St-6_Core 4, 1601.9 m. C) St-6_Core 4, 1601.4 m. D) St-2 ~1528.6m. Lower part of a sharp-based prograding shoreface above SB6.*

Figure 7*: Facies examples of shoreface deposits (FA2AB). A and B) Amalgamated tempestites interbedded with burrow-mottled interval. Core intervals St-17, ~1607m and St-2, ~1544 m, respectively. C) Low-energy shoreface. St-14, 1630.6m.*

Figure 8*. Facies examples of lagoonal heteroliths (FA3A). All examples come from an interval between TS4 and MFS4. A-C) Bioturbated heteroliths characterized by Planolites-dominated trace fossil suite pointing to low-salinity setting. Rare possible Siphonichnus (Si). Core depths: A) St-18, core 2, 1648 m. B) St-14, ~1711.8 m, right above TS4. C) St-14, 1706.2 m (inclined core), near MFS4 gradationally overlying FA5. D) Wave-dominated lagoonal or embayment heteroliths. The facies forms an intermediate occurrence with upper offshore setting (FA1B). St-15, ~1603m, a few meters below MFS4.*

Figure 9*. Sand-dominated heterolithic stratification (HS) interpreted as tidally-influenced (FA3B). Red arrows indicate examples of double mud-drapes. All illustrated examples represent a transgressive interval occurring between TS4 and MFS4. Figures A and B come from ~25° inclined core and may thus represent paleohorizontal strata. A) St-14, ~1707.4m. B) St-14, ~1709.6m. C) St-15, ~1607.2m.*

Figure 10*. Facies examples of "blocky sandstone" interval (FA4), tentatively interpreted as fluvio-deltaic. A) Fine-grained, well-sorted, apparently structureless sandstone. St-17, core 4, 1665.4 m. The core piece is ~20 cm high. B) Part of cross-bedded set with distinct grading within foreset laminae. St-18, core 3, 1651.8 m. C) Part of cross-bedded set, medium-grained sandstone with cementation that enhances the foreset laminae. St-18, core 3, 1653.7 m D) An erosional, mud-clast bearing scour truncating into well-sorted, upper fine-grained sandstone. St-14, ~1685.5m.*

Figure 11*. Facies examples of upward fining top of blocky sandstone interval coinciding with TS4 or TS5 (FA4B). The deposits are interpreted as estuarine. A) A cross-bedded set with thick bottom set rich in coaly*

debris. ST-19, 1644.6-1645m. B) Mud-draped cross-bedding. The overstep strata is probably due to inclined core. St-14, 1717-1717.20m. C) Structureless to cross-bedded sandstone with mud-drapes and local burrow mottling. St-14, 1669 m, a few meters below TS5.

Figure 12. *Examples of root-bearing deposits (FA5). A) A multicolored interval interpreted as a paleosoil. Examples of coaly filaments (roots) are indicated by yellow arrows. St-15, 1603.5-1603.7m. B) Root-bearing, well-sorted very fine-grained sandstone. Roots are overprinted by equillibrium-burrows descending from an erosional drowning surface, which is further overlain by wave-influenced lagoonal heteroliths. St-14, 1660.5m. C) Deformed fine-grained sandstone showing roots. Top of unit shows erosional and burrowed contact overlain by green sand (glauconite?). The transgressive interval represents MFS4 and is situated only a few cm below SB5.*

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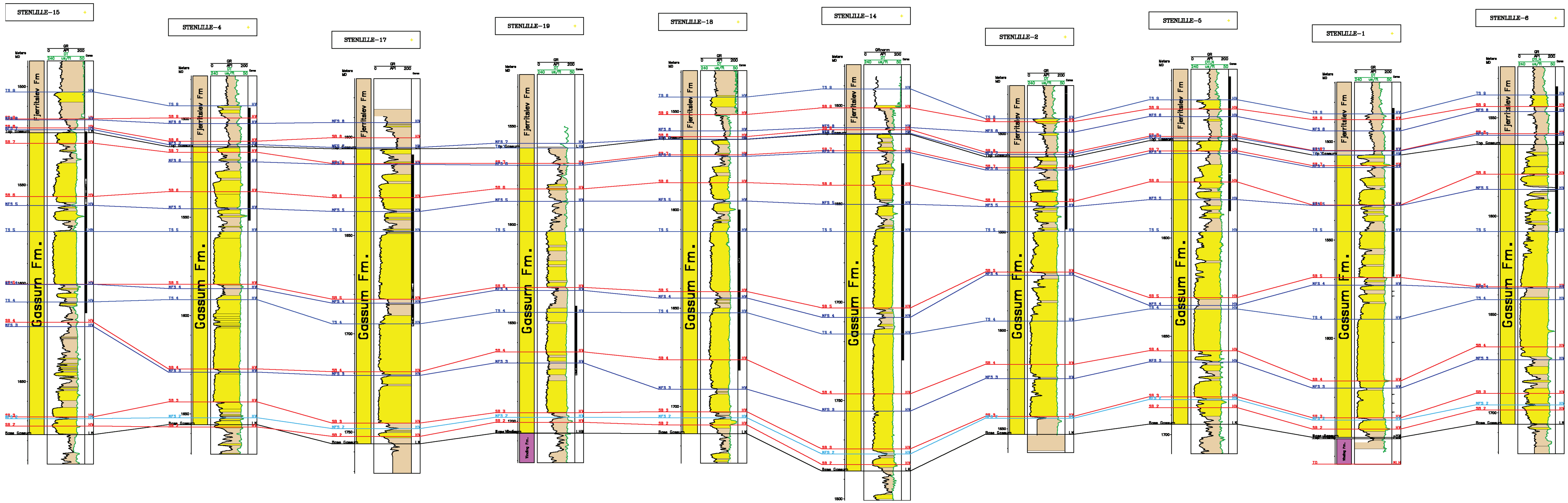
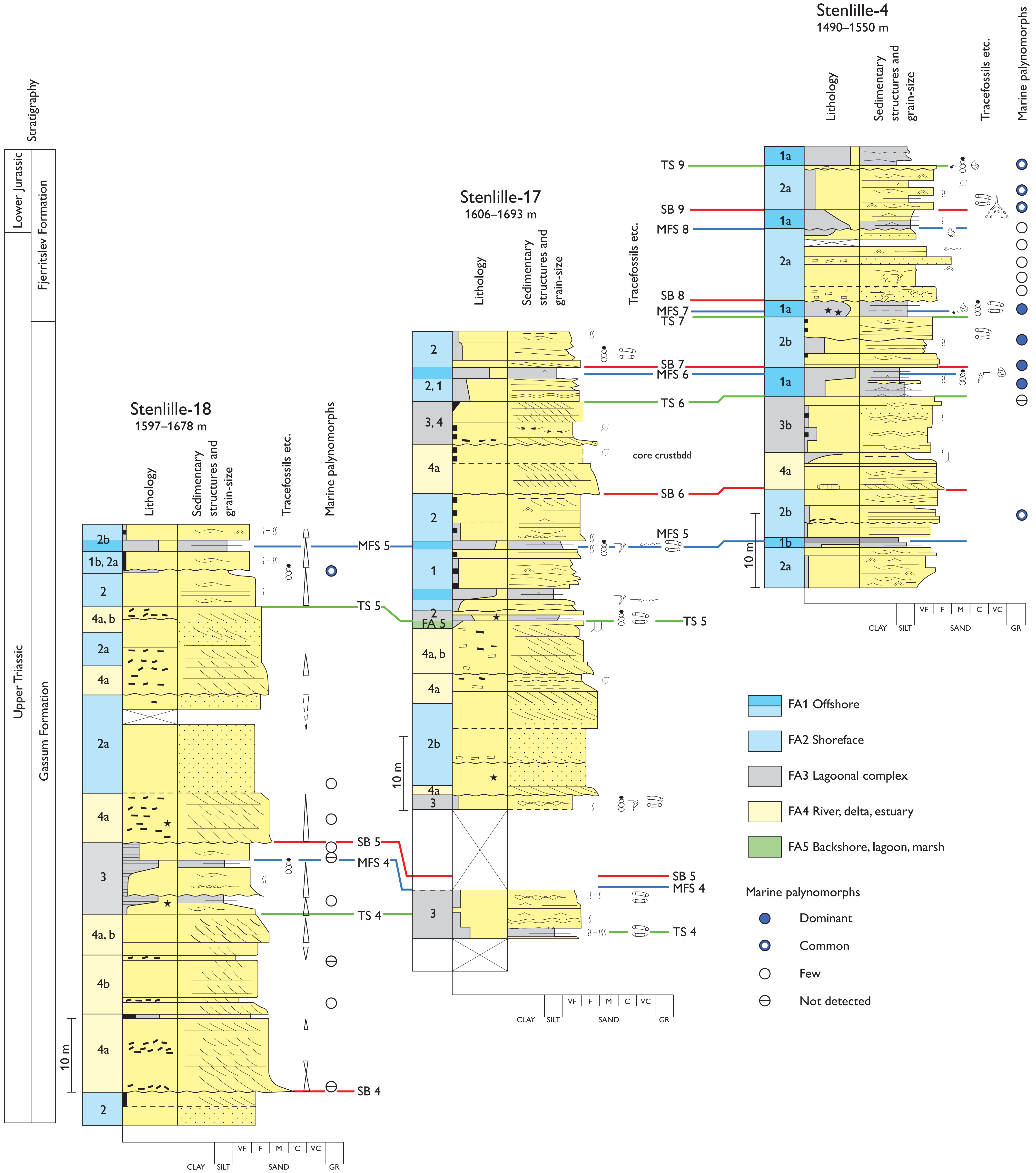
Figure 2 – log panel


STENLILLE-15
STENLILLE-4
STENLILLE-17
STENLILLE-19
STENLILLE-18
STENLILLE-14
STENLILLE-2
STENLILLE-5
STENLILLE-1
STENLILLE-6
Fjerritslev Fm
Gassum Fm.

CCUS project – part of work package 6.

Figure 3 – Summary sedimentological section



Log ST-18_17_4_skala 1-500

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Figures 4-12 – Facies Plates

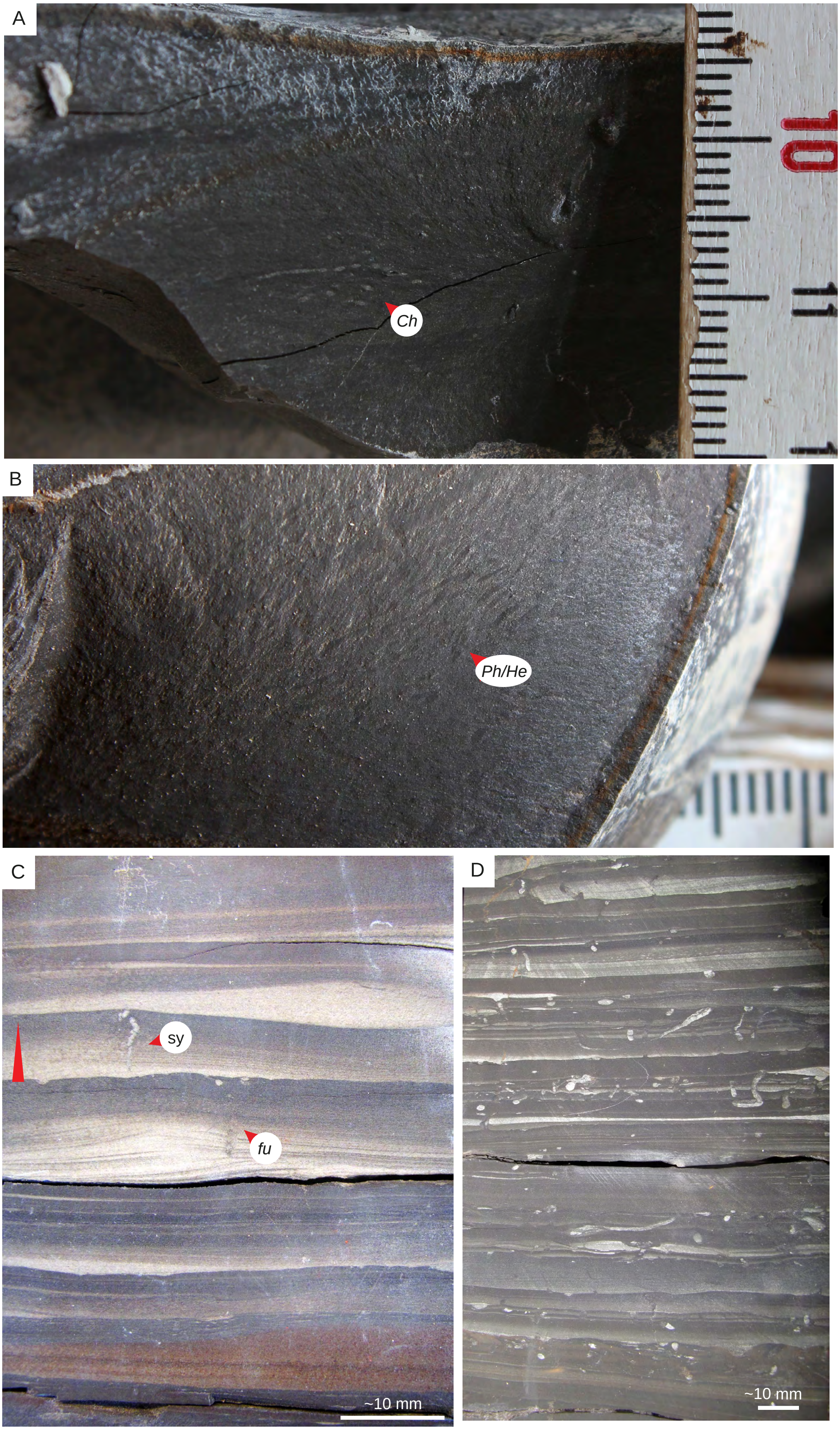


Figure 4.

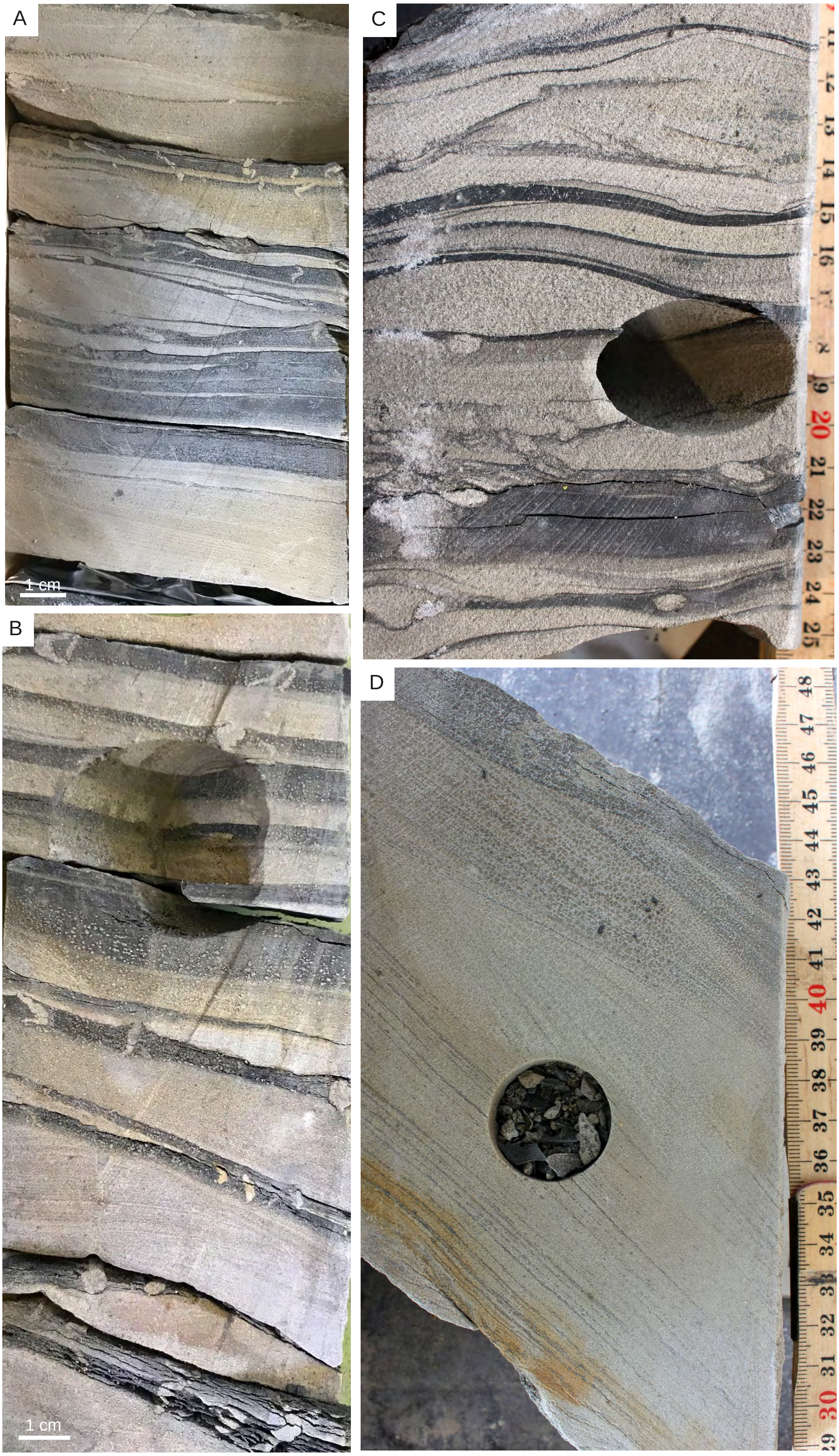


Figure 5.

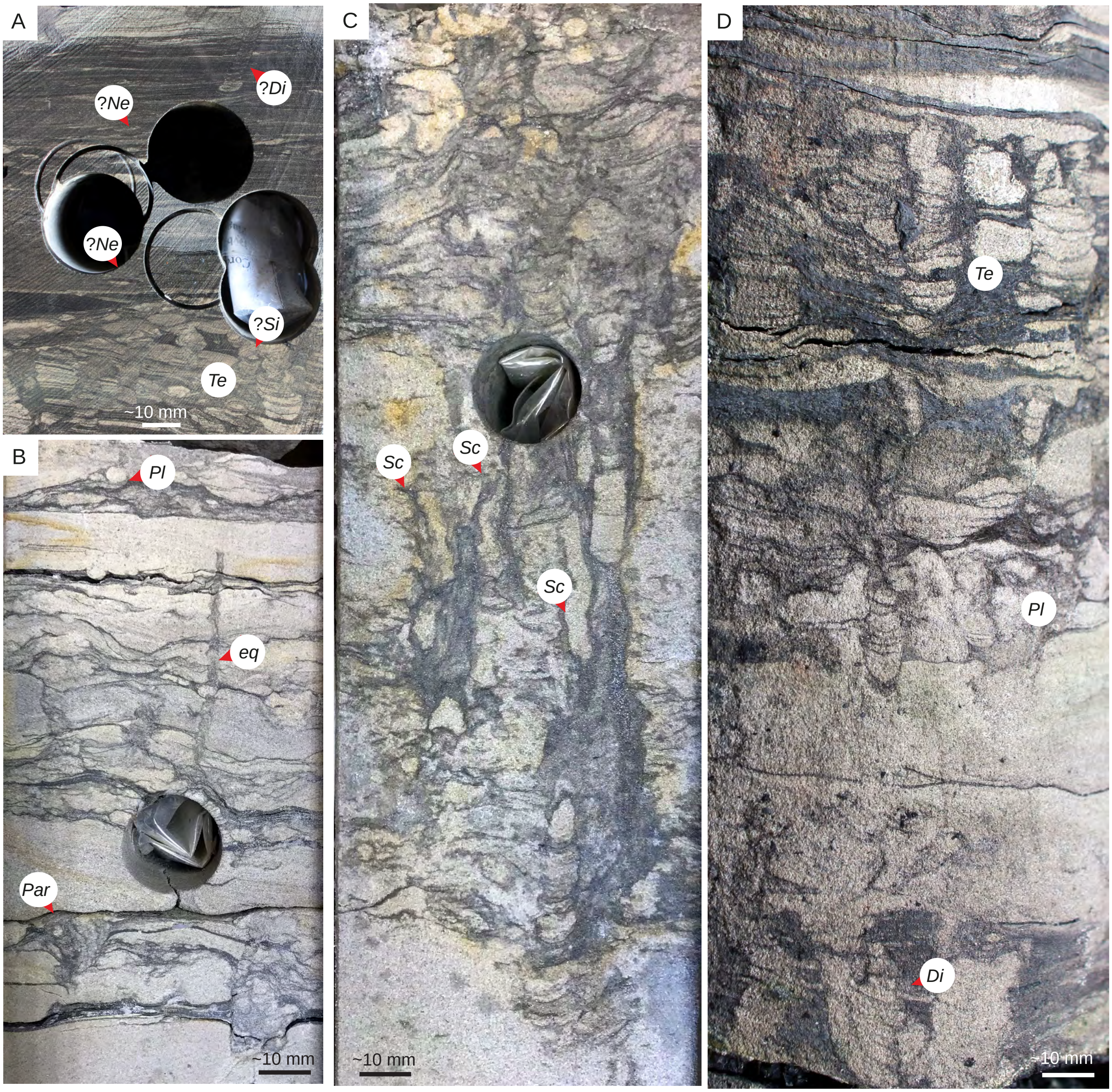


Figure 6.

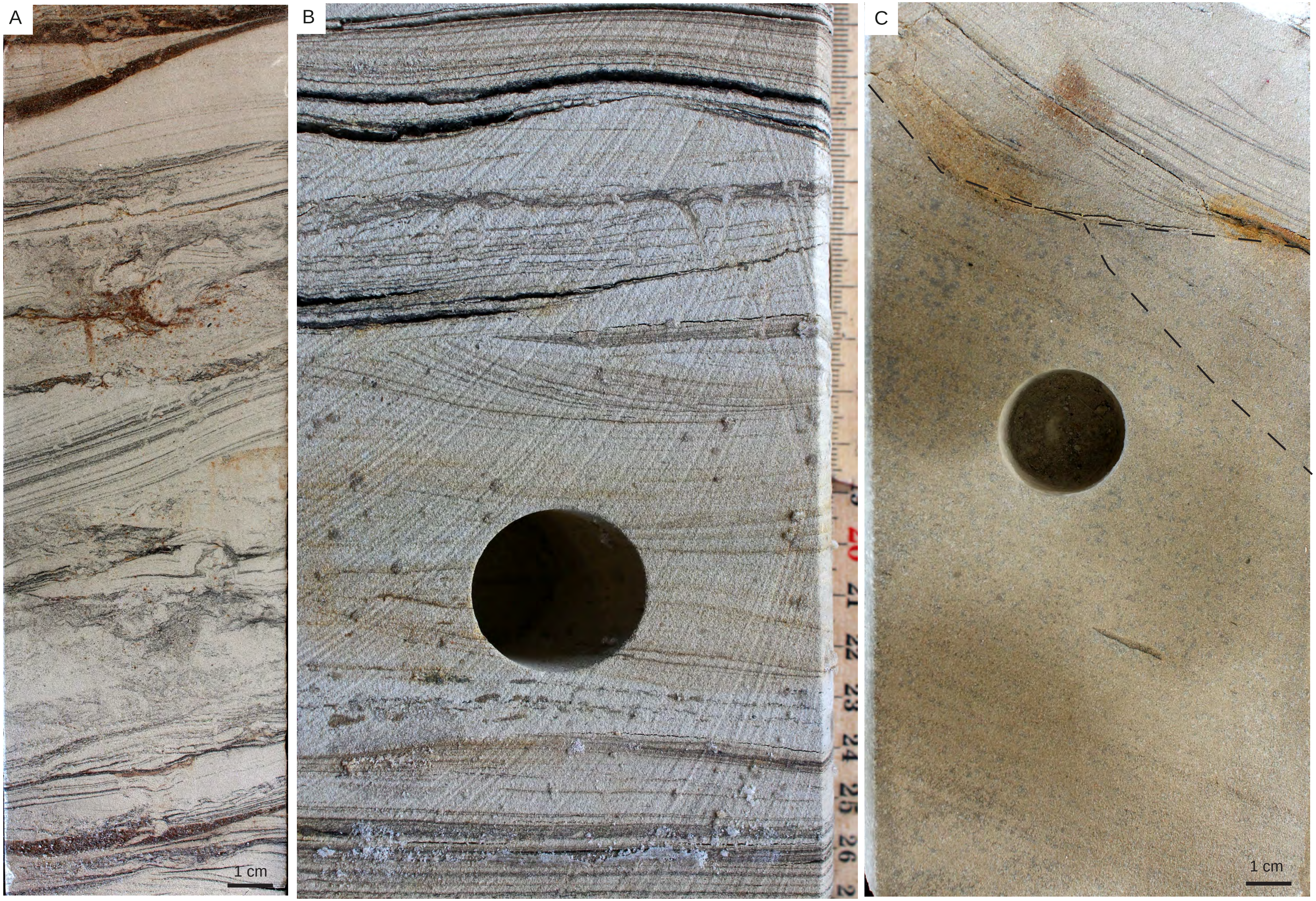


Figure 7.

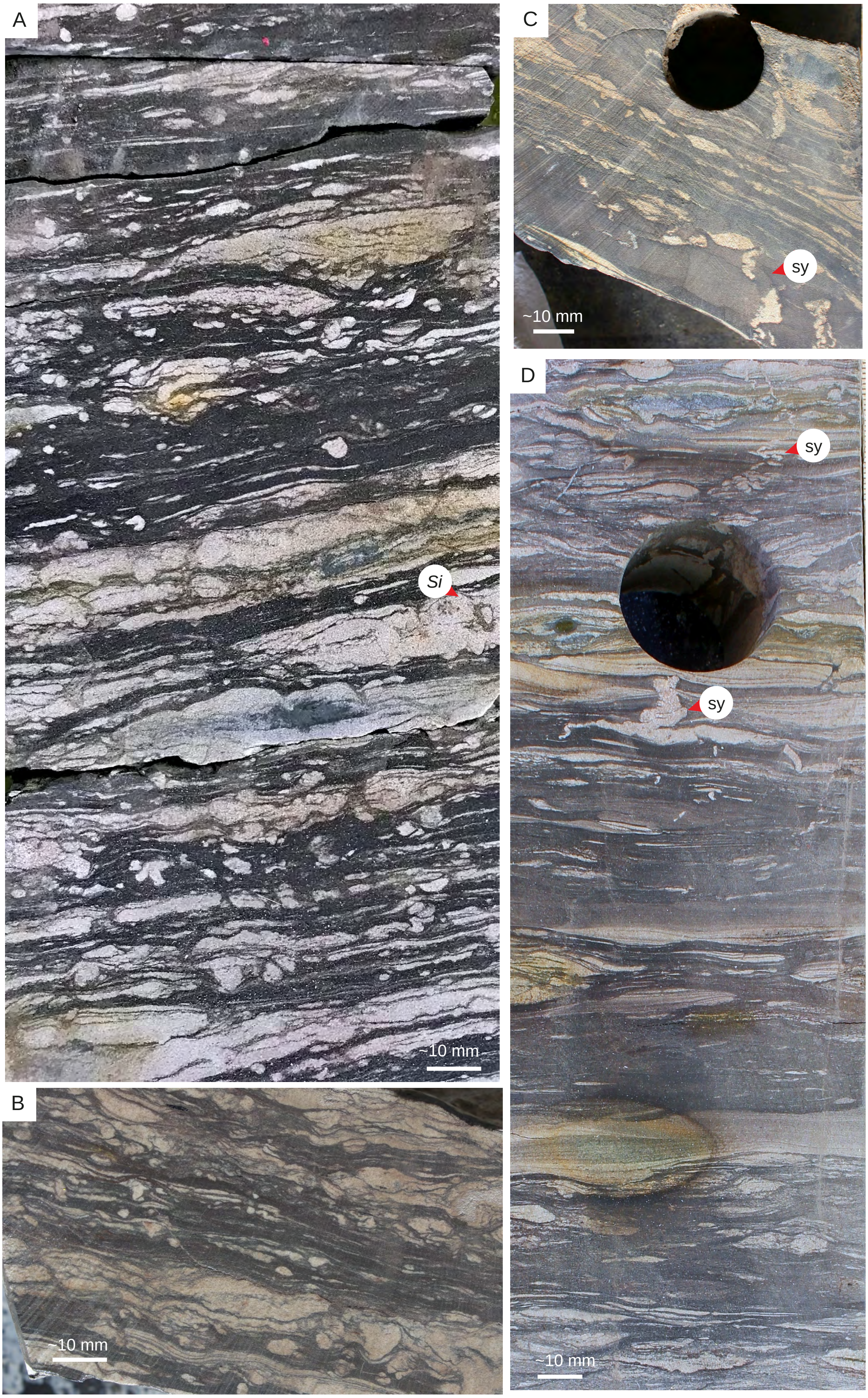


Figure 8.

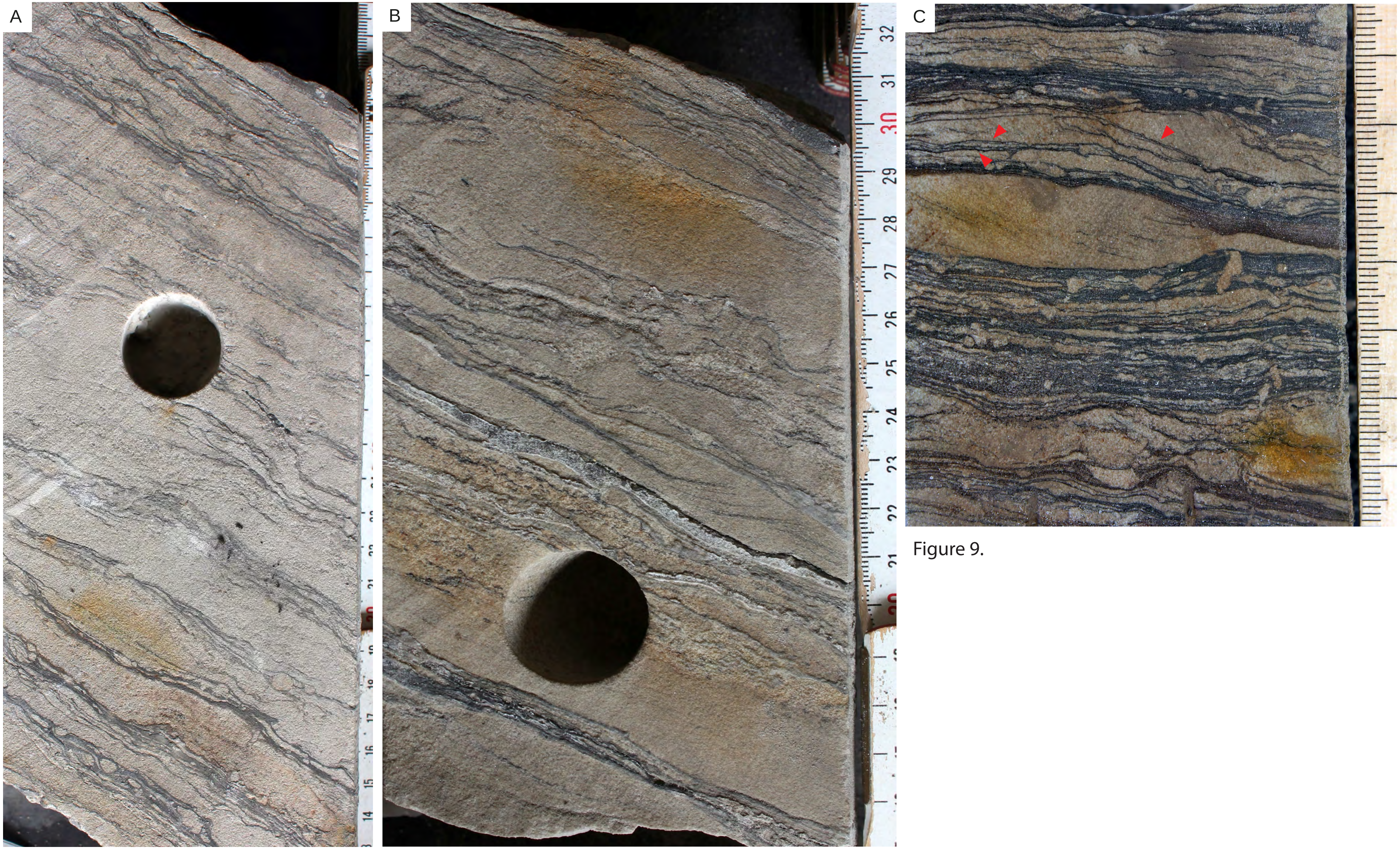


Figure 9.

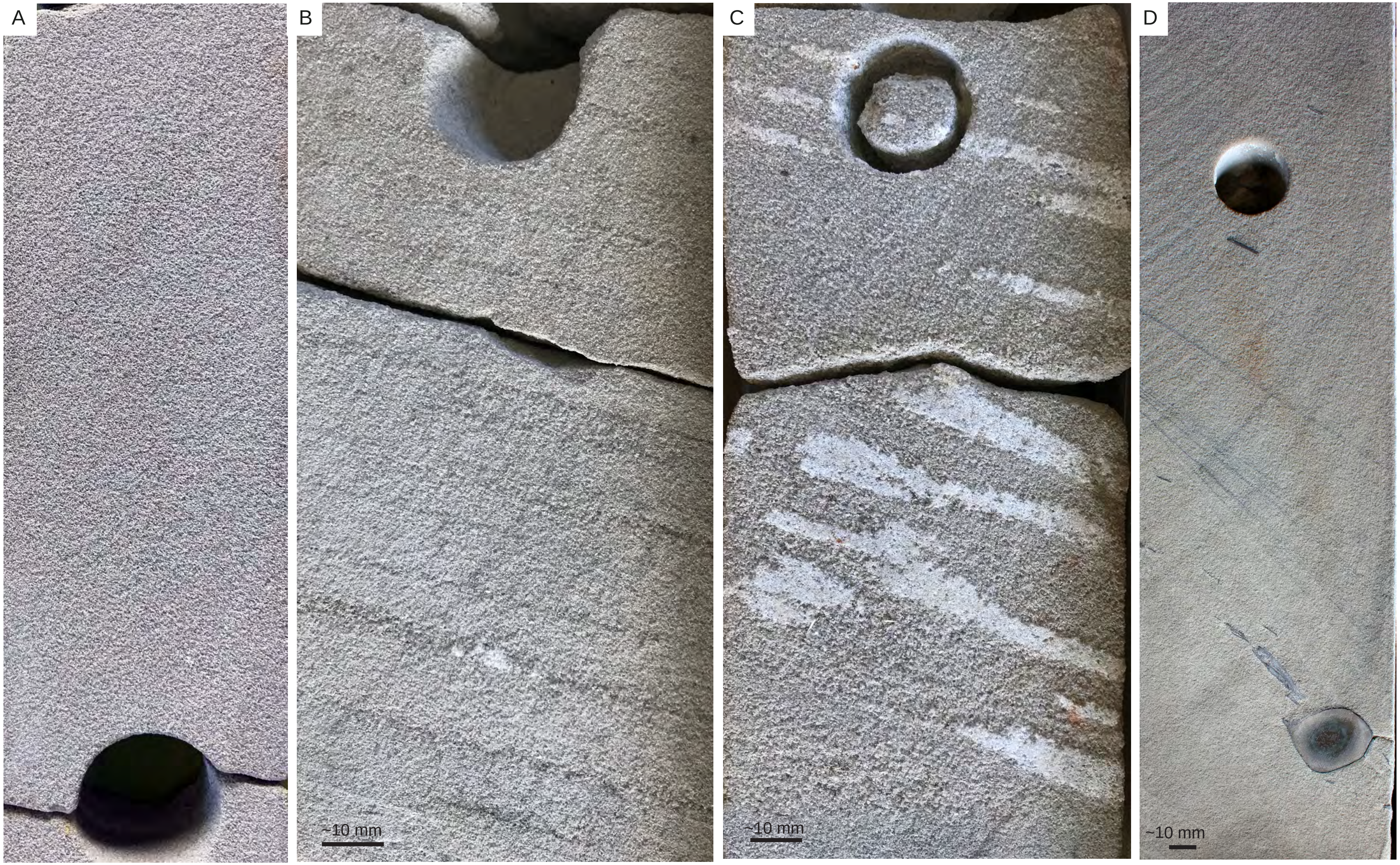


Figure 10

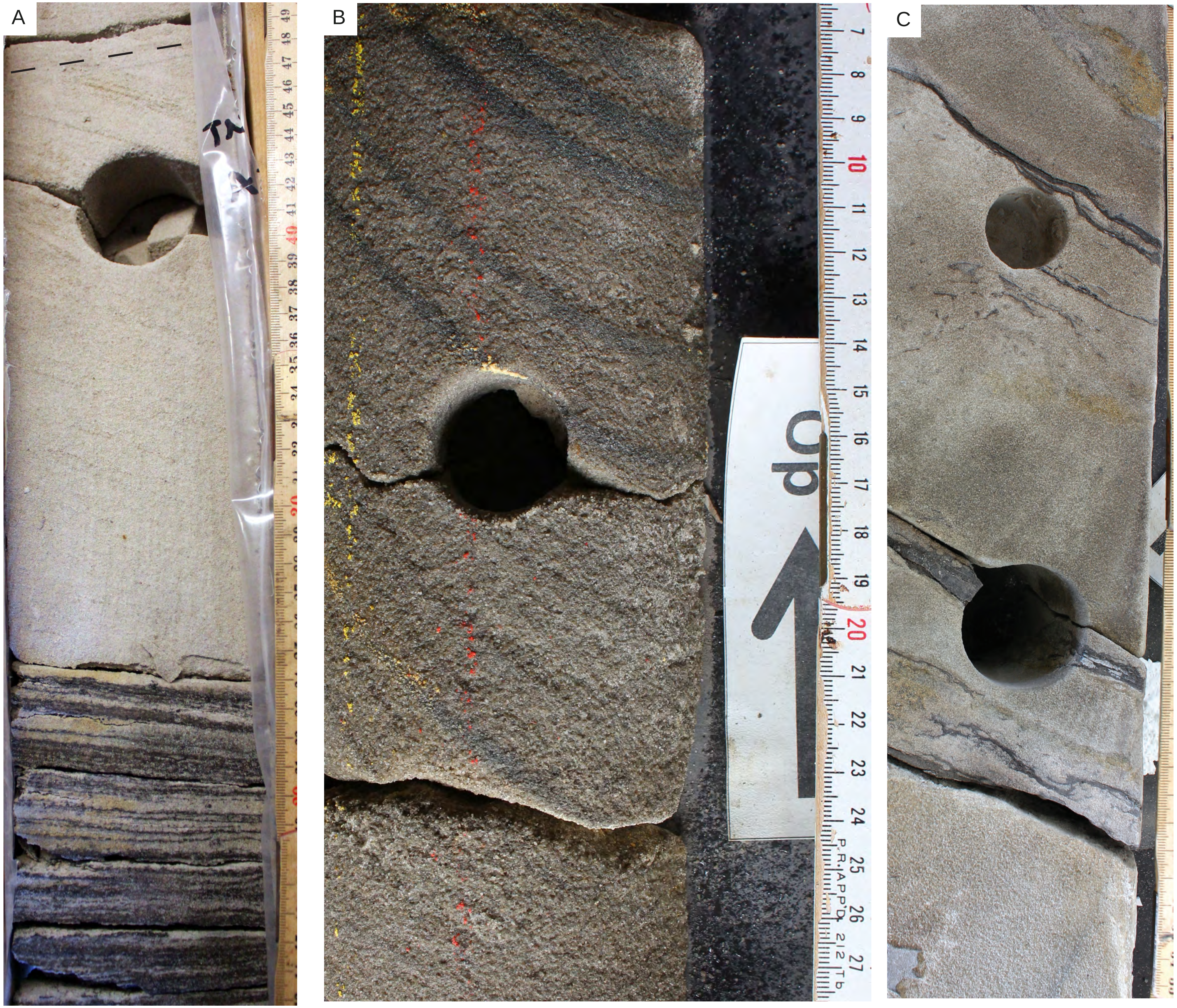


Figure 11.

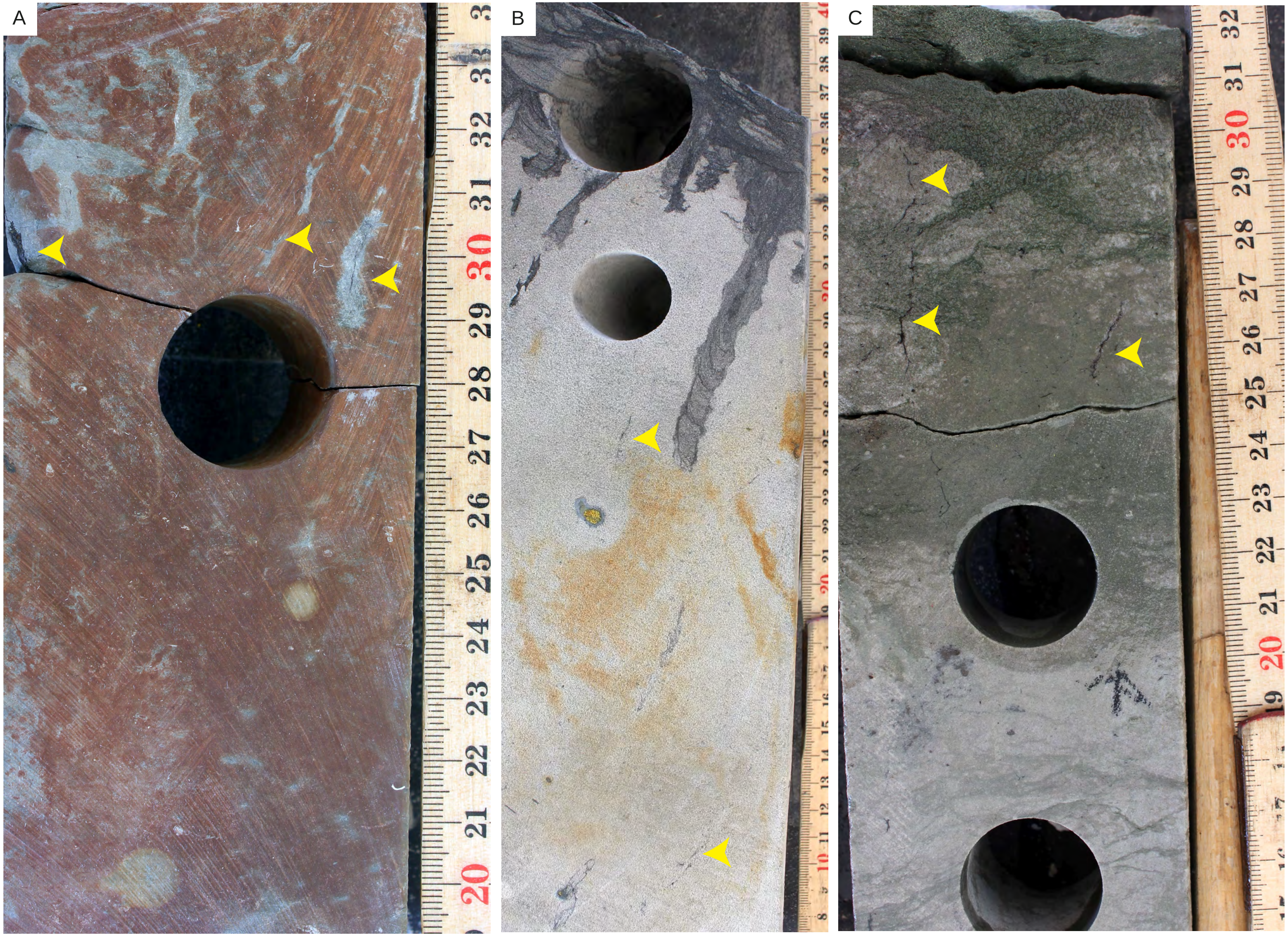


Figure 12.

Sedimentological logs 1:100

Lithology

- Coal
- Clay
- Mud, silt
- Sand
- Sand with coal debris
- Heterolithic sandstone/mudstone
- Pyrite
- Cementation
- Coal clasts
- Mud/shale clasts

Sedimentary structures

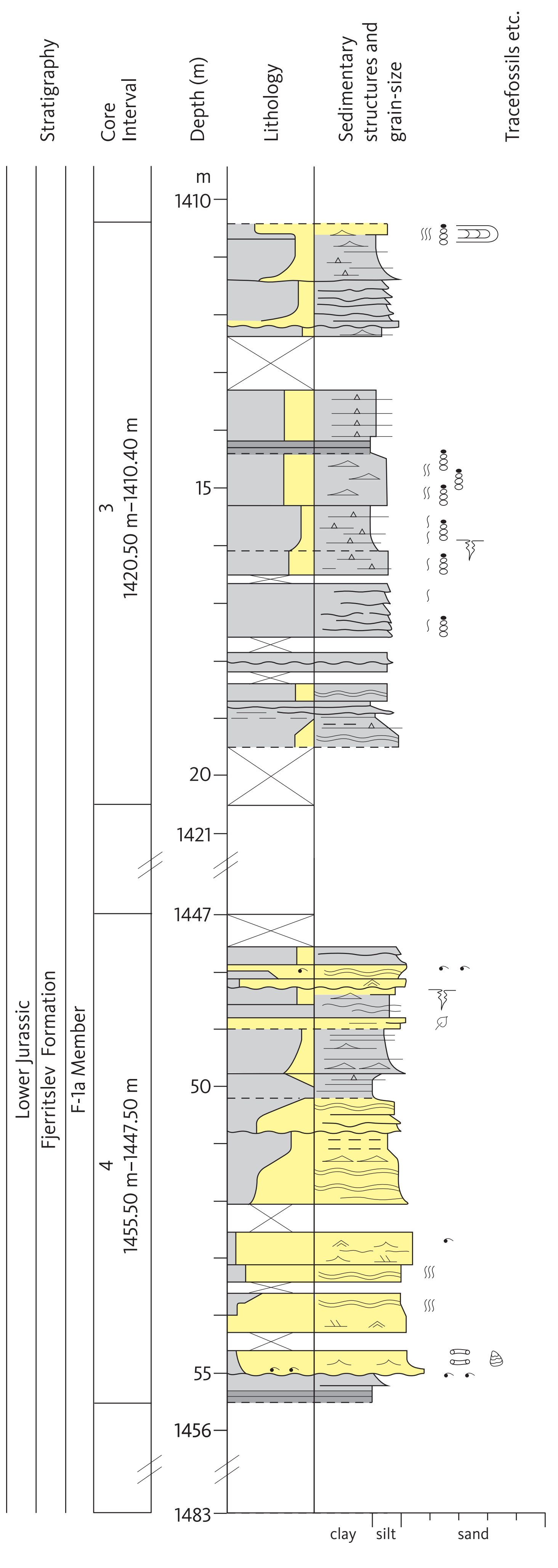
- Cross-bedding
- Cross-bedding with coal debris
- Trough cross-bedding
- Hummocky cross-stratification
- Wavy bedding
- Flaser bedding
- Cross-lamination
- Wave-ripple cross-lamination
- Sand-streaks (in mudstone)
- Lenticular bedding
- Silt-streaks (in mudstone)
- Structureless
- Irregular mud-drape, often bioturbated
- Soft-sediment deformation structure
- Injected sand
- Water-escape structure
- Synaxis-crack
- Solemark
- Fault
- *Chondrites*
- *Diplocraterion parallelum*
- *Planolites* isp.
- *Teichichnus* isp.
- Escape structure
- Bioturbation
- *Rhizocorallium.* isp.
- *Rhizocorallium irregulare*

- Fossil wood
- Plant remains
- Roots
- Shell
- Bivalves

Marine palynomorphs

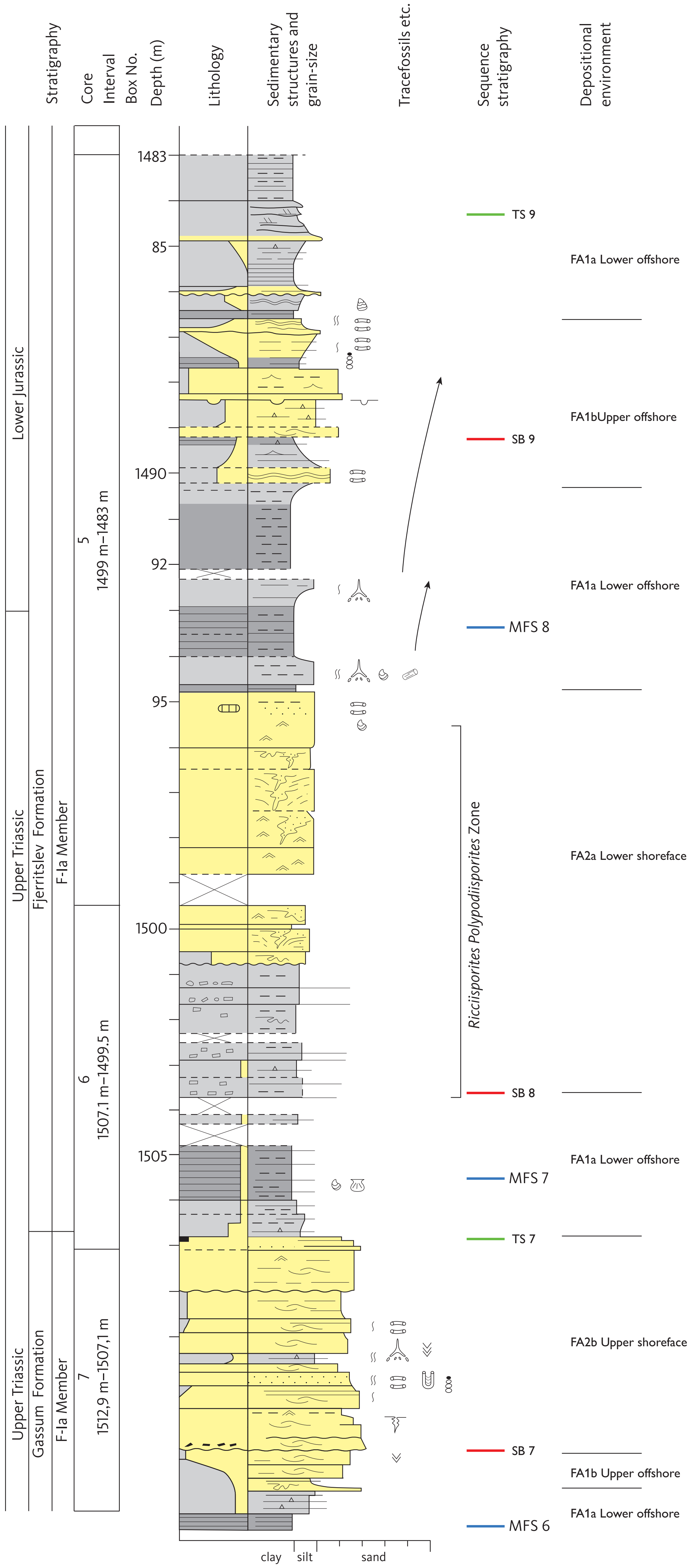
- Dominant
- Common
- Few
- Not detected

Stenlille-1



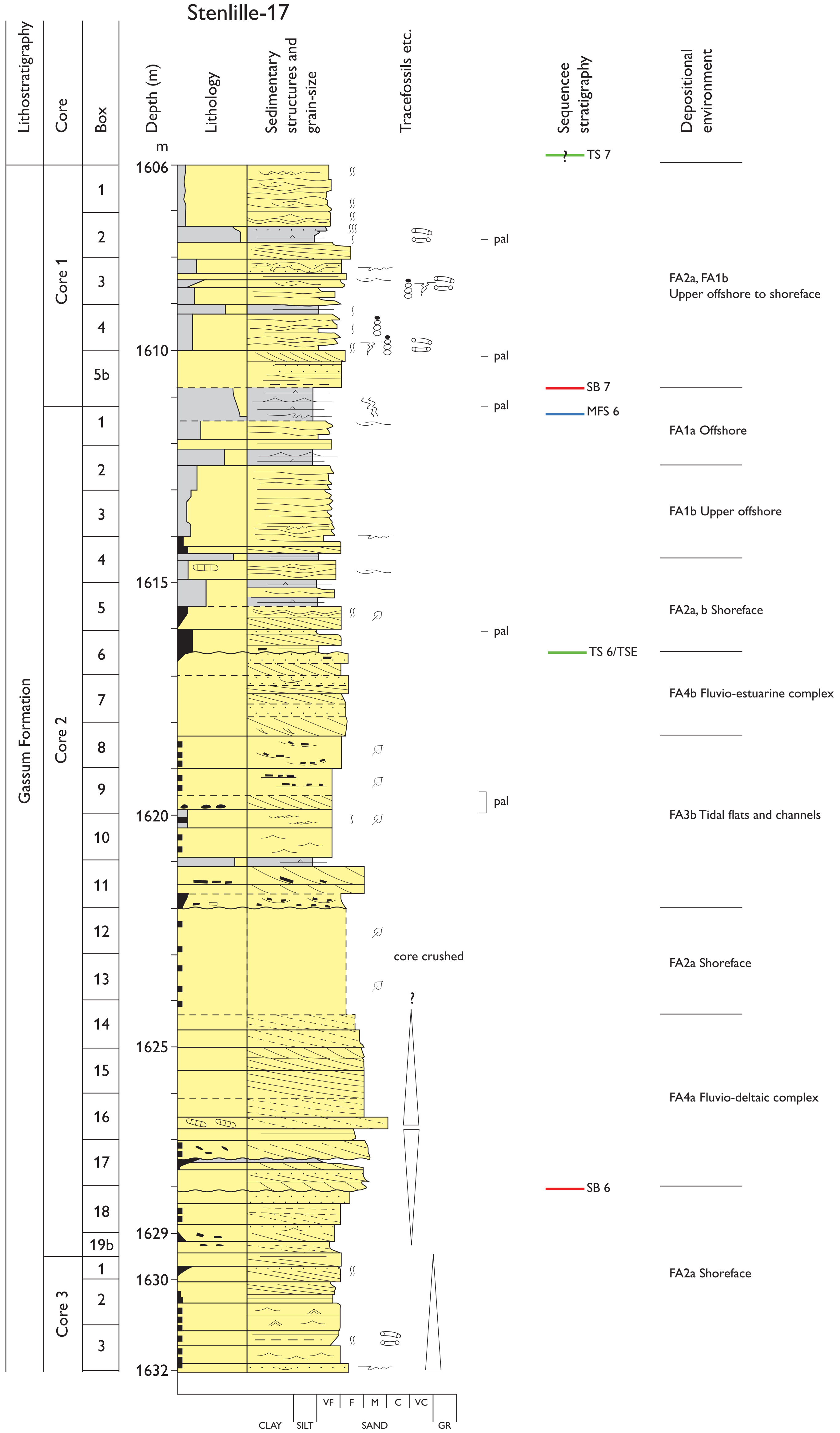
ST-1_cores 3-5_skala 1:100

Stenlille-1



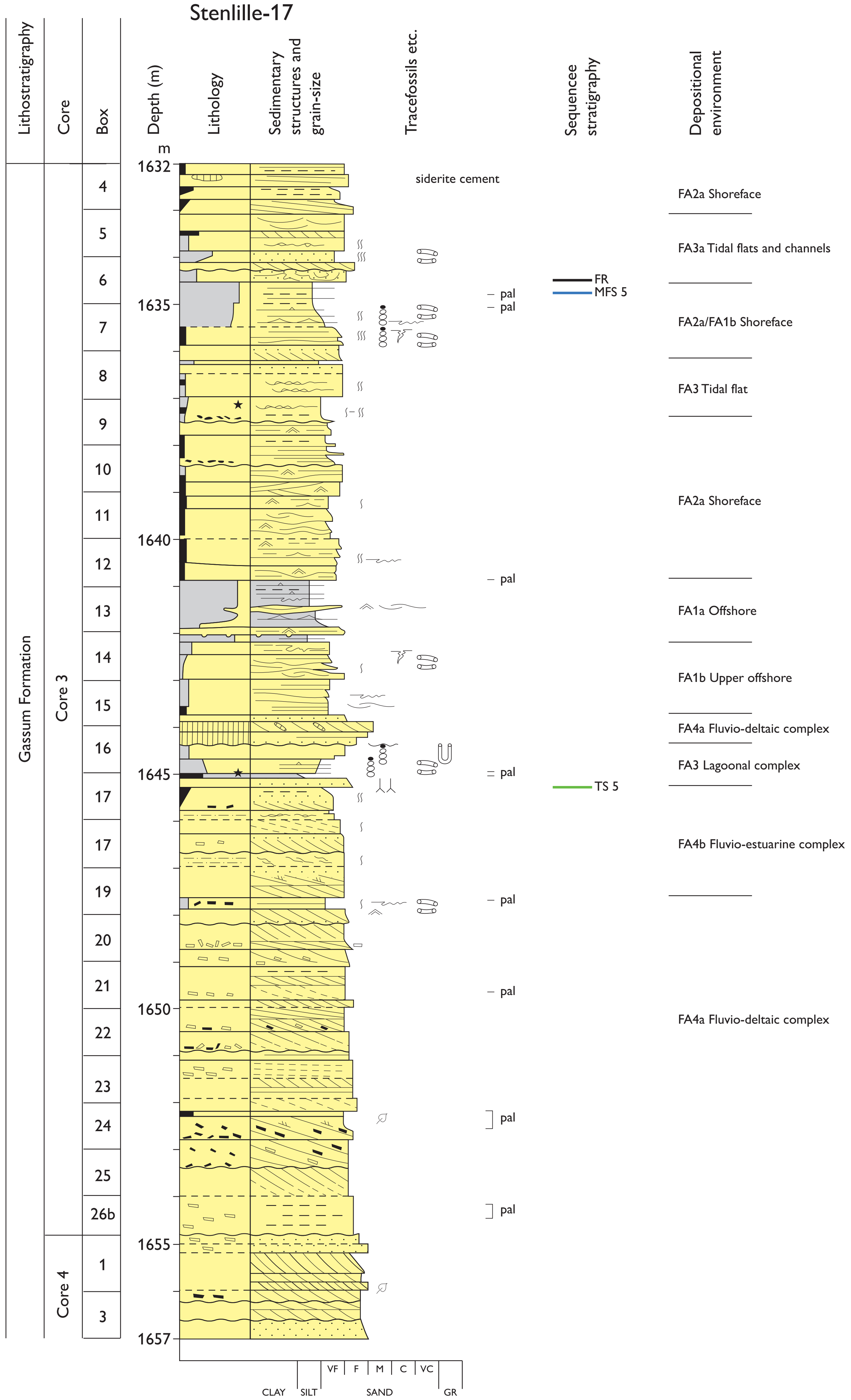
ST 1_cores 5-7_skala 1:100

Stenlille-17

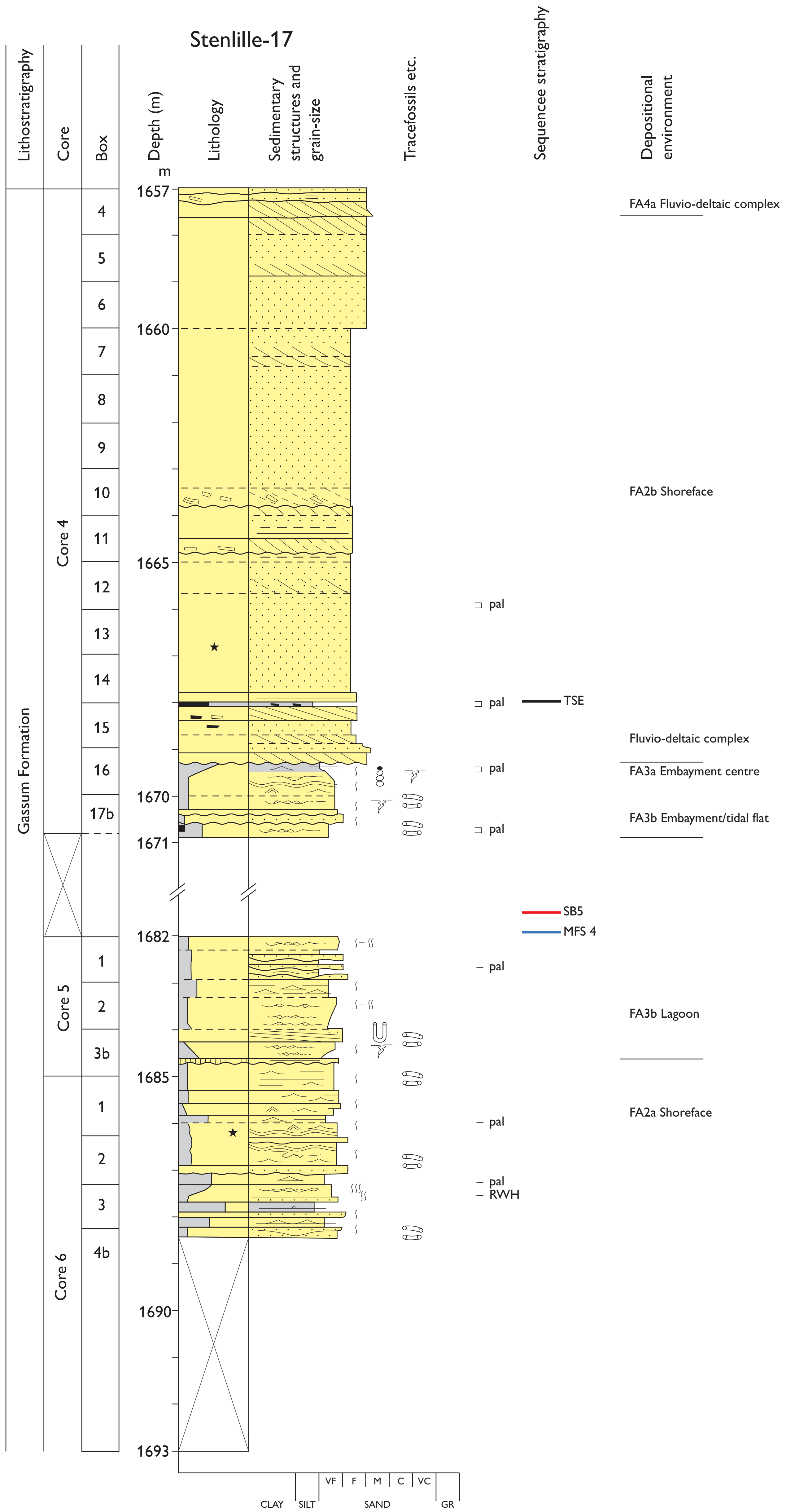


ST-17_cores 1-3_skala 1:100

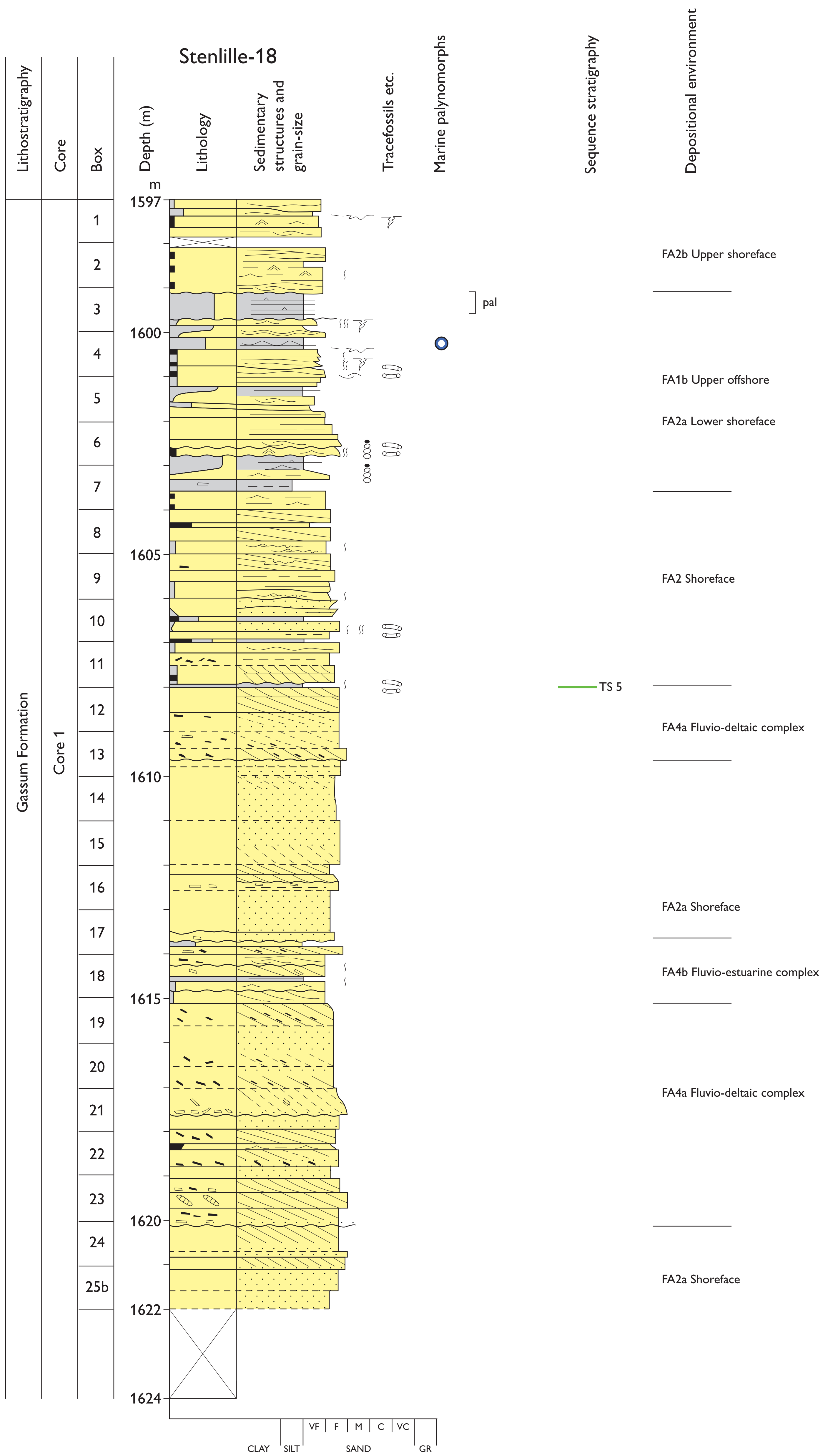
Stenlille-17



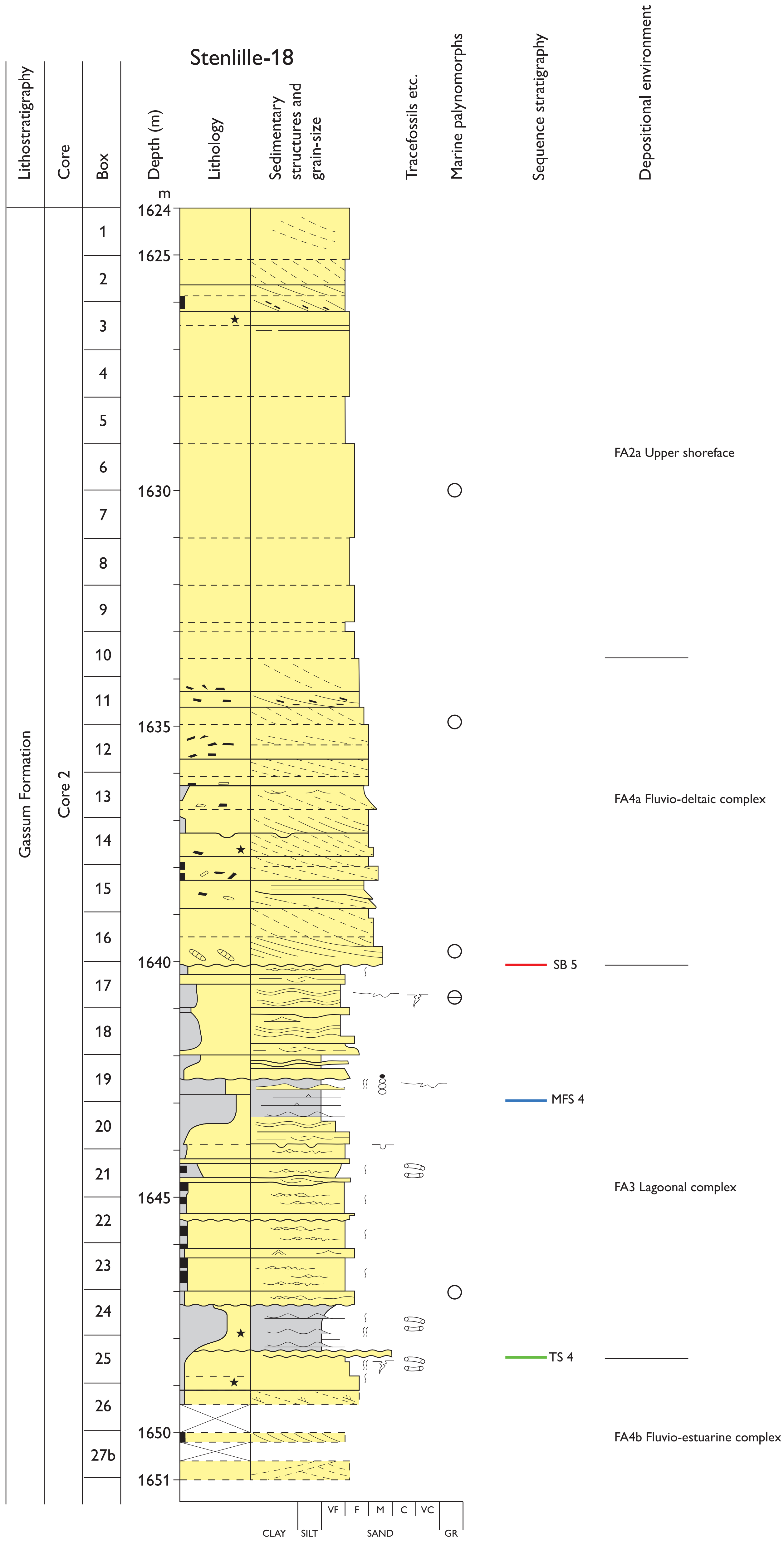
ST-17_cores 3-4_skala 1:100



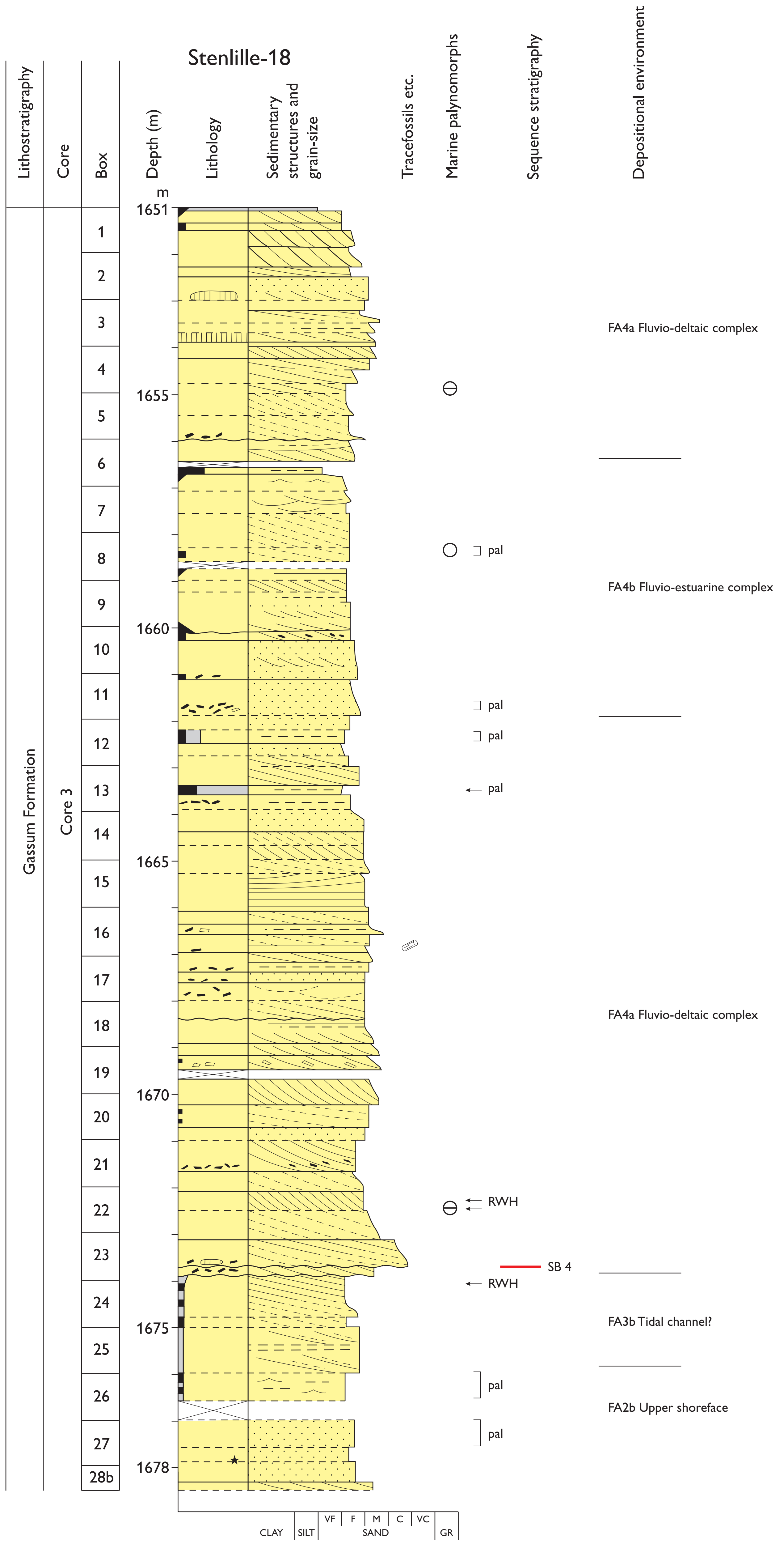
ST-17_cores 4-6_skala 1:100



ST-18_cores 1_skala 1:500

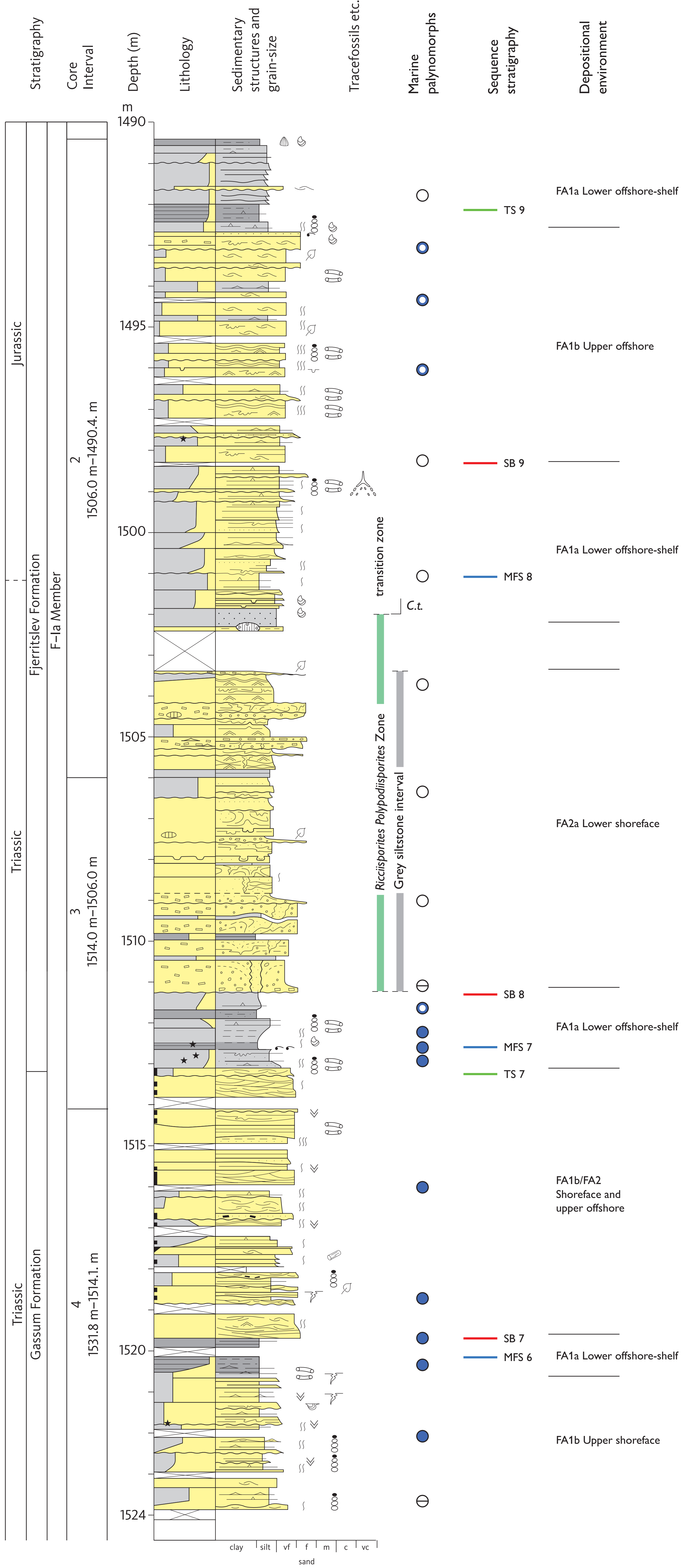


ST-18_core2_skala 1:100



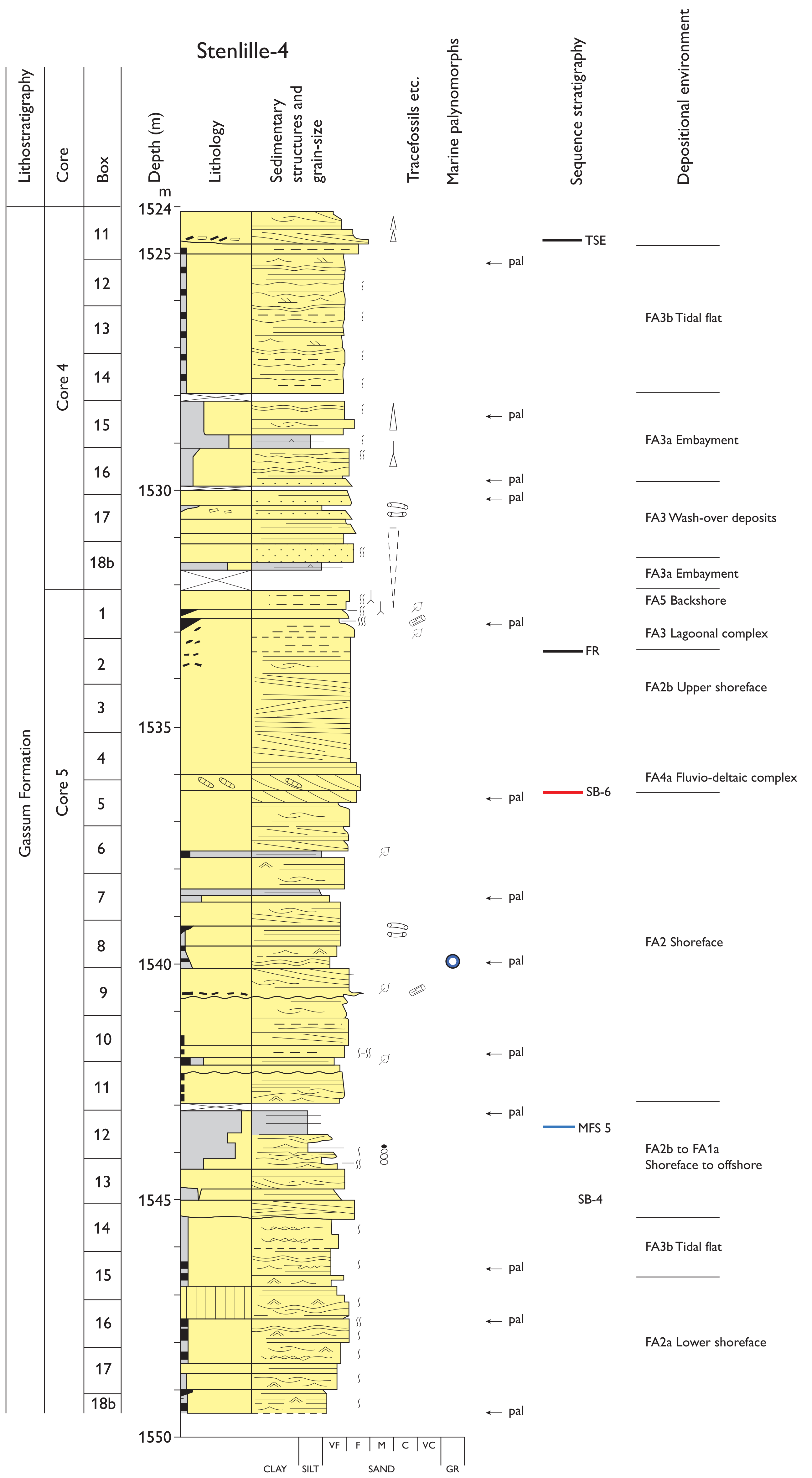
ST-18_core 3_skala 1:100

Stenlille-4

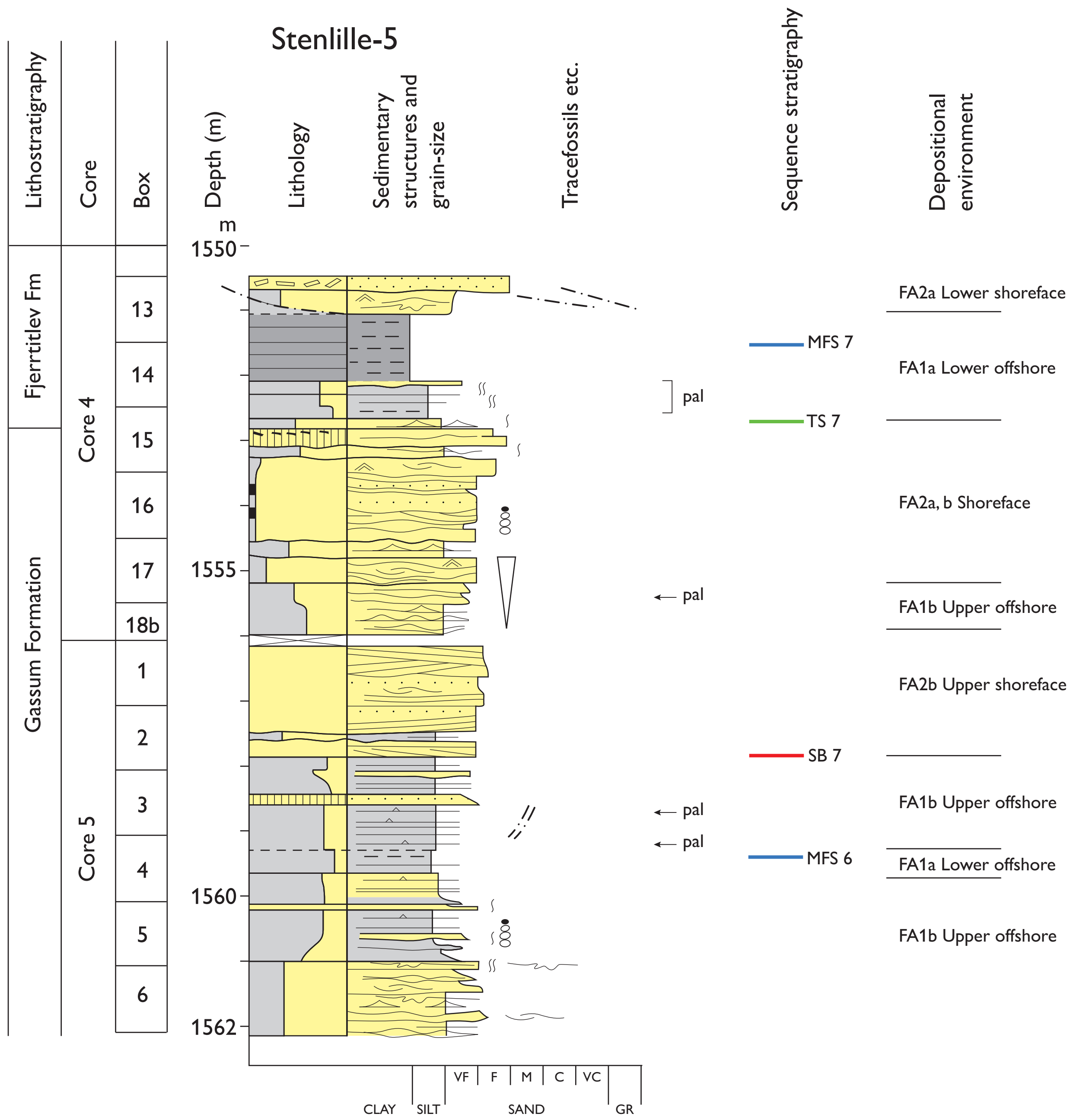


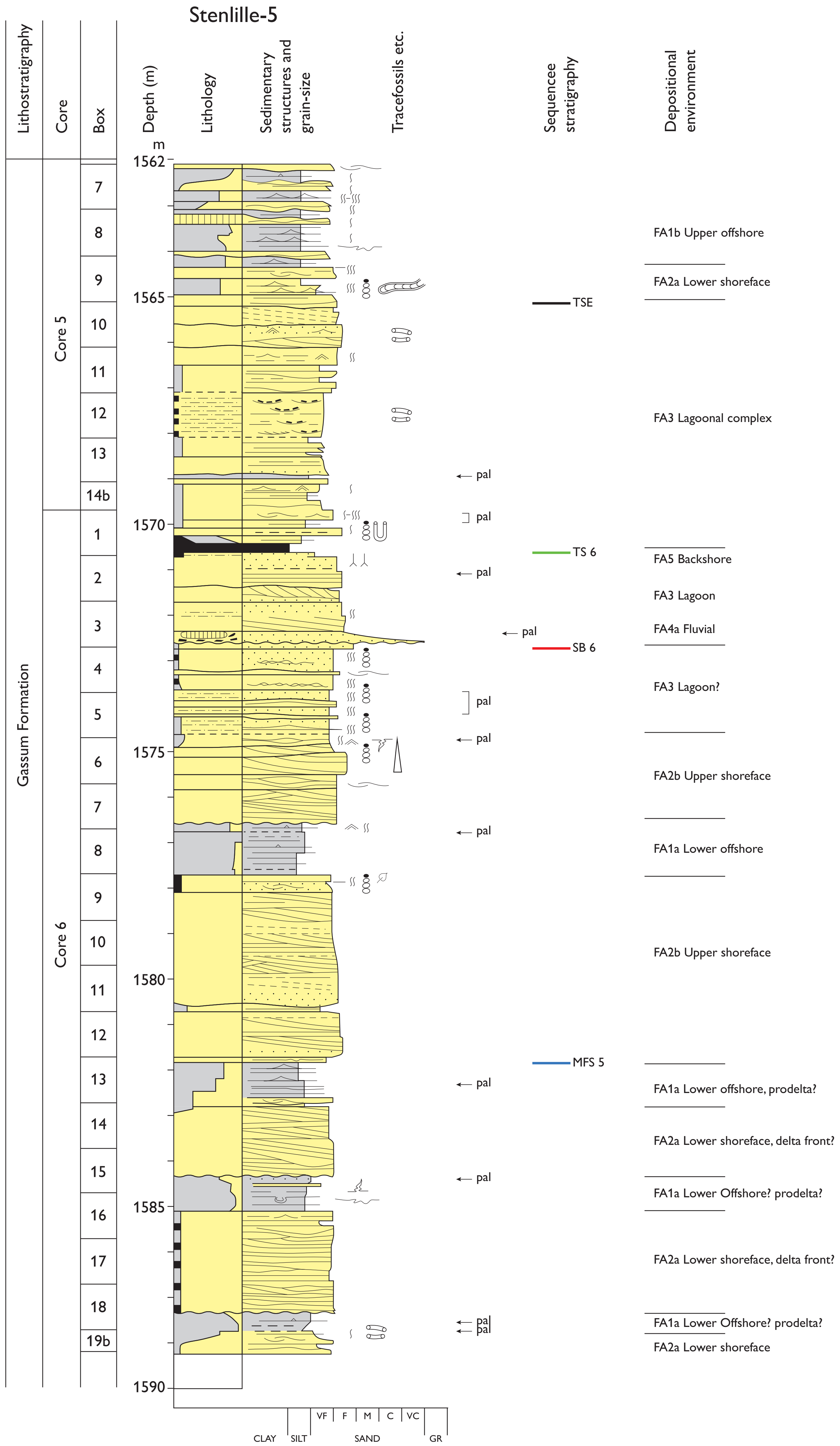
ST-4_cores 2-4_skala 1:100

Stenlille-4

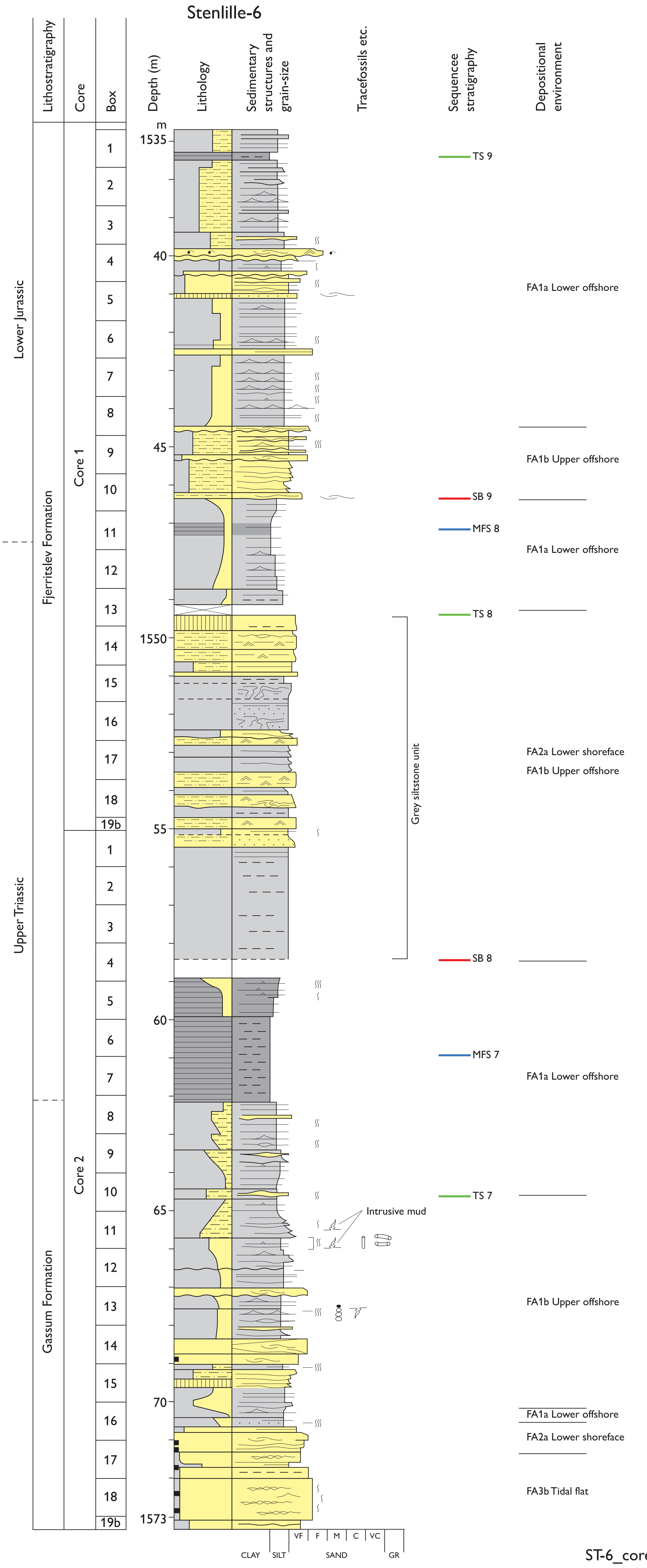


ST-4_cores 4-5_skala 1:100


Stenlille-5
Lithostratigraphy
Core
Box
Depth (m)
Lithology
Sedimentary structures and grain-size
Tracefossils etc.
Sequence stratigraphy
Depositional environment
m
1550
1555
1560
1562
Fjerritslev Fm
Gassum Formation
Core 4
Core 5
13
14
15
16
17
18b
1
2
3
4
5
6
pal
pal
pal
pal
MFS 7
TS 7
SB 7
MFS 6
FA2a Lower shoreface
FA1a Lower offshore
FA2a, b Shoreface
FA1b Upper offshore
FA2b Upper shoreface
FA1b Upper offshore
FA1a Lower offshore
FA1b Upper offshore
CLAY
SILT
VF
F
M
C
VC
SAND
GR

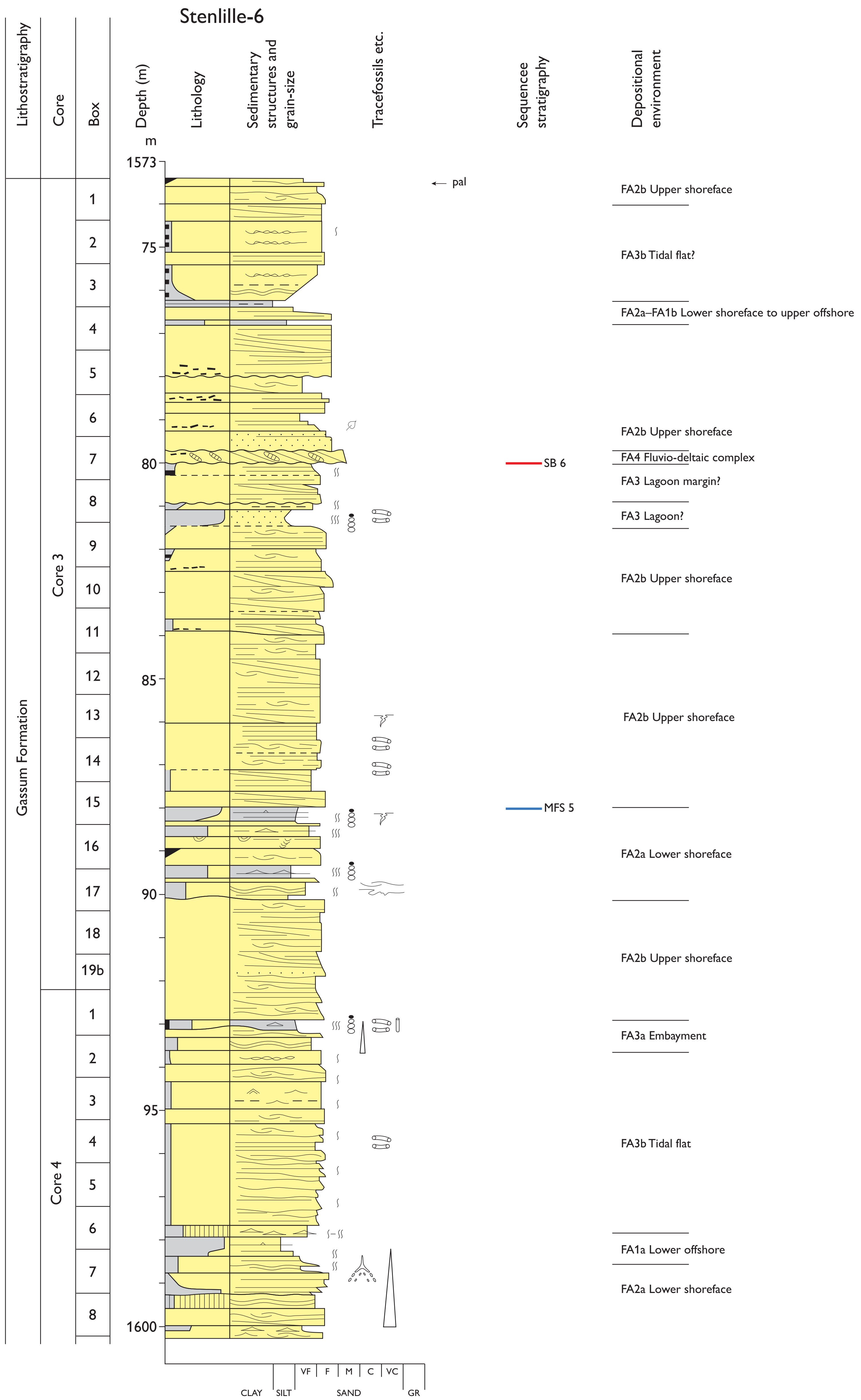


Stenlille-5
Lithostratigraphy
Core
Box
Depth (m)
Lithology
Sedimentary structures and grain-size
Tracefossils etc.
Sequencee stratigraphy
Depositional environment
m
1562
1565
1570
1575
1580
1585
1590
Gassum Formation
Core 5
Core 6
7
8
9
10
11
12
13
14b
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19b
pal
TSE
TS 6
SB 6
MFS 5
FA1b Upper offshore
FA2a Lower shoreface
FA3 Lagoonal complex
FA5 Backshore
FA3 Lagoon
FA4a Fluvial
FA3 Lagoon?
FA2b Upper shoreface
FA1a Lower offshore
FA2b Upper shoreface
FA1a Lower offshore, prodelta?
FA2a Lower shoreface, delta front?
FA1a Lower Offshore? prodelta?
FA2a Lower shoreface, delta front?
FA1a Lower Offshore? prodelta?
FA2a Lower shoreface
CLAY
SILT
VF
F
M
C
VC
SAND
GR



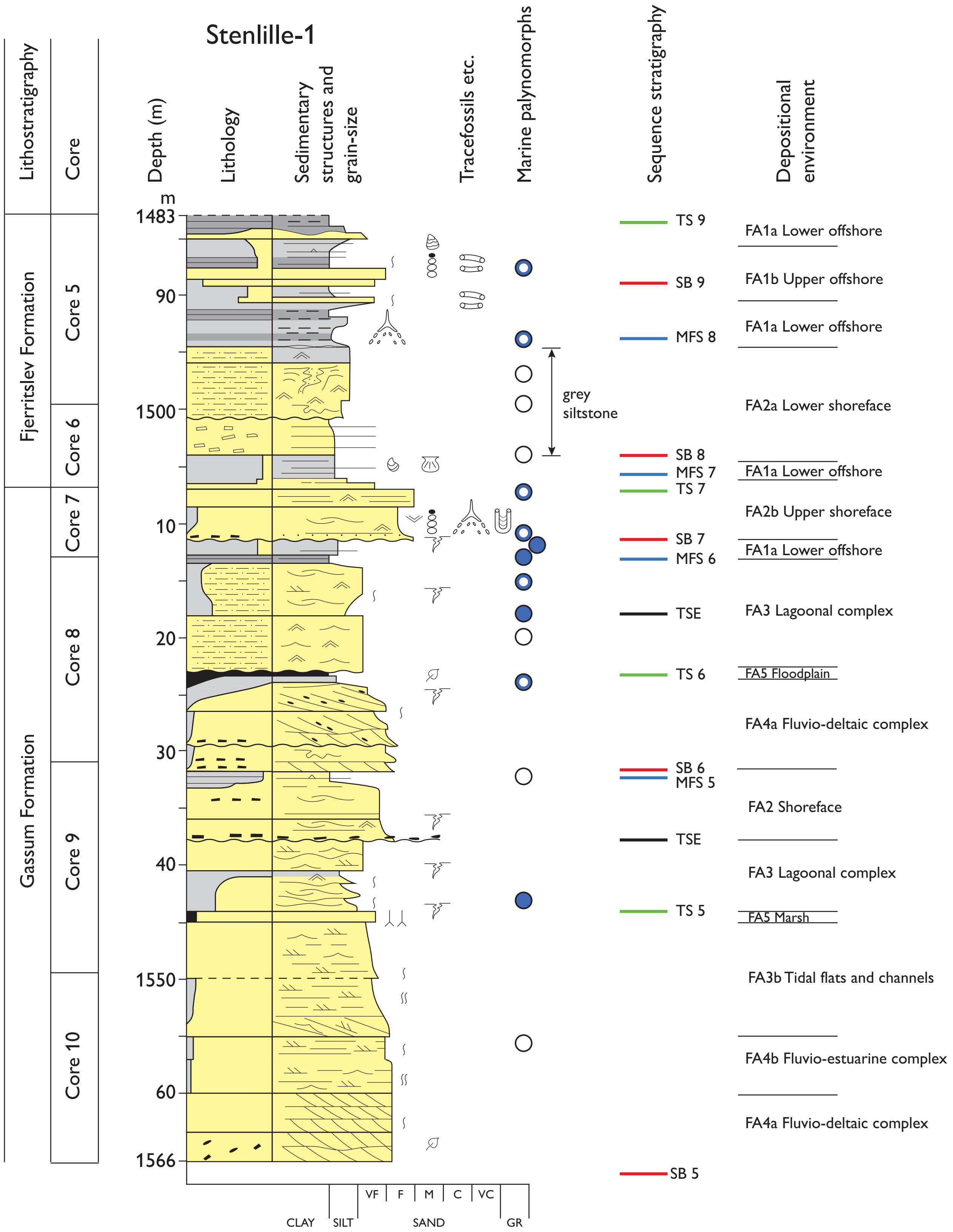
ST-6_cores 1-2_skala 1:100

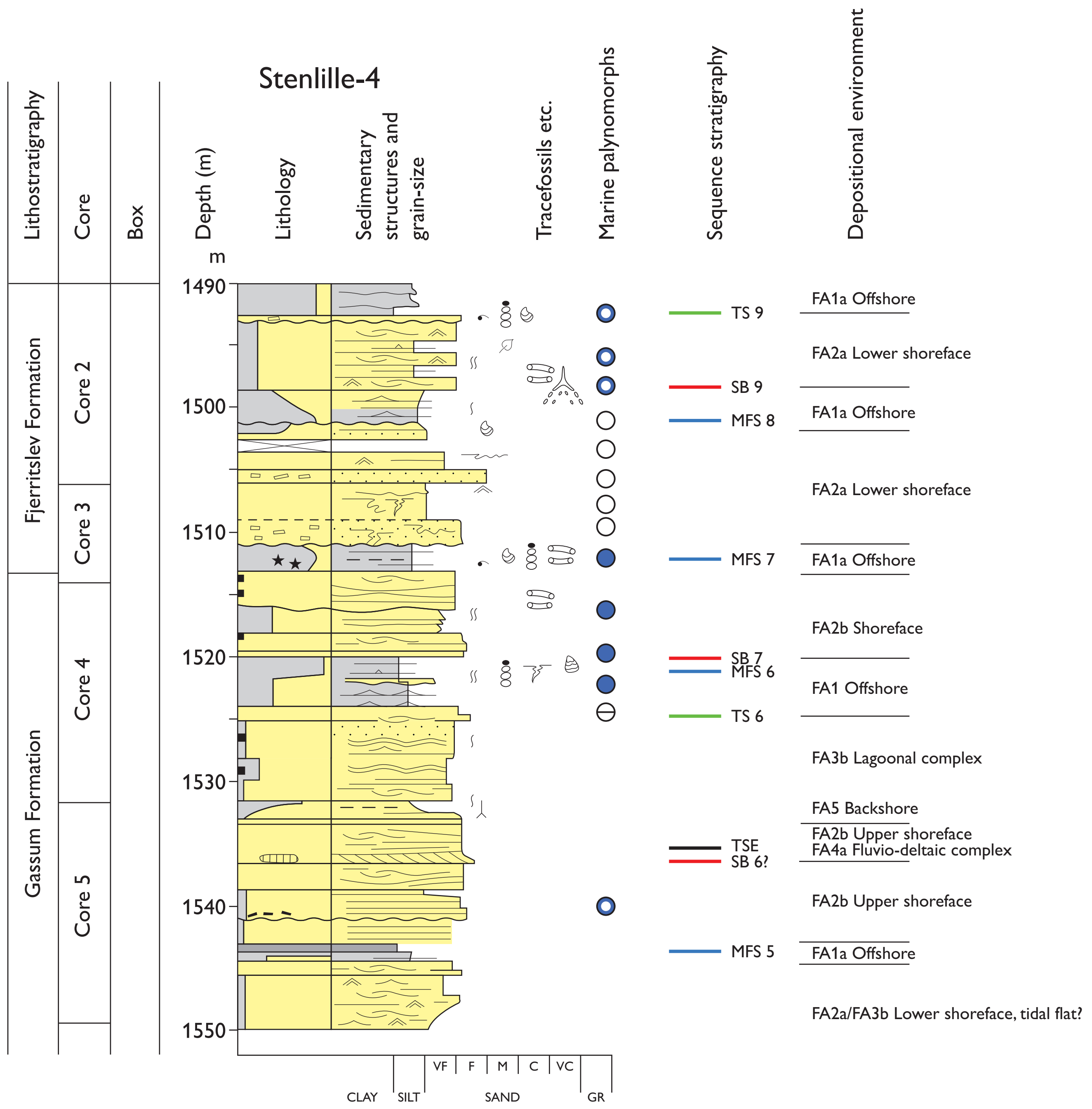
Stenlille-6



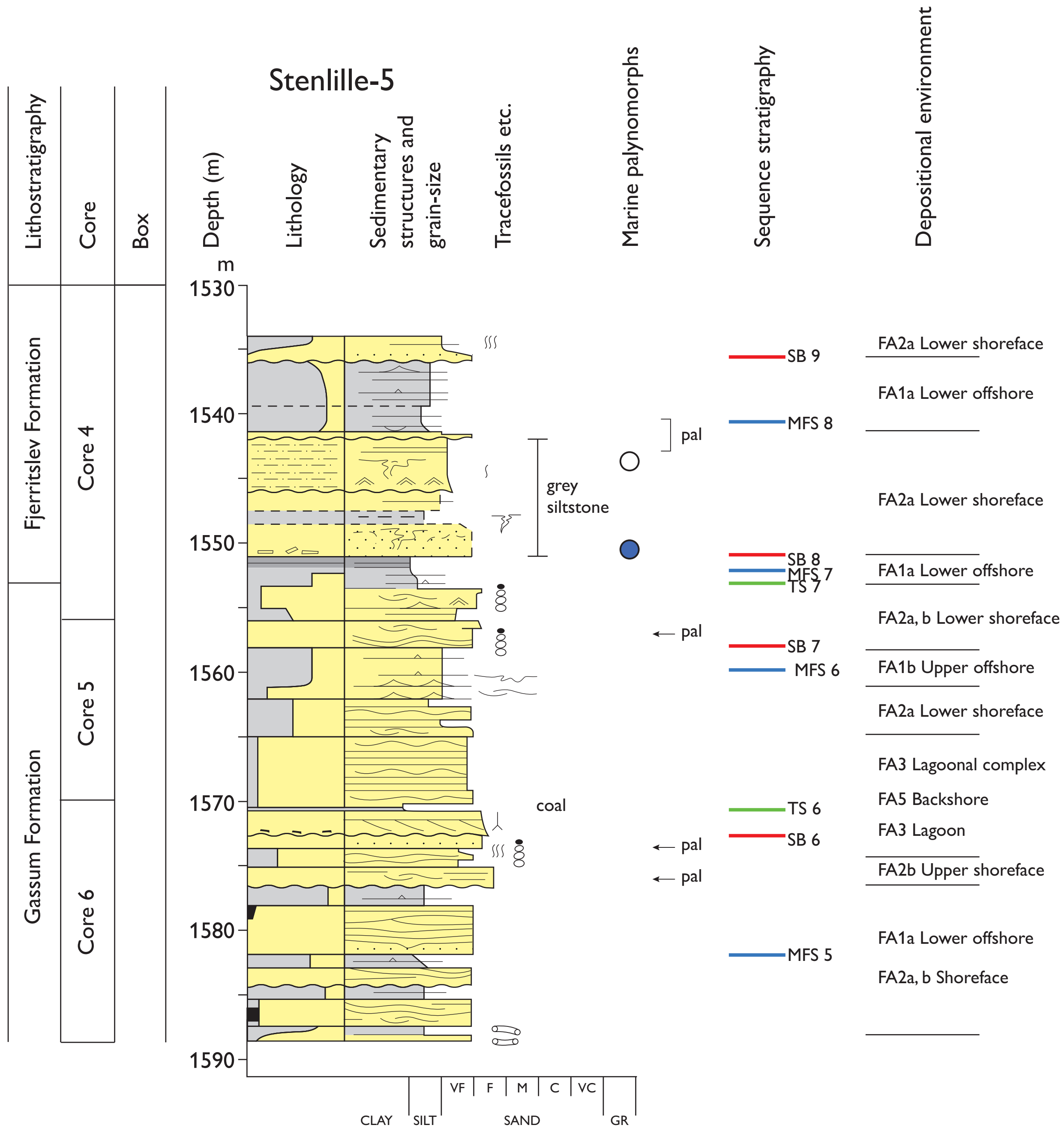
ST-6_cores 3-4_skala 1:100

Sedimentological logs 1:500

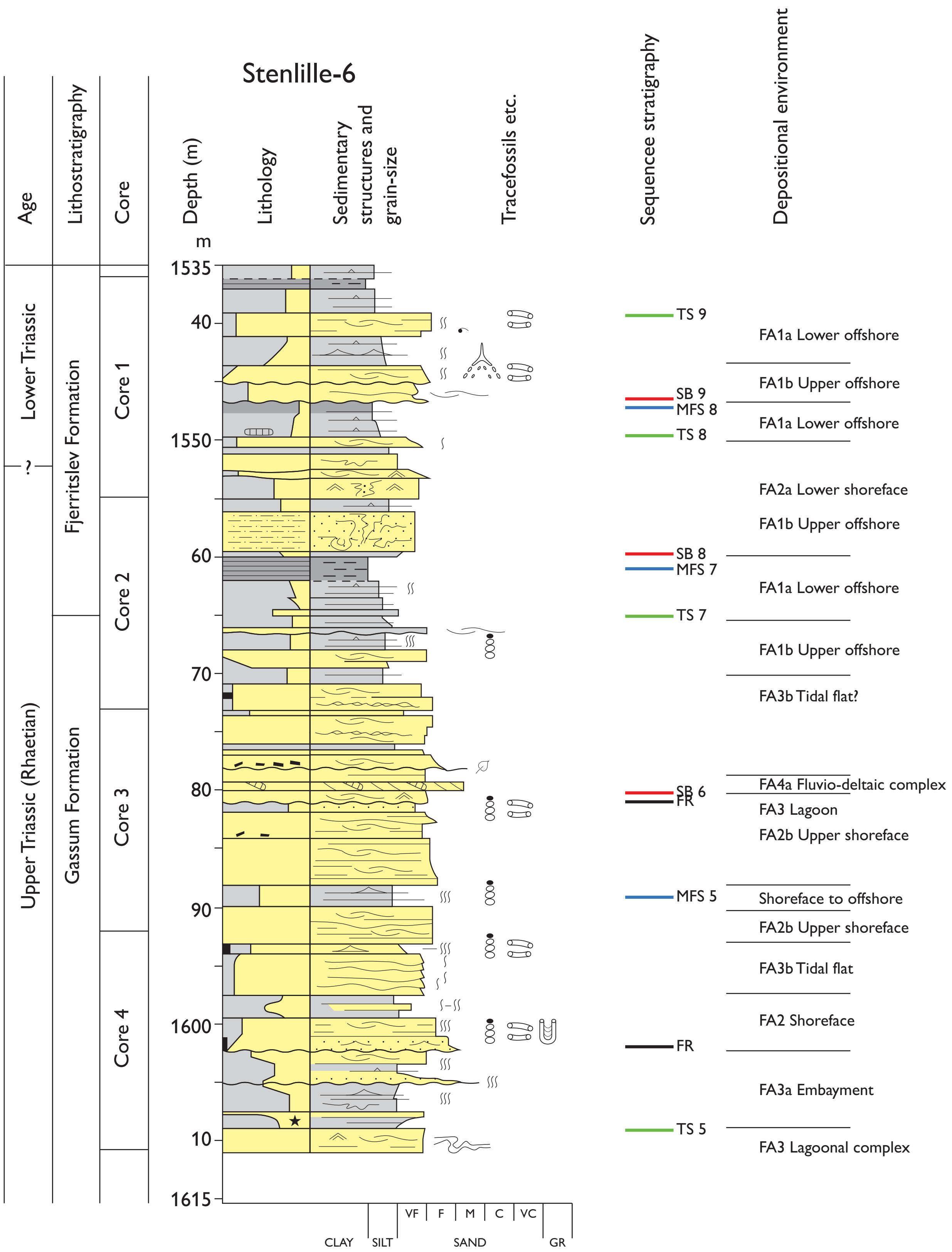

Stenlille-1
Lithostratigraphy
Core
Depth (m)
Lithology
Sedimentary structures and grain-size
Tracefossils etc.
Marine palynomorphs
Sequence stratigraphy
Depositional environment
Fjerritslev Formation
Gassum Formation
Core 5
Core 6
Core 7
Core 8
Core 9
Core 10
m
1483
90
1500
10
20
30
40
1550
60
1566
CLAY
SILT
VF
F
M
C
VC
SAND
GR
grey siltstone
TS 9
SB 9
MFS 8
SB 8
MFS 7
TS 7
SB 7
MFS 6
TSE
TS 6
SB 6
MFS 5
TSE
TS 5
SB 5
FA1a Lower offshore
FA1b Upper offshore
FA1a Lower offshore
FA2a Lower shoreface
FA1a Lower offshore
FA2b Upper shoreface
FA1a Lower offshore
FA3 Lagoonal complex
FA5 Floodplain
FA4a Fluvio-deltaic complex
FA2 Shoreface
FA3 Lagoonal complex
FA5 Marsh
FA3b Tidal flats and channels
FA4b Fluvio-estuarine complex
FA4a Fluvio-deltaic complex



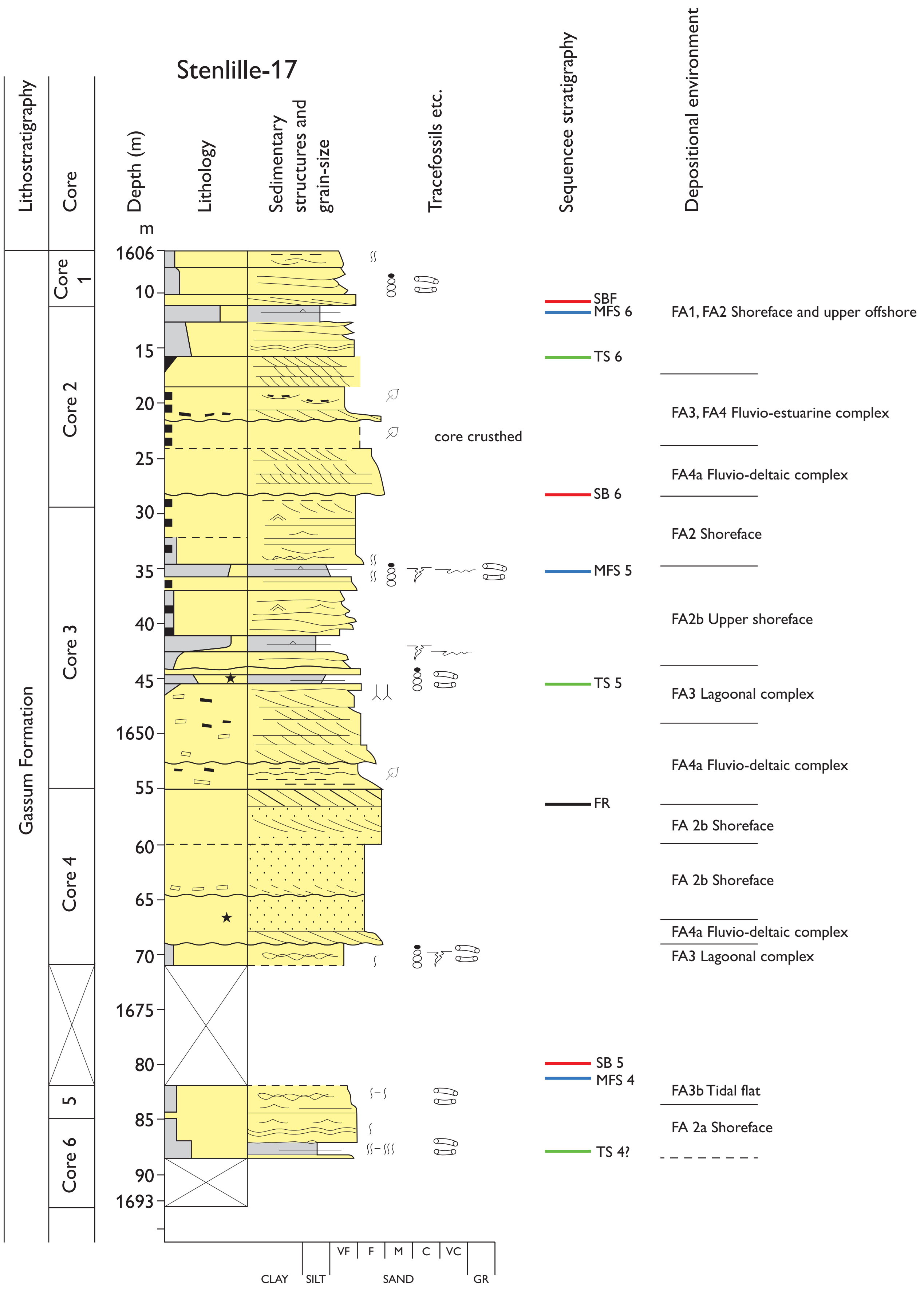
ST-4_cores 2-5_skala 1:500



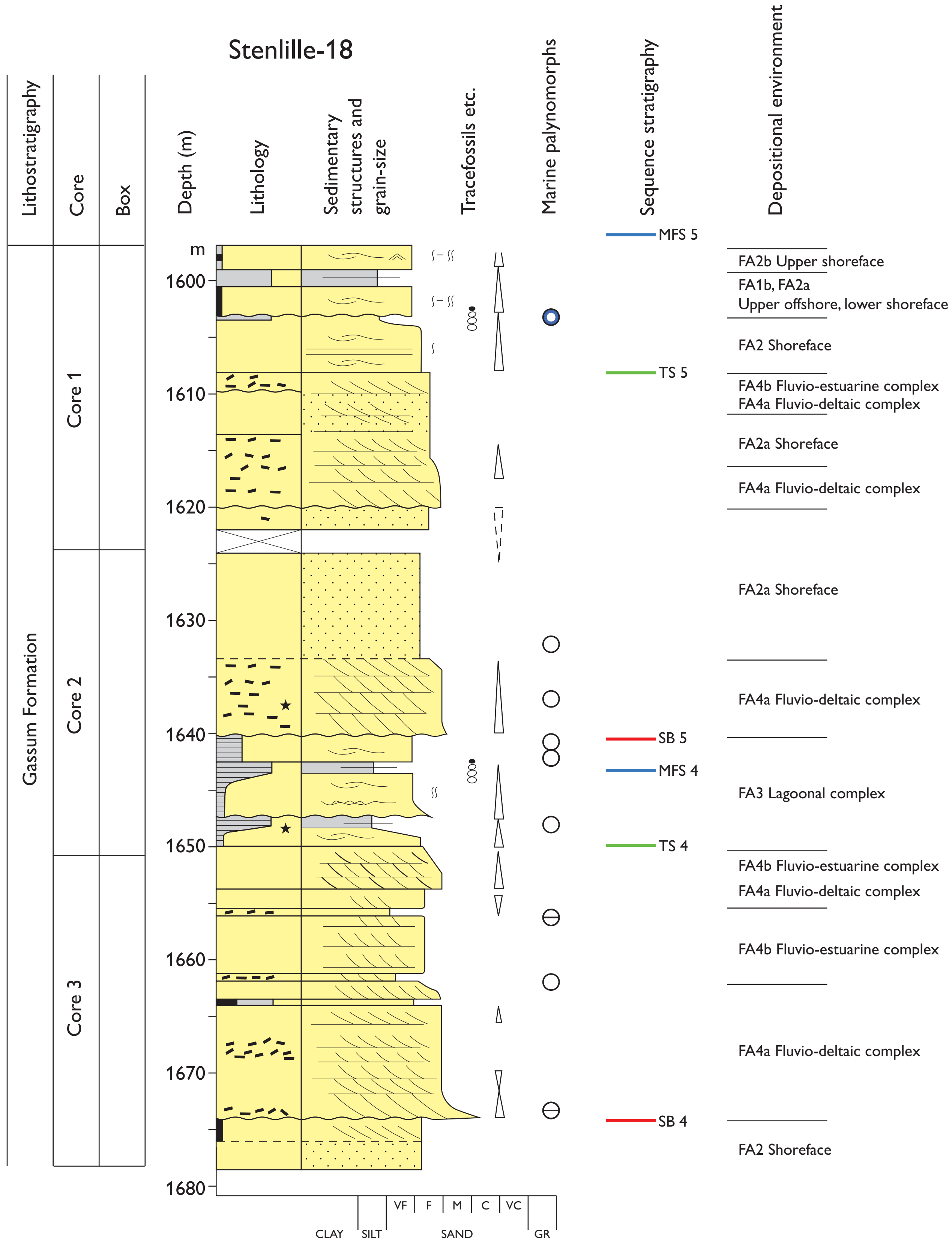
ST-5_cores 4-6_skala 1:500



ST-6_cores 1-4_skala 1:500



ST-17_cores 1-6_skala 1:500



ST-18_cores 1-3_skala 1:500

Danish Ministry of Climate,
Energy and Utilities

Geological survey of
Denmark and Greenland (GEUS)

Øster Voldgade 10
DK-1350 Copenhagen K
Denmark

GEUS is a research and advisory
institution in the Danish Ministry
of Climate, Energy and Utilities