DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE **RAPPORT 2020/36**

Capture, Storage and Use of CO_2 (CCUS)

Palynology of the Gassum and lowermost Fjerritslev formations in the Stenlille area: biostratigraphic and palaeoenvironmental implications
(Part of Work package 5 in the CCUS project)

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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 a palynological investigation of the depositional environment of the Gassum Formation and the lowermost part of the Fjerritslev Formation of the Stenlille structure within a sequence stratigraphic framework.

Content

Dansk sammendrag

Palynologi er studiet af organiske syre-resistente mikrofossiler, der omfatter bland andet: sporer og pollen fra landplanter, ferskvandsmikroalger fra søer og floder, og marine fytoplankton (dinoflagellater og akritarker) fra hav. Foruden disse fossile grupper indeholder en palynologisk prøve oftest også vedrester, kulpartikler, planterester og amorft materiale. En prøve der stammer fra landområder vil typisk ikke indeholde marine fytoplankton, mens en prøve af materiale dannet til havs kan indeholde både marine mikroalger, og afhængig af hvor langt fra land den er dannet, forskellige mængder af sporer og pollen og ferskvandsalger.

Der er her udført en palynologisk undersøgelse af cuttings (cu; borespåner), sidevægskerner (swc) og kerneprøver (co) fra syv brønde på tværs af Stenlille-strukturen, med det formål at tolke variationer i aflejringsmiljø over intervallet fra bund Gassum Formationen til den nedre del af Fjerritslev Formationen. Undersøgelsen er et bidrag til etablering af en reservoirmodel for Gassum formationen i den nærliggende Havnsø struktur. Kerneprøver anses for at være de mest pålidelige idet dybde of sedimentær facies kendes præcist, mens prøver af borespåner ofte vil indeholde en del spåner fra overliggende lag. Resultaterne vises på et sydvest–nordøst orienteret logpanel og indenfor det sekvens stratigrafiske rammeværk præsenteret i Vosgerau et al. (2020) og Hovikoski & Pedersen (2020).

Cuttingsprøver fra Vinding formationen under basis af Gassum Formationen i Stenlille-4 i sydvest og Stenlille-6 i nordøst indikerer, at sedimenterne herfra blev dannet i kystnære områder. Kun en enkelt cu-prøve (Stenlille-15) er analyseret fra intervallet fra basis af Gassum Formationen til sekvensgrænsen SB2 og denne indikerer ligeledes aflejring i et kystnært miljø. Ingen prøver er analyseret fra Sekvens 2.

Inden for Sekvens 3 skiftede aflejringsmiljøet i sydvest mellem kystnært, grundmarint, terrestriskt og kystnært, i følge cuttingsprøver fra Stenlille-15. Kystnær sedimentation kan også påvises i den øvre del af sekvensen i Stenlille-4. I nordøst synes kystnære til grundmarine forhold at være udviklet, baseret på analyser af cu-prøver fra Stenlille-6. Her kan prøverne dog muligvis være forurenet af, at yngre materiale er faldet ned i borehullet under boringen.

Længst mod sydvest (repræsenteret ved Stenlille-15) synes sedimenterne at være dannet på land og i kystnære miljøer under Sekvens 4. Kystnære sedimentation er også påvist i Stenlille-4. I Stenlille-18 svinger miljøet også mellem at være kystnært og land, men i Stenlille-1 og længst i nordøst i Stenlille-6 ses skift mellem kystnære og lavmarine miljøer.

Inden for Sekvens 5 udvikledes fuldt marine forhold omkring TS5 i sydvest, i følge prøver fra Stenlille-15, men i Stenlille-4 var forholdene mere grundmarine. I Stenlille-18 og Stenlille-1 synes der at have været grundmarin til kystnære aflejringsmiljøer, medens der primært var et kystnære miljø i nordøst.

I den nedre del af Sekvens 6 var der kystnære aflejringsforhold i sydvest (Stenlille-4), mens prøver fra den øvre del af sekvensen viser fuldt marine forhold. De fuldt marine forhold er også påvist i cuttingsprøver fra den øvre del af Sekvens 6 i Stenlille-15. Et lignende skift fra grundmarine til fuldt marine forhold ses op gennem Sekvens 6 i Stenlille-1.

Prøver fra den nedre del af Sekvens 7 viser, at der rådede fuldt marine forhold i Stenlille-området. Det er kun i en enkelt prøve fra toppen af Gassum Formationen i Stenlille-2, at der ses indikationer på et kystnært miljø, men også her er der et skift til fuldt marine forhold ved basis af Fjerritslev Formationen. Under aflejringen af den øvre del af sekvensen sker der et havniveau fald og grundmarine forhold synes at råde i området.

Sekvens 8 kan med fordel opdeles i to dele, adskilte af MFS8. Den nedre del svarer til de såkaldte ”event beds” for den slut-Triassiske masseuddøen (Lindström et al. 2012, 2015). Dette interval er tolket som dannet i et lavmarint miljø men med stor tilførsel af sedimenter fra land. Dette kan ses på den store mængede omlejrede palynomorfer i prøver fra både Stenlille-4 og Stenlille-1, der indikerer samtidig øget forvitring og erosion på land. Lige under MFS8 sker en opblomstring af ferskvandsalger, enten på grund af øget tilførsel af ferskvand eller udvikling af lagunemiljøer. I den øvre del, over MFS8, indikerer data fra Stenlille-4, -2, -5, og -1 kystnære til grundmarine forhold og et faldende input af ferskvand opad.

I den øverste del af det undersøgte interval, dvs i den nedre del af Sekvens 9, viser analyser af prøver fra Stenlille-4 kystnære til fuldt marine forhold, medens prøver fra Stenlille-2 og -1 viser en udvikling fra grundmarine til fuldt marine forhold.

Analysen har således frembragt indikationer på den vertikale og laterale fordeling af aflejrings miljøer og bjergartstyper, som anvendes som input til den sekvenstratigrafiske tolkning af Gassum og Fjerritslev formationerne i Stenlille området, som danner udgangspunkt for en model for den nærliggende Havnsø struktur.

Summary

A palynological investigation of core, sidewall core and cuttings samples from seven wells across the Stenlille structure, has been carried out, in order to provide information on the variations in the depositional environment over the stratigraphic interval covering the Gassum to lowermost Fjerritslev formations with the scope of providing input to the reservoir model for the closely located Havnsø structure. The results are displayed on a well transect from southwest to northeast, and divided into sequences following the sequence stratigraphic framework used in Vosgerau et al. (2020) and Hovikoski & Pedersen (2020). The results of the palynological assessment of the depositional environment are summarized below and in Table 1.

Below the base of the Gassum Formation, cuttings samples from Stenlille-4 in the SW, and Stenlille-6 in the NE representing the upper part of the Vinding Formation, both indicate marginal marine conditions in the Stenlille area in accordance with the interpretation of Bertelsen (1978) of the Vinding Fm.

One sample from Stenlille-15 is so far the only sample from the Base Gassum Fm–SB2 interval, and it indicates that marginal marine conditions prevailed in the southwest.

No samples have been analyzed from Sequence 2 so far.

Within Sequence 3 conditions seem to have fluctuated between marginal marine, shallow marine, terrestrial, and marginal marine environment the southwest, as indicated by cuttings samples from Stenlille-15. One sample from the top of the Sequence 3 in Stenlille-4 also indicates marginal marine conditions. In the northeast marginal marine to shallow marine conditions may have prevailed, as indicated by cuttings samples from Stenlille-6, although the data can be disturbed by caving of younger material.

Within Sequence 4, while terrestrial to possibly marginal marine conditions prevailed in Stenlille-15 furthest to the southwest, marginal marine conditions developed in Stenlille-4. In Stenlille-18 conditions also fluctuated between marginal marine and fully terrestrial, while further to the northeast, in Stenlille-1 and -6 marginal marine to shallow marine conditions developed.

In Sequence 5 fully marine conditions had formed around TS5 in the southwest, as indicated by a core sample in Stenlille-15, but in Stenlille-4 shallow marine conditions prevailed. Shallow marine to marginal marine environments developed in Stenlille-18 and -1, while in Stenlille-6 further to the northeast, marginal marine conditions prevailed.

In the lower part of Sequence 6 marginal marine conditions had developed to the southwest (Stenlille-4), but in the upper part fully marine conditions developed. This is corroborated by a cuttings sample from the upper part of Sequence 6 in Stenlille-15, which also suggests fully marine conditions. Similarly, in Stenlille-1 to the northeast, conditions fluctuated between shallow marine and fully marine.

To the southwest, fully marine conditions continued in Sequence 7 in Stenlille-4. Fully marine conditions were also recorded in Stenlille-5 and -1 to the northeast. In Stenlille-2, from the center of the structure, a core sample from the top of the Gassum Fm suggests deposition in a marginal marine environment, but at the base of the Fjerritslev Fm fully marine conditions had developed. A shallowing towards the top of Sequence 7 is registered in Stenlille-2 and -1 towards shallow marine conditions.

In Sequence 8, the interval below MFS8 in Stenlille-4 and -1 represents the end-Triassic event beds; the Grey siltstone interval of Lindström et al. (2012, 2015). This interval is interpreted as having been deposited in a shallow marine environment with high input of siliciclastic material and increased abundances of reworked palynomorphs, signaling ongoing weathering and erosion on land. Just below MFS8 blooms of freshwater algae are recorded signaling either large scale input of freshwater to the basin or a development of lagoonal conditions. Above MFS8 data from Stenlille-4, -2, -5 and -1, indicate marginal marine to shallow marine conditions with high input of freshwater continuing in the northeast, but decreasing up section.

In the lower part of Sequence 9 marginal to fully marine conditions developed in Stenlille-4 in the southwest, while further to the northeast shallow marine to fully marine conditions prevailed in Stenlille-2 and Stenlille-1.

Introduction

In order to better understand variations in depositional environment across the Stenlille structure, through the Gassum to the lower part of the Fjerritslev formations, a palynological investigation has been carried out on core (co), sidewall core (swc) and cuttings (cu) samples from Stenlille wells along a transect from the southwest to the northeast (Fig. 1). The purpose is to provide input to the reservoir model for the closely located Havnsø structure. Palynology is herein not only used for biostratigraphic purposes, i.e. dating of the sedimentary succession, but also for providing environmental data for the sedimentological report (Hovikoski & Pedersen, 2020) and seismic 3D interpretation (Vosgerau et al. 2020).

Quantitative assessments of the palynological assemblages in the studied samples allows assignment to general categories of depositional environment. This is because spores and pollen, and also freshwater algae, represent vegetation on land and in lakes, mires and rivers, while marine dinoflagellate cysts, prasinophytes and acritarchs represent the marine environment. The following distinctions are made:

- ***Fully marine conditions.*** Marine phytoplankton; i.e. dinoflagellate cysts, acritarchs and prasinophytes, are dominant to highly abundant. In general, wind pollinated pollen are more abundant in these samples as they can be transported further from the coast.
- ***Shallow marine conditions.*** Marine phytoplankton are abundant. The spore-pollen flora is often quite varied, depending on proximity to freshwater sources that can transport spores and non-wind dispersed pollen to the basin.
- ***Marginal marine conditions.*** Minor amounts of marine phytoplankton are present. Freshwater algae may be common. Depending on which type of marginal marine environment the assemblage represents, the spore-pollen flora can vary in composition.
- ***Terrestrial conditions.*** Spores and pollen dominate. Freshwater algae can be present depending on the type of terrestrial environment.

For cuttings samples, 200 palynological specimens have been counted per sample. Since cuttings samples are often contaminated by caved material during the drilling operations, estimate of the confirmed caved percentage in each sample is given. For sidewall cores and core samples up to 300 specimens were counted per sample. In some cases, where very few or no palynomorphs were identified in the samples, an assessment of the palynodebris, i.e. black phytoclasts, wood remains, plant tissues, cuticles or amorphous organic matter, have been noted. The overall palynological composition of the samples can be seen in a sequence stratigraphic framework along the transect on Figure 2 and is summarized in Table 1.

Database

The palynological data reported herein are from seven of the Stenlille wells, namely: Stenlille-15, Stenlille-4, Stenlille-18, Stenlille-2, Stenlille-5, Stenlille-1 and Stenlille-6. The detailed results are shown on Figures 3–9. Due to COVID-19 restrictions at GEUS during the spring, summer and autumn of 2020, additional analyses of samples from Stenlille-2, -5, -14, -17, -18, and -19, have been delayed.

Parts of the data reported herein have previously been reported in various publications dealing with the end-Triassic mass extinction event and the Triassic–Jurassic boundary (e.g. Dybkjær 1991; Lindström 2016; Lindström et al. 2012, 2015, 2017, 2019). The detailed palynology of Stenlille-1 and Stenlille-4 across that interval will be published in an upcoming paper (Lindström et al. in prep.).

Results

The results are presented under sequence stratigraphic intervals following Vosgerau et al. (2020). The results for each interval are discussed below in ascending order, and within each interval the data from the wells are presented in the order the wells are located from southwest to northeast along the transect shown on Figs. 1 and 2. The results are furthermore compared and summarized under "Interval comments". In addition, the results for each well are summarized in Table 1. Range charts for each well are displayed on Figs. 3–9.

Below base Gassum Fm

Stenlille-4 (Fig. 4)

A cuttings sample (1662 m) from the uppermost Vinding Formation, below the base of the Gassum Fm, is dominated by terrestrial spores and pollen, with only minor percentages of marine acritarchs and dinoflagellate cysts, 3.5%, that may be *in situ* or caved from Rhaetian beds above. If they are *in situ,* they indicate a marginal marine environment., which is in line with the interpretation that the Vinding Formation comprises shallow and restricted marine deposits (Bertelsen 1978; Nielsen 2003) The presence of *Vallasporites ignacii* and *Enzonalasporites vigens* may indicate an age not younger than the early Rhaetian (Schulz and Heunisch 2005) (Fig. 4). The presence of the acritarch *Celyphus stenlillensis* is noteworthy, as Batten et al. (1994) suggest that it is of marine affinity. The confirmed caved palynomorphs comprise 3% of the total assemblage, but because many of the spore and pollen taxa are long-ranging, the true percentage may be higher.

Stenlille-6 (Fig. 9)

A cuttings sample (1713–1716 m) from the uppermost Vinding Formation, below the base of the Gassum Fm, is dominated by spores and pollen, with minor amounts of marine acritarchs and dinoflagellate cysts, 6.6%, that may be *in situ* or caved from Rhaetian beds above (Fig. 9). Late Early Jurassic and younger (Cretaceous) dinoflagellate cysts are present in the sample, indicating caving from these intervals. The confirmed caved palynomorphs comprise 2.5% of the total assemblage, but because many of the spore and pollen taxa are long-ranging, the true percentage may be much higher. If the marine phytoplankton are *in situ*, this indicates a marginal marine environment, further corroborating the palaeoenvironmental interpretation by Bertelsen (1978).

Interval comments

Cuttings samples from Stenlille-4 in the SW and Stenlille-6 in the NE both indicate marginal marine conditions.

Sequence 1 (in part; Base Gassum Fm–SB2):

Stenlille-15 (Fig. 3)

A cuttings sample from 1675m contains a relatively sparse palynoflora that is dominated by spores and pollen, with minor percentages, 3.5%, of marine acritarchs, predominantly *Celyphus stenlillensis*, a palynomorph suggested to be of marine affinity by Batten et al. (1994). There are no confirmed caved occurrences in this sample (Fig. 3).

Interval comments

The sample from Stenlille-15 is so far the only sample from the Base Gassum Fm–SB2 interval and indicates that marginal marine conditions prevailed in the SW (Fig. 2; Table 1).

Sequence 2 (SB2–SB3):

No samples were analyzed from this interval.

Sequence 3 (SB3–SB4):

Stenlille-15 (Fig. 3)

Seven cuttings samples from 1666m to 1633m were analysed within the SB3–SB4 interval. They are all dominated by spores and pollen. From 1666m to 1642m there is an increase in the abundance of marine dinoflagellate cysts, primarily *Dapcodinium priscum*, but also occurrences of *Rhaetogonyaulax rhaetica* and *Lunnomidinium scaniense α* and *ß*, suggesting deposition in a marginal marine environment with increased marine influence up section (Fig. 3). The assemblage from 1642m contains large amounts of blade shaped wood fragments, plant tissue and tube-like tissue. This sample also contains higher abundances of bisaccate pollen compared to the assemblages below and above, and this together with the large amounts of blade-shaped wood may indicate deposition in a lagoonal to shoreface environment (compare e.g. with Dybkjær et al. 2019), i.e. marginal marine to shallow marine conditions.

The marine influence appears to have ceased in the samples from 1636m and 1633m. In the assemblage from 1636m, *Classopollis* spp. have decreased markedly in abundance. The spore-pollen flora is dominated by *Perinopollenites elatoides,* with common *Aratrisporites* spp. (Fig. 3). The pollen *Perinopollenites elatoides*, was produced by cupressacean conifers that are believed to have grown in forested mires close to the coast (see e.g. Petersen and Lindström 2012; Petersen et al. 2013). Spores assigned to *Aratrisporites* were produced by isoetalean lycopsids (Balme 1995), of which some species were halophytes colonizing broad

tidal flats (Retallack 1975). This may suggest deposition on a coastal plain. Rare occurrences of dinoflagellate cysts may corroborate this interpretation. In the succeeding assemblage from 1633m, no marine palynomorphs were recorded and *Perinopollenites elatoides* dominate, while only minor *Aratrisporites* are recorded. This may suggest deposition in a coastal mire.
The two uppermost cuttings samples from the SB3–SB4 interval again show evidence of marginal marine influence with rare occurrences of marine acritarchs and dinoflagellate cysts. The spore-pollen flora is dominated by *Perinopollenites elatoides.*

Stenlille-4 (Fig. 4)

One cuttings sample from 1629m close to the top of the SB3–SB4 interval is dominated by spores and pollen, with very minor amounts of marine acritarchs and dinoflagellate cysts. Confirmed caved palynomorphs account for 2% of the palynoflora and includes Sinemurian and Cretaceous dinoflagellate cysts (Fig. 4). Hence, there is a possibility that the marine acritarchs are also caved. The sample contains lots of cuticles and wood fragments. The high abundances of *Perinopollenites elatoides*, which may suggest deposition in a flood plain environment (e.g. Dybkjær et al. 2019).

Stenlille-6 (Fig. 9)

Two cuttings samples from 1683–1677m and 1671–1677m are dominated by spores and pollen. Both samples contain marine acritarchs and dinoflagellate cysts. The amount of confirmed caving in the samples are 5.5% and 4.9%, respectively, and includes Sinemurian and Cretaceous palynomorphs (Fig. 9). Except for a specimen tentatively assigned to *Sverdrupiella* sp., the only Rhaetian dinoflagellate cyst present in the samples is *Dapcodinium priscum,* with 2% and 5.9%, respectively. There is a possibility that these are caved. If not, the abundances of marine palynomorphs indicate deposition in marginal marine to shallow marine environments.

Interval comments

In Sequence 3 conditions seem to have fluctuated between marginal marine, shallow marine, terrestrial, and marginal marine environment in Stenlille-15 to the SW. One sample from the top of the interval in Stenlille-4 also indicates marginal marine conditions. In Stenlille-6 to the northeast, marginal marine to shallow marine conditions may have prevailed, although the data can be disturbed by caving of younger material (Fig. 2; Table 1).

Sequence 4 (SB4–SB5):

Stenlille-15 (Fig. 3)

Two core samples were prepared from the SB4–SB5 interval. The lower sample from 1613.64–1613.65m is completely dominated by spores and pollen, and no marine palynomorphs were registered. The spore-pollen flora continues to be dominated by *Perinopollenites elatoides,* and in this sample *Chasmatosporites* spp. are also common (Fig. 3). The depositional environment is interpreted as terrestrial. The succeeding core samples, 1604.27–1604.29m, has not yet been counted, but does contain rare dinoflagellate cysts. This probably indicates a marginal marine environment.

Stenlille-4 (Fig. 4)

A cuttings sample from 1593m is dominated by terrestrial palynomorphs, but contains rare marine dinoflagellate cysts, *Dapcodinium priscum* and *Rhaetogonyaulax rhaetica*, and acritarchs that may be *in situ.* The freshwater alga *Botryococcus braunii* was also registered (Fig. 4). The sample also contains rare caved palynomorphs from the Hettangian and Pliensbachian. The spore-pollen flora is dominated by *Perinopollenites elatoides*, and bisaccate pollen are common. Together, this may indicate a marginal marine environment.

Stenlille-18 (Fig. 5)

Five core samples from the SB4–SB5 interval indicate an environment fluctuating between terrestrial to marginal marine. The lowermost sample (1674.30–1674.60m) is totally dominated by spores and pollen indicating deposition in a terrestrial environment. It also contains a lot of black phytoclasts and black wood remains. The two succeeding samples (1663.5–1663.6m and 1662.4m) were not counted, as these are dominated by wood remains and plant tissue with very few palynomorphs. No marine palynomorphs were observed in these two core samples. In the remaining samples, marine palynomorphs are present but rare, indicating marginal marine environments, except for the assemblage from 1656.65m which only contains spores and pollen, and indicates fully terrestrial deposition. *Ricciisporites tuberculatus* dominates the lowest sample (Fig. 5). In the others, cheirolepid pollen and *Perinopollenites elatoides* are abundant. The upper two samples are dominated by *P. elatoides.*

Stenlille-1 (Fig. 8)

Two sidewall cores were analyzed from the upper part of Sequence 4, and these were both dominated by spores and pollen, with low abundances of marine dinoflagellate cysts and acritarchs. The freshwater alga *Botryococcus braunii* also occurs in low abundances (Fig. 8). The spore pollen flora is dominated by *P. elatoides, R. tuberculatus* and cheirolepidacean pollen. Deposition most likely took place in a marginal marine to shallow marine environment.

Stenlille-6 (Fig. 9)

One cuttings sample from the upper part of the massive sandstone unit in Sequence 4 contains common marine dinoflagellate cysts, primarily *D. priscum*, but also *R. rhaetica.* The spore-pollen flora is dominated by *Perinopollenites elatoides,* with abundant tree fern spores, cheirolepidiacean pollen and *R. tuberculatus. Ovalipollis ovalis* is also common (Fig. 9). Confirmed caving is 2%. If *in situ* the marine phytoplankton indicate marginal to shallow marine conditions.

Interval comments

In Sequence 4 terrestrial conditions prevailed in Stenlille-15 in the SW, and marginal marine conditions developed in Stenlille-4. In Stenlille-18 the conditions fluctuated between marginal marine and fully terrestrial, and in Stenlille-1 marginal marine to shallow marine conditions developed, the latter also in Stenlille-6 to the NE (Fig. 2; Table 1). In general, the massive sandstone in the lower part of Sequence 4 appear to have been deposited in a terrestrial environment.

Sequence 5 (SB5–SB6):

Stenlille-15 (Fig. 3)

One core sample, 1572.21–1572.22m, is dominated by marine dinoflagellate cysts and acritarchs. *Dapcodinium priscum* is the most dominating dinocyst, but the assemblage also contains *Beaumontella? caminuspina*, *Lunnumidinium scaniense ß*, and *Suessia swabiana* (Fig. 3). The spore-pollen flora is dominated by cheirolepidiacean pollen (35%); *Classopollis classoides, C. meyerianus, Corollina (Geopollis) zwolinskai,* and *Granuloperculatipollis rudis* (Fig. 3). Members of the extinct conifer family, Cheirolepidiaceae, are generally considered to have preferred a subtropical to tropical, drier climate (Vakhrameev, 1981, 1991). The cheirolepids were wind-pollinated (Ziaja 2006). At least some members were adapted to coastal habitats (Batten 1974; Abbink 1998). *Perinopollenites elatoides* are common, but not dominant. This suggests deposition in a fully marine environment, off a coast with cheirolepid conifers.

Stenlille-4 (Fig. 4)

Two cuttings samples, from 1572m and 1557m, and one core sample from 1543.5m were analyzed from the SB5–SB6 interval. The samples are dominated by terrestrial palynomorphs, but marine dinoflagellate cysts and acritarchs are common. The most common marine palynomorph in all three samples is *Dapcodinium priscum,* but *Rhaetogonyaulax rhaetica* and *Beaumontella? caminuspina* was also registered. The core sample also contains *Celyphus stenlillensis* (Fig. 4). No freshwater algae were recorded. The spore-pollen flora in the cuttings samples is dominated by cheirolepidacean conifer pollen, and *Perinopollenites elatoides* are also abundant. In the core sample *P. elatoides* dominates over the cheirolepidacean pollen. There are no confirmed caved palynomorphs in the two cuttings samples. The depositional environment is interpreted as shallow marine.

Stenlille-18 (Fig. 5)

Four core samples were analyzed from the SB5–SB6 interval. The three lowest samples are dominated by spores and pollen, with very low abundances of marine acritarchs and dinoflagellate cysts, indicating deposition in marginal marine environments. Cheirolepidacean conifer pollen dominates together with *P. elatoides,* and tree fern spores (*Deltoidospora*) (Fig. 5).

The upper sample contains an assemblage dominated by spores and pollen but with abundant marine phytoplankton, indicating shallow marine conditions. *Dapcodinium priscum* and *Lunnomidinium scaniense α* are abundant. The spore-pollen flora is dominated by *Perinopollenites elatoides* (Fig. 5).

Stenlille-1 (Fig. 8)

Three core samples were analyzed from Sequence 5. The lowest one is similar in composition to the previous two samples from Sequence 4, with low amounts of marine dinoflagellate cysts, and a terrestrial flora dominated by *P. elatoides, R. tuberculatus* and cheirolepidiacean pollen, indicating deposition in a marginal marine environment. However, no freshwater algae were recorded in this sample. The middle sample is dominated in equal parts of spores and pollen, and marine dinoflagellate cysts. *Dapcodinium priscum* dominates the marine phytoplankton, but *Lunnomidinium scaniense α, Beaumontella? caminuspina* and *Suessia swabiana* were also recorded (Fig. 8). The spore-pollen flora is dominated by cheirolepidiacean conifer pollen. The depositional environment is interpreted as fully marine. In the upper sample the influence of marine dinoflagellate cysts and acritarchs have decreased. *Dapcodinium priscum* is common, together with low amounts of the freshwater alga *B. braunii*. *Perinopollenites elatoides* and *R. tuberculatus* dominate the spore-pollen flora (Fig. 8). The depositional environment is interpreted as marginal marine to shallow marine.

Stenlille-6 (Fig. 9)

One cuttings sample from the lowermost part of Sequence 5 contains common marine acritarchs and a few specimens of *D. priscum.* Confirmed caving is 2.5%. The spore-pollen flora is dominated by tree fern spores and bisaccate pollen, with common cheirolepidiacean pollen and *P. elatoides* (Fig. 9). If the marine phytoplankton are *in situ* this indicates marginal marine conditions.

Interval comments

In Sequence 5 fully marine conditions appear to have developed around TS5 in Stenlille-15 in the SW, while shallow marine conditions prevailed in Stenlille-4, with shallow marine to marginal marine in Stenlille-18 and -1, and marginal marine conditions in Stenlille-6 to the NE (Fig. 2; Table 1).

Sequence 6 (SB6–SB7):

Stenlille-15 (Fig. 3)

One core sample, 1535.67–1535.69m, has only been partially counted, as it contains large amounts of thinwalled, fragmented and folded laevigate palynomorphs of unknown affinity, and is therefore a very difficult sample to analyze. Further preparation may resolve this issue.

Stenlille-4 (Fig. 4)

Fifteen core samples are included in this interval (Fig. 4). The lowermost sample from 1525.8m differ markedly from the rest of the samples above. It is totally dominated by terrestrial palynomorphs, with only rare occurrences of marine palynomorphs, including the dinocysts *Lunnomidinium scaniense ß* and *B?. caminuspina,* the acritarch *C. stenlillensis* and the prasinophyte *Cymatiosphaera polypartita* (Fig. 4). *Perinopollenites elatoides* dominates the spore-pollen flora. The depositional environment is interpreted as marginal marine.
The remaining fourteen samples, from 1523.79m to 1517.24m, show somewhat fluctuating variations in composition, but always with a high abundance or dominance of marine palynomorphs, with *D. priscum* being dominant. The spore-pollen flora is generally dominated by cheirolepid conifer pollen, with abundant *P. elatoides* and common *Ricciisporites tuberculatus* (Lindström 2016; Lindström et al. 2015, 2017). The depositional environment is interpreted as fully marine.

Stenlille-1 (Fig. 8)

In Sequence 6, samples were analyzed from the middle to the upper part. In general, conditions fluctuate between shallow marine to fully marine in the more finegrained parts of the core. A shallowing upwards into a sandstone at 1522–1518m is accompanied by a decrease in abundance of marine phytoplankton, but at the top of the sandstone this pattern appears to reverse into shallow marine conditions. This is succeeded by fully marine conditions were marine dinoflagellate cysts dominates the assemblages. *Dapcodinium priscum* is the dominant marine phytoplankton, but many other dinocysts are also registered within Sequence 6 (Fig. 8). Freshwater algae were also recorded in low amounts. In the sandstone at 1522–1518m the spore-pollen flora is dominated by *P. elatoides* and *R. tuberculatus*, but otherwise cheirolepidiacean conifer pollen and *P. elatoides* dominates. The depositional environment is interpreted as fluctuating between shallow marine and fully marine conditions.

Interval comments

In the southwest, marginal marine conditions had developed in the lower part of Sequence 6 in Stenlille-4, but in the upper part fully marine conditions developed. This is corroborated by a cuttings sample from the upper part of Sequence 6 in Stenlille-15, which also suggests that fully marine conditions prevailed. Similarly, in Stenlille-1 to the NE, conditions fluctuated between shallow marine and fully marine (Fig. 2; Table 1).

Sequence 7 (SB7–SB8):

Stenlille-4 (Fig. 4)

Thirteen core samples from this interval show that deposition took place in a predominantly fully marine environment, with high abundances to dominance of marine palynomorphs, primarily *D. priscum. Rhaetogonyaulax rhaetica* was also recorded in high abundances around 1513m (Fig. 4). In the spore-pollen flora there is a decreasing trend in the abundance of cheirolepid pollen, and *P. elatoides* and *R. tuberculatus* are still abundant (Lindström 2016; Lindström et al. 2015, 2017). The depositional environment is interpreted as fully marine.

Stenlille-2 (Fig. 6)

Data from Dybkjær (1991) show a marked change from marginal marine deposition with only minor marine acritarchs and dinoflagellate cysts at the top of the Gassum Fm, to fully marine to shallow marine in the lowermost part of the Fjerritslev Fm (Fig. 6).

Stenlille-5 (Fig. 7)

One core sample from the SB7–SB8 interval is dominated by marine dinoflagellate cysts, primarily *Rhaetogonyaulax rhaetica*, signaling fully marine conditions. The spore-pollen flora is dominated by *Ricciisporites tuberculatus* with abundant *Deltoidospora* (Fig. 7).

Stenlille-1 (Fig. 8)

In Sequence 7 conditions are fully marine in Stenlille-1, but with an upwards declining trend in marine phytoplankton abundance from MFS7 to the top of the interval where shallow marine conditions prevail. *Dapcodinium priscum* is generally the most dominant phytoplankton, but around MFS7 *Rhaetogonyaulax rhaetica* and acritarchs also become abundant. The spore-pollen flora is dominated by *P. elatoides* and cheirolepidiacean pollen, with sporadic peaks in *Ricciisporites tuberculatus* (Fig. 8). First cheirolepidiacean pollen and then *P. elatoides* decrease in abundance up section in the upper part of the interval (Lindström et al. 2012; Lindström, 2016). The depositional environment is interpreted as fully marine to shallow marine.

Interval comments

In Sequence 7 fully marine conditions had developed in Stenlille-4 in the SW, as well as in Stenlille-5 and -1 in the NE, while in Stenlille-2 a core sample from the top of the Gassum Fm suggests marginal marine conditions, while the base of the Fjerritslev Fm is fully marine. There appears to be a shallowing towards the top of Sequence 7, where shallow marine conditions had developed in Stenlille-2 and -1.

Sequence 8 (SB8–SB9):

Stenlille-4 (Fig. 4)

This interval can be divided into two different parts; below and above MFS8. The interval below MFS8 represents the end-Triassic mass extinction interval. The assemblages are characterized by low amounts of marine palynomorphs, mainly acritarchs and sparse occurrences of *D. priscum* and *R. rhaetica.* The spore-pollen flora is dominated by ground fern and tree fern spores, while, apart from *R. tuberculatus*, pollen grains are much less abundant (Fig. 4). The interpretation is that this interval was deposited in shallow marine environment, while the vegetation on land point to deforestation and dominance of pioneering vegetation of ferns and fern allies (van de Schootbrugge et al. 2009). The amount of reworking of material from Ordovician–Silurian, Carboniferous and Middle Triassic is significant, signaling increased weathering and erosion (e.g. Lindström et al. 2012; van de Schootbrugge et al. 2020). The interval is easily recognized palynologically all over the Danish Basin.
The interval above MFS8 again contains abundant dinoflagellate cysts and acritarchs, indicating at least a shallow marine environment. Here, it needs to be noted that several typical Triassic dinoflagellate cysts went extinct during the end-Triassic mass extinction, hence, the marine signal may partially reflect lack of marine phytoplankton after the crisis. In the spore-pollen flora fern spores and *Perinopollenites elatoides* dominate, probably reflecting mires developing along the coast. This is preceded by a brief bloom of freshwater algae, primarily *Botryococcus braunii,* probably reflecting increased runoff of freshwater (Fig. 4).

Stenlille-2 (Fig. 6)

Two core samples (data from Dybkjær 1991) from the uppermost part of this interval contain low amounts of marine acritarchs and dinoflagellate cysts. The samples are dominated by spores and pollen, primarily *Deltoidospora,* but *P. elatoides* and in the upper sample also *P. minimus* are abundant (Fig. 6). The low amounts of marine phytoplankton may indicate marginal marine environments, or possibly a shallow marine environment lacking phytoplankton in the aftermath of the end-Triassic crisis.

Stenlille-5 (Fig. 7)

A core sample from the middle part of the interval is dominated by *Deltoidospora* spp. and *Polypodiisporites polymicroforatus* spores, and *R. tuberculatus* pollen, and represents the pioneering flora of the mass extinction interval (Fig. 7). Low amounts of marine dinoflagellate cysts and acritarchs are present indicating a marginal marine or possibly shallow marine environment following the same argument as above.

Stenlille-1 (Fig. 8)

As in Stenlille-4, Sequence 8 in Stenlille-1 can be divided into two different parts; below and above MFS8. The interval below MFS8 represents the end-Triassic mass extinction interval. There, marine phytoplankton only occur in low abundances. Ground fern and tree fern spores dominate the spore-pollen flora together with *R. tuberculatus*, reflecting pioneering vegetation on land (van de Schootbrugge et al. 2009) (Fig. 8). The amount of reworking of material from Ordovician–Silurian, Carboniferous and Middle Triassic is significant, signaling increased weathering and erosion (Lindström et al. 2012; van de Schootbrugge et al. 2020). This interval represents the end-Triassic mass extinction (Lindström et al. 2017). The interpretation is that this interval was deposited in shallow marine environment (Lindström et al. 2012, 2015). A brief bloom of *Botryococcus braunii* is registered just below MFS8, followed by a brief bloom of another freshwater alga *Lecaniella* (Fig. 8).
In the interval above MFS8 marine dinoflagellate cysts, predominantly *D. priscum,* again become common to abundant, but freshwater algae continue to be common is some samples but decrease in abundance up section (Fig. 8). Spores and pollen dominate the assemblages, primarily *P. elatoides* and tree fern spores (*Deltoidospora*). Towards the top of the interval *P. minimus* becomes abundant (Fig. 4). The depositional environment is interpreted as marginal marine to shallow marine with high input of freshwater.

Interval comments

The interval below MFS8 in Stenlille-4 and -1 represents the end-Triassic mass extinction event beds, the Grey siltstone interval of Lindström et al. (2012, 2015). This interval is interpreted as having been deposited in a shallow marine environment with high input of siliciclastic material and increased abundances of reworked palynomorphs, signaling ongoing weathering and erosion on land. Below MFS8 blooms of freshwater algae occurred. Above MFS8 data from Stenlille-4, -2, -5 and -1, indicate marginal marine to shallow marine conditions with high input of freshwater in the northeast.

Sequence 9 (in part; Above SB9 to top of core):

Stenlille-4 (Fig. 4)

The interval above SB9 (to 1490.42m) is interpreted to have been deposited in shallow marine to marine conditions, similar to the interval between MFS8 and SB9. The spore-pollen flora remains dominated by fern spores and *P. elatoides,* but the pinacean conifer pollen *Pinuspollenites minimus* also becomes abundant (Fig. 4).

Stenlille-2 (Fig. 6)

Data from eight core samples, originally reported by Dybkjær (1991), indicate deposition in a shallow marine environment, however, while dinoflagellate cysts are usually rare, acritarchs may be abundant. The spore-pollen flora continues to be dominated by *Deltoidopora* and *Pinuspollenites minimus* (Fig. 6).

Stenlille-1 (Fig. 8)

In the interval from SB9 to top of the core, abundant marine dinoflagellate cysts and acritarchs indicate fully marine to shallow marine conditions. *Dapcodinium priscum* is the most dominant phytoplankton, and the typical Triassic dinocysts have disappeared. The influence of freshwater appears to have ceased. The spore-pollen flora is dominated by tree fern spores, *P. elatoides,* and *Pinuspollenites minimus* (Fig. 8).

Interval comments

In the lower part of Sequence 9 marginal to fully marine conditions developed in Stenlille-4 in the southwest, while further to the northeast shallow marine to fully marine conditions prevailed in Stenlille-2 and Stenlille-1.

Suggestion for further work on the palynology of the Gassum and lowermost Fjerritslev formations in the Stenlille area

Unfortunately COVID restrictions have delayed the preparation of palynological material, and therefore also the palynological analyses. Additional material that remains to be studied include core material from the Gassum Formation in Stenlille-2, -14, -15, -17, and -19, which will increase our understanding of how the depositional environment changed through time. In addition, a more high-resolution subdivision of the existing palynostratigraphic zonation is expected, with particular focus on the middle and lower parts of the Gassum Formation. A refined palynological zonation encompassing the upper parts of Gassum Formation and the lower parts of the Fjerritslev Formation was introduced by Lindström (2016). The upper part of the Gassum Formation in Stenlille-1 and -4 was assigned to the *Granuloperculatipollis–Classopollis–Perinopollenites* (GCP) Zone. The preliminary data of this study (as indicated by the CONISS analysis on the range charts, see Figs. 3–9), suggest that palynological assemblages from the middle and lower part of the Gassum Formation can be separated biostratigraphically from the GCP Zone, and most likely subdivided into two different subzones. Further work is needed to confirm this. Traditionally, palynological sampling tends to be carried out on more fine-grained sediments, e.g. shales and siltstones, as these generally contain high abundances of palynomorphs per gram of rock. Here, we have targeted more coarse-grained units with reservoir potential, to explore the potential for discriminating between various sand-generating depositional environments, and the preliminary results are promising. Future, more high resolution, sampling of cores encompassing the reservoir units across the Stenlille structure will allow for a more detailed depositional model to be constructed, which in combination with a refined palynostratigraphical framework for the entire Gassum Formation will be important for correlation of the different sequence stratigraphic surfaces and units, and will be essential for steering future drilling operations in the area including the potential CO_2 storage site of Havnsø.

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Figures and table

Figure 1

The Stenlille structure outlined by closed depth (below sea level) contours. The figure is provided by DONG and reused from a report by Larsen. The stippled line shows the transect, along the wells Stenlille-15, -4, -18, -2, -5, -1, and -6, from southwest to northeast .

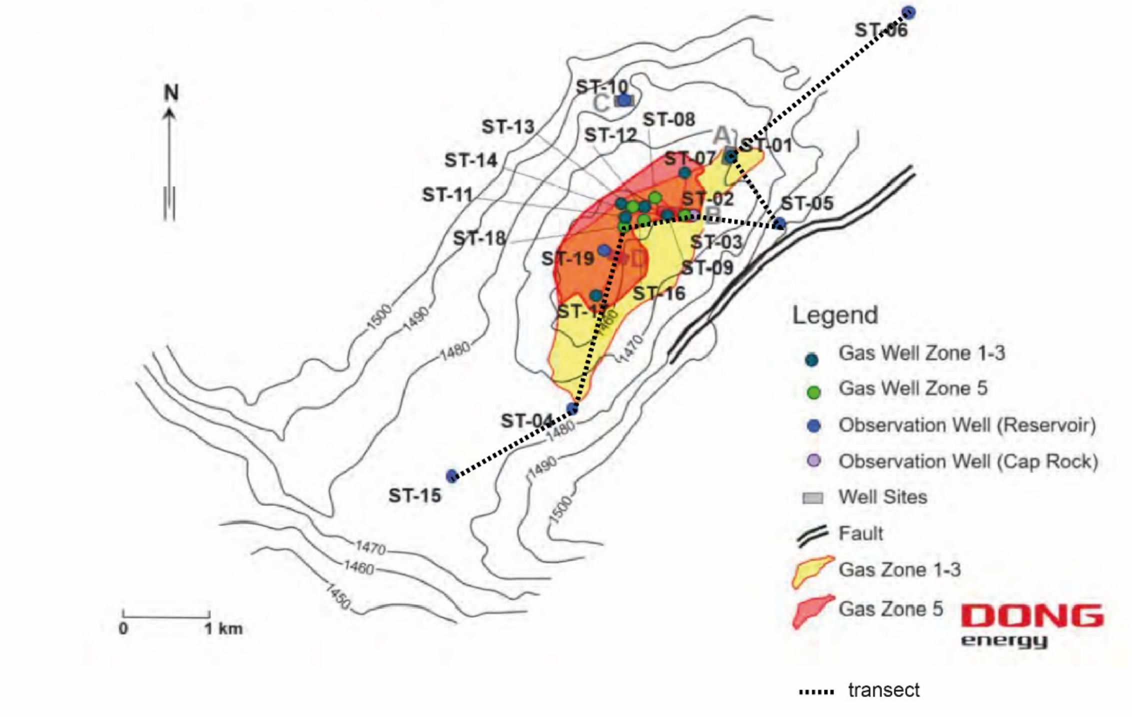

Figure 2

General palynological composition of the analyzed samples from Stenlille-15, -4, -18, -2, -5, -1, and -6, displayed in a sequence stratigraphic framework (Hovikoski & Pedersen 2020; Vosgerau et al. 2020). The different palynological categories are: AC=acritarchs, AL=freshwater algae, ALBO=*Botryococcus braunii* and *Pediastrum*, ALIN=freshwater algae of uncertain affinity, DC=dinoflagellate cysts, FT=foraminiferal test linings, FU=fungi, MM=miscellaneous microfossils, MP=miscellaneous palynomorphs, PF=palynofacies, SP=spores and pollen. These categories can also be found on Figures 3–9.

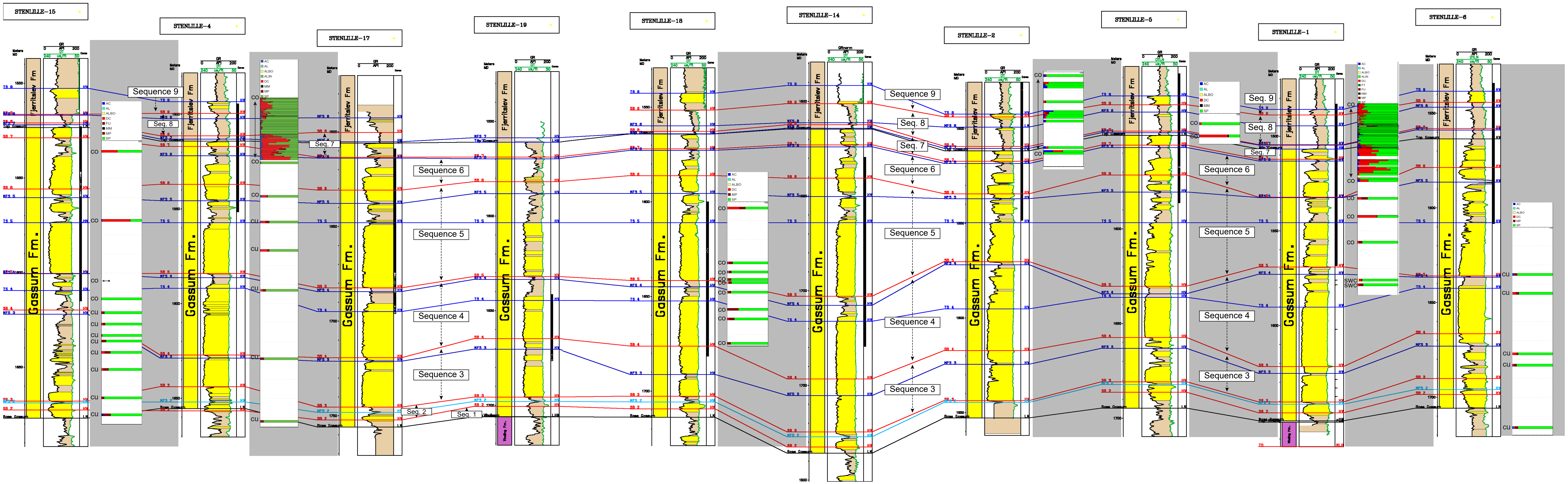
STENLILLE-15
STENLILLE-4
STENLILLE-17
STENLILLE-19
STENLILLE-18
STENLILLE-14
STENLILLE-2
STENLILLE-5
STENLILLE-1
STENLILLE-6
Fjerritslev Fm
Gassum Fm.
Sequence 9
Seq. 9
Seq. 8
Seq. 7
Sequence 6
Sequence 5
Sequence 4
Sequence 3
Seq. 2
Seq. 1

Figure 3

Palynostratigraphic range chart of Stenlille-15.

Sofie Lindström
Scale: 1:500

Stenlille-15

GEUS

Text Keys

*1 quant/semi-quant abundance, % panel
*2 Below SB2: Marginal marine
*3 (Rw excluded)
*4 quant/semi-quant abundance, % all Paly.
*5 quantitative abundance, % all Paly.
*6 (Rw only; Cv excluded)

Boundary Types

Confident

Sampling

Cutting
Core
Sidewall Core

Taxon Categories

AC - Acritarchs
AL - Algae
ALBO - Botryococcus and pediastrum
DC - Dinoflagellate cysts
FU - Fungi
MM - Miscellaneous microfossils
MP - Miscellaneous palynomorphs
PF - Palynofacies
SP - Spores and pollen

Figure 4

Palynostratigraphic range chart of Stenlille-4, data from Lindström et al. (2012, 2015, 2017, 2019, and in prep.).

Sofie Lindström
Scale: 1:150

Stenlille-4

Text Keys
*1 quant/semi-quant abundance, % panel
*2 quant/semi-quant abundance, % all Paly.
*3 (Rw excluded)

Boundary Types
Confident

Sampling
Cutting

Core
Sidewall Core

Taxon Categories
AC - Acritarchs
AL - Algae
ALBO - Botryococcus and pediastrum
ALIN - Incertae sedis
DC - Dinoflagellate cysts
FU - Fungi
MM - Miscellaneous microfossils
MP - Miscellaneous palynomorphs
PF - Palynofacies
SP - Spores and pollen

Figure 5

Palynostratigraphic range chart of Stenlille-18.

Sofie Lindström
Scale: 1:500

Stenlille-18

GEUS

Text Keys

*1 quant/semi-quant abundance, % panel
*2 quant/semi-quant abundance, % all Paly.
*3 (Rw excluded)
*4 quantitative abundance, % all Paly.
*5 (Rw only; Cv excluded)

Boundary Types

Confident

Sampling

Cutting
Core
Sidewall Core

Taxon Categories

AC - Acritarchs
AL - Algae
ALBO - Botryococcus and pediastrum

DC - Dinoflagellate cysts
FU - Fungi
MP - Miscellaneous palynomorphs
PF - Palynofacies
SP - Spores and pollen

Figure 6

Palynostratigraphic range chart of Stenlille-2, data from Dybkjær (1991).

Sofie Lindström
Scale: 1:300

Stenlille-2

G E U S

Text Keys
*1 quant/semi-quant abundance, % panel
*2 quant/semi-quant abundance, % all Paly.
*3 (Rw excluded)
*4 quantitative abundance, % all Paly.
*5 SP *Corollina meyeriana* (SP *Classopollis meyerianus*)
*6 (Rw only)
*7 (Rw only; Cv excluded)

Boundary Types
Confident

Sampling
Cutting
Core
Sidewall Core

Taxon Categories
AC - Acritarchs
AL - Algae
ALBO - Botryococcus and pediastrum
DC - Dinoflagellate cysts
FU - Fungi
MP - Miscellaneous palynomorphs
PF - Palynofacies
SP - Spores and pollen

Figure 7

Palynostratigraphic range chart of Stenlille-5.

Sofie Lindström
Scale: 1:500

Stenlille-5

GEUS

Text Keys
*1 quant/semi-quant abundance, % panel
*2 quant/semi-quant abundance, % all Paly.
*3 (Rw excluded)
*4 quantitative abundance, % all Paly.
*5 (Rw only)
*6 (Rw only; Cv excluded)

Boundary Types
Confident

Sampling
Cutting
Core
Sidewall Core

Taxon Categories
AC - Acritarchs
AL - Algae
ALBO - Botryococcus and pediastrum
DC - Dinoflagellate cysts
FU - Fungi
MM - Miscellaneous microfossils
MP - Miscellaneous palynomorphs
PF - Palynofacies
SP - Spores and pollen

Figure 8

Palynostratigraphic range chart of Stenlille-1, data from Lindström et al. (2012, 2015, 2017, 2019, and in prep.).

Sofie Lindström
Scale: 1:150

Stenlille-1

Text Keys

*1 quant/semi-quant abundance, % panel
*2 (Rw only; Cv excluded)
*3 quant/semi-quant abundance (100 = 40mm, scale tick = 10 counts)
*4 quant/semi-quant abundance, % all Paly.
*5 quantitative abundance, % all Paly.
*6 (Rw excluded)

Boundary Types
Confident

Sampling
Cutting
Core
Sidewall Core

Taxon Categories
AC - Acritarchs
AL - Algae
ALBO - Botryococcus and pediastrum
ALIN - Incertae sedis
DC - Dinoflagellate cysts
FT - Foram test linings
FU - Fungi
MM - Miscellaneous microfossils
MP - Miscellaneous palynomorphs
PF - Palynofacies
SP - Spores and pollen

Figure 9

Palynostratigraphic range chart of Stenlille-6.

Sofie Lindström
Scale: 1:500

Stenlille-6

Text Keys
*1 quant/semi-quant abundance, % panel
*2 quant/semi-quant abundance, % all Paly.
*3 (Rw excluded)
*4 quantitative abundance, % all Paly.
*5 (Rw only; Cv excluded)

Boundary Types
Confident

Sampling
Cutting
Core
Sidewall Core

Taxon Categories
AC - Acritarchs
AL - Algae
ALBO - Botryococcus and pediastrum
DC - Dinoflagellate cysts
FU - Fungi
MP - Miscellaneous palynomorphs
PF - Palynofacies
SP - Spores and pollen

Table 1.

A summary of the depositional environments based on the palynological investigation of wells in the Stenlille area.

	Stenlille-15	Stenlille-4	Stenlille-18	Stenlille-2	Stenlille-5	Stenlille-1	Stenlille-6
Sequence 9 (in part)		Marginal to fully marine		Shallow marine		Fully marine to shallow marine	
Sequence 8		Above MFS8, shallow marine. Below MFS8, shallow marine with high input of siliciclastic mtrl		Above MFS8, Shallow marine to marginal marine	Marginal marine or shallow marine (depauperated)	Above MFS8, shallow marine to marginal marine with freshwater input. Below MFS8, shallow marine with high input of siliciclastic mtrl	
Sequence 7		Full marine		Fluctuating from marginal marine to fully marine to shallow marine	Fully marine	Fully marine to shallow marine	
Sequence 6	Fully marine	Upper part, fully marine. Lower part marginal marine				fluctuating between shallow marine and fully marine	
Sequence 5	Fully marine	Shallow marine	Marginal marine to shallow marine			Marginal marine to shallow marine	Marginal marine
Sequence 4	terrestrial to possibly marginal marine environment	Marginal marine	Fluctuating between marginal marine and terrestrial			Marginal marine to shallow marine	Shallow marine
Sequence 3	Fluctuating between marginal marine, shallow marine, terrestrial, and marginal marine environment	Marginal marine					Marginal marine to shallow marine
Sequence 2							
Base Gassum to SB2	Marginal marine						
Below Base Gassum		Marginal marine					Marginal marine