DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2014/29

# Extended evaluation of possible geothermal reservoirs in the Helsingør area including geological data from Helsingborg and Øresund

## Contribution to an evaluation of the geothermal potential

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Lars Henrik Nielsen, Lars Kristensen,
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DANISH MINISTRY OF CLIMATE, ENERGY AND BUILDING

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# Preface

This report is prepared by GEUS and SGU for Forsyning Helsingør with the objective to improve the understanding of the geothermal potential of sandstone formations in the Helsingør area.

An initial assessment of the geothermal potential in the Helsingør area was presented in a report (Hjuler et al. 2013) based on relevant well and seismic data. From this report it becomes clear that the unavailability of quality data in the study area in combination with complicated regional geology impedes a well substantiated characterization of quality and continuity of the potential sandstone reservoirs. The report, however, also showed that several formations including the Lower Cretaceous Unit, the Lower Jurassic Unit, the Gassum Formation and the Bunter Sandstone Formation possess geothermal potential.

The geothermal potential of these formations were further examined and verified in a petrographical analysis of selected cuttings samples from the Karlebo-1/1A well (Nielsen et al. 2014).

A new study based on the vast amount of geodata from the Helsingborg area was proposed in order to further strengthen the reservoir quality assessments presented in Hjuler et al. (2013) and Nielsen et al. (2014). The objective was to obtain more information of the spatial distribution and quality of potential reservoirs in the Helsingør area by evaluating and analysing the significant amounts of geological data available from the Helsingborg area. In the *first phase* of this study an overview of the vast amount of samples and data was established. The results of the *second phase* include analyses of biostratigraphy, cores (porosity-permeability), petrophysics, petrography and shallow seismic data in order to facilitate comparison and correlation of Danish wells to a constructed composite succession in the Helsingborg area. In the last *third phase* of the study the geothermal potential in the Helsingør area is re-assessed by integration of the Helsingborg data and data from the tunnel line between Helsingør and Helsingborg (Larsen et al. 1968) with the previous assessment (Hjuler et al. 2013). In addition, a parallel study on the relation between porosity and permeability has been performed for Sjælland, and the results of this study have also been utilised and integrated with the Helsingborg study.

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# 1 Dansk sammenfatning

Den foreliggende rapport er udarbejdet af GEUS med bistand fra SGU for Forsyning Helsingør med det formål at styrke vurderingen af det geotermiske potentiale ved Helsingør ved at inddrage omfattende geologisk datamateriale fra Helsingborg-området samt data fra Øresundsboringerne, som udførtes i 60'erne i forbindelse med en mulig tunnel mellem Helsingør og Helsingborg.

## 1.1 Denne og tidligere undersøgelser

Rapporten tager udgangspunkt i GEUS' præliminære geologiske model for Helsingør-området (Hjuler et al. 2013) samt borespåneundersøgelsen for Karlebo-1 boringen (Nielsen et al. 2014). I Hjuler et al. (2013) sammenstilledes alle tilgængelige danske geologiske data med det formål at kortlægge potentielle geotermiske reservoirer i undergrunden ved Helsingør og evaluere disses kvalitet. Kombinationen af Helsingørs beliggenhed i et geologisk set kompliceret område og et ringe datagrundlag afstedkom en geologisk model med et markant forbedringspotentiale både med hensyn til beskrivelsen af undergrundens opbygning og vurdering af kvaliteten af mulige reservoirer, som kendes fra de sjællandske dybe boringer. Rapporten sandsynliggjorde, at flere formationer med geotermisk potentiale findes i Helsingør området.

Som et led i en forbedret karakterisering af reservoirerne i Helsingørs undergrund blev borespåner fra den nærmeste boring, Karlebo-1A, analyseret. Udkommet af analyserne, præsenteret i Nielsen et al. (2014) understøtter GEUS' generelle geologiske model for NØ-Sjælland og påviser desuden en ringe cementeringsgrad i sandsten fra Nedre kridt, Nedre Jura og Gassum Formationen.

I Hjuler et al. (2013) og Nielsen et al. (2014) tager evalueringen af det geotermiske potentiale afsæt i sjællandske boringer vest og syd for Helsingør. For yderligere at styrke karakteriseringen af reservoirernes kvalitet samt vurdere deres rumlige udbredelse er det omfattende geologiske materiale og boringsdata fra Helsingborg by blevet inddraget og evalueret. Undersøgelsen, som således også omfatter data fra området øst for Helsingør, er inddelt i tre faser. Formålet med den *første fase* var at skabe overblik over det eksisterende datamateriale samt indsamlede prøver. I *Anden fase* blev en række specialanalyser udført på det geologiske materiale og boringsdata med det formål at konstruere et vertikalt geologisk Helsingborg-profil til sammenligning med de tidligere analyserede danske boringer. Denne rapport er resultatet af *tredje fase*, hvor Helsingborg-profilet er blevet korreleret med de danske boringer, og reservoirkvalitet og udbredelse reevalueret og sammenholdt med eksisterende viden i Hjuler et al. (2013) og Nielsen et al. (2014). Dataanalyser og -bearbejdningen er detaljeret dokumenteret i de efterfølgende afsnit.

## 1.2 Resultater og konklusioner

Helsingborg-profilet og Øresundsboringerne har konfirmeret tilstedeværelsen af lag fra Gassum Formationen og Nedre Jura, Mellem Jura og antageligvis Nedre kridt øst for Helsingør. Sammenholdt med formationernes tilstedeværelse i de danske boringer er formodningen om disse lags (Gassum, Nedre Jura og Nedre Kridt) tilstedeværelse i Helsingør-områdets undergrund betydeligt bestyrket; forekomst af Mellem Jura-lag er fortsat meget usikkert. Størstedelen af Helsingborg-profilet svarer tidsmæssigt til Gassum Formationen og indeholder adskillige sandstenslag af forskellig vertikal udstrækning. De udførte laboratoriemålinger på disse sandstenslag angiver generelt høje porøsiteter og permeabiliteter, hvilket har øget sikkerheden i vurderingen af Gassum-sandstenene.

Grundet Øresundsområdets komplekse geologi findes op til 200 m tykke lag svarende til Gassum Formationen tæt på overfladen ved Helsingborg, mens de ved Helsingør er vurderet til begravelsesdybder på 2 km eller mere. Undergrundens struktur mellem de to byer vides at indeholde betydelige geologiske forstyrrelser, heriblandt flere store forkastninger. Det er derfor ikke muligt at følge sandstenslag fra Helsingborg-profilet og "direkte" til de danske boringer, men de detaljerede analyser udført i denne rapport dokumenterer, at det er meget sandsynligt, at Gassum Formationen er tilstede under Helsingør, og at den indeholder sandstenslag, der udgør potentielle geotermiske reservoirer.

Nøgleværdierne for de potentielle reservoirer, som denne rapport har sandsynliggjort, er præsenteret i tabellen nedenfor. Dybden til såvel som tykkelsen af de enkelte enheder er udregnet som middelværdien af en "high case" og en "low case", som forventes at udspænde det mulige udfaldsrum. Et vigtigt udkomme af dette studium er en væsentlig større sikkerhed, for så vidt angår vurderingen af Gassum Formationen, hvilket udmøntes i en relativt lille forskel på high case og low case for dette reservoir.

I kontrast hertil er der stor forskel på high case og low case, hvad angår dybder og tykkelser for Nedre Kridt og Nedre Jura. Den store forskel forventes at kunne reduceres betydeligt ved indsamling af nye seismiske data, idet disse forudses at bekræfte tilstedeværelsen af Nedre Kridt og Nedre Jura, hvilket vil reducere usikkerheden vedr. disse to reservoirer betydeligt med deraf afledt positiv effekt på vurderingen af deres potentiale.

Estimerede reservoirparametre for Helsingør-området baseret på nye Helsingborg- og Øresund-data kombineret med data fra danske boringer. Dybder og tykkelser er middelværdier af high case og low case.

| **Prognose; Helsingør-omr. Res. parameter** | **Top - Basis af enhed** (m MD) | **Enhed tyk.** (m) | **Sst. tykkelse** | | **Gnm. Por.** (%) | **Gnm. gas perm.** (mD) | **Gennemsnit reservoir perm.** [1)] (mD) | **Reservoir transmissivitet** [1)] (Dm) |
|---|---|---|---|---|---|---|---|---|
| | | | **Gross Sand** (m) | **Net Sand** (m) | | | | |
| Nedre Kridt | 2130 – 2200 | 70 | 13 | 10 | 20 | 250 | 300 | 3 |
| Fjerritslev Fm | 2200 – 2308 | 108 | 0 | 0 | - | - | - | 0 |
| N. Jura-res. | 2308 – 2383 | 75 | 26 | 18 | 20 | 315 | 395 | 7 |
| Gassum Fm | 2383 – 2530 | 147 | 64 | 47 | 22 | 603 | 755 | 36 |
| Bunter Sst. Fm | 3100 – ? | 300 [2)] | 140 [2)] | 48 [2)] | 17 | 40 | 50 | 3 |

[1)]: Reservoir skala. [2)]: Parametre fra Margretheholm 1A og -2.

# 2 Introduction

In connection with the preliminary assessment of the geothermal potential in the subsurface below Helsingør, GEUS primarily used available well data and core material from deep wells in Zealand (Karlebo-1, Lavø-1 and Margretheholm-1, -2 and the Stenlille wells, see **Figure 1**) combined with GEUS' overall geological models of the subsurface structure and composition (Hjuler et al. 2013). The assessment of the potential in Helsingør is complicated by the fact that the available Danish data points are sparse and located far from the areas of interest in Helsingør.

The sparse database gives rise to two principal uncertainties in assessing the geothermal potential of Helsingør:

1. The poor seismic coverage is primarily reflected in the uncertainty regarding the depth and thickness of potential reservoir-bearing formations and the presence of faults. These uncertainties can only be reduced by the acquisition of new seismic data along relevant lines.

2. The lack of information from deep wells in the Helsingør area causes uncertainty regarding evaluation of the properties of reservoir-bearing formations.

In order to strengthen the database and improve assessment options geological data from the Helsingborg area is involved and compared with the existing data from Zealand. From a geological point of view, information from the Scanian and Danish sedimentary layers is of similar relevance as the layers originally were deposited in the same basin area as one continuous layer. Subsequently, geological processes have caused the layers to break up along major faults with the consequence that potential geothermal layers remained at great depth below Helsingør, whereas they were uplifted and now crops out and form the bedrock in the Helsingborg area. Here, the layers may therefore be studied in coastal cliffs along parts of the Øresund coast and in a number of outcrops and shallow boreholes in the Helsingborg area.

The available geological data from Helsingborg provides comprehensive and relevant material from geological layers, which essentially corresponds to the middle–upper parts of the Gassum Formation. The data set is located closer to the area of interest than the data available from the deep wells of Zealand. The data set is expected to provide relevant information (e.g. net/gross ratio, cumulative thickness of reservoir sandstones, porosity-permeability etc.) from the geological layers corresponding to the upper Rhaetian–Hettangian part of the Gassum Formation.

Based on the overview of the Helsingborg data (*phase 1* of the Helsingborg study) an analysis program has been designed in order to qualify the assessment of the geothermal potential in the Helsingør area. The following eight analyses have been performed:

1. Evaluation of geological strata of selected representative wells in order to develop a statistical breakdown of the layer lithologies – i.e. a specification of the reservoir sandstone versus non-reservoir lithology (net/gross ratio)

2. Analysis of 20 biostratigraphic samples, mainly from marine clay beds, in order to determine age and in preparation for correlation between wells

3. Identification of geological marker layers such as coal beds, marine clay beds, characteristic sandstone layers etc.

4. Interpretation of petrophysical well logs from selected representative wells for identification of reservoir sandstones, interpretation of net/gross ratio and assessment of porosity and permeability

5. Measurement of gas permeability on 30 representative plugs obtained from core samples of reservoir sandstones identified in point 1, 3 and 4

6. Petrographic and diagenetic analyses of 25 samples of reservoir sandstones by examination of thin sections in light microscope using transmitted light to determine diagenetic development and degree of cementation

7. Evaluation of relevant shallow seismic lines in order to identify faults that split the subsurface in the Helsingborg area into separate fault blocks

8. Preparation of a correlation plot based on selected representative wells and incorporating the results of points 1–7. The plot will provide the necessary overview of the development and distribution of layers the subsurface in order to enable the construction of a vertical, composite profile that can be correlated and compared with the deep wells in Zealand

This draft report lists the results for each analysis and presents preliminary interpretations of well log data.

# 3 Geological and geophysical data base

## 3.1 H+ project in Helsingborg

Between 2006 and 2010 a series of geological and geophysical investigations were carried out in the central parts of Helsingborg. The aim was to obtain subsurface information of the geological conditions for a planned railway tunnel project called the H+ project. The campaign in 2006 included drilling of 18 percussion and 9 cored boreholes to depths between 30 and 40 meters. In 2009 a more extended and concentrated investigation was carried out in the southern parts of Helsingborg, including 20 percussion and 10 cored boreholes to c. 30 meters depth. All boreholes start and terminate in the Höganäs Formation, primarily the Helsingborg Member. They represent, however, different sections of the formation due lateral local variations in tectonic uplift. The maximum thickness of the Helsingborg Member is estimated to be in the range of 200 m and the joint section of boreholes from the H+ project covers most of this interval, at least main part of the lower and middle part of the Helsingborg Member.

Wire-line logging has been performed in all wells, including GR, conductivity and resistivity. Sonic, Density and Flow logging was performed primarily in the boreholes drilled in 2006 and in some of the 2009 boreholes. A reflection seismic survey was also performed in the south parts of Helsingborg. This gives valuable information on the general bedding and faults, and helped in the lateral correlation of beds between boreholes.

The H+ project was put on hold in 2011 and most of the core material was disposed, beside six complete cored boreholes and c. 350 core samples, which were handed over to the Geological Survey of Sweden for storage and research. These were accompanied by a comprehensive amount of data from various analyses and characterizations, including:

- Lithological descriptions and geotechnical analysis
- Wire-line log panels
- Photographs of cores

This data constitute the main base for the studies and geological characterization presented here.

## 3.2 Older data from the Helsingborg area

The general geology of the Helsingborg area is primarily described in Troedsson (1947), Sivhed & Wikman (1986), Norling (1970, 1972), Norling et al. (1993), Pienkowski (1991) and Ahlberg (1990, 1994). Their characterization and descriptions are still the foundations upon which the interpretation of new data rests. Especially since many older outcrops and data from older cored boreholes are either covered or lost.

One of the older core drillings, Köpinge-3 located in south Helsingborg, is well described by Erdmann (1915) and by Sivhed & Wikman (1986). The borehole constitutes an important reference regarding the composition of the Höganäs Formation as the borehole penetrates almost the whole formation. It is only the uppermost part of the Helsingborg Member that is missing.

## 3.3 Performed investigations

This study has included the following elements of work and deliverables:

- Compilation of well data (logs, core samples, descriptions)
- Statistical processing of the amount of sandstone beds in the boreholes
- Preparation and microscopical investigation on 25 sandstone core samples for the determination of the modal composition (mineralogy, cementation, matrix, pores) of the dominant sandstone types (**Enclosure 1**)
- Preparation and analysis of porosity, permeability and density on 30 sandstone samples
- Biostratigraphical investigation on 20 core samples for correlation purposes
- Compilation of composite logs with wire-line logs, core photos, logs and analytical data (**Enclosure 2**)

# 4 Geological setting

Helsingborg is situated in an area heavily affected by fault movements in the Sorgenfrei-Tornquist Zone (STZ). This zone extends from the North Sea across North Jutland, through the Kattegat, crosses Skåne and continues through the Southern Baltic and Poland. The zone is composed of several major fault zones where the Romeleåsens Fault Zone (RFZ) forms the southwestern boundary of the STZ.

Tectonic movements in the STZ during Late Cretaceous resulted in the geological picture that we largely see today. Regional compression in the crust resulted in stress release and formation of a complex reverse fault zone with large "hanging" rock blocks and steeply dipping bedrock layers along the main fault. This flexure zone is 2−5 km wide and extends in a NW−SE direction outside the port of Helsingborg (**Figure 2**−**Figure 3**). The zone is known from boreholes and seismic surveys in Øresund (Larsen et al. 1968) and from boreholes at Rydebäck (Norling 1970).

The bedrock down to about 100 m depth in Helsingborg is dominated by Lower Jurassic strata of the Höganäs Formation, subdivided into three members, i.e. the Vallåkra, Bjuv and Helsingborg members. The formation, of which the Helsingborg Member constitutes the main part, reaches a total thickness of approximately 250 m in the Höganäs Basin. Almost the complete Höganäs Formation is penetrated in the Köpinge-3 borehole in the south part of Helsingborg. Only the uppermost part of the Helsingborg Member is missing in this borehole. The described sequence in this borehole is the most complete and representative succession of the Höganäs Formation in Helsingborg.

Descriptions and mappings performed by Troedsson (1947), Erdmann (1915), Sivhed & Wikman (1986) and Ahlberg (1990) show that the main part of the Lower Jurassic succession down to about 50 m depth in Helsingborg is dominated by beds belonging to the lower and middle part of the Helsingborg Member. The position of the so called A coal seam in the Rhaetian has been used as a reference level. The position of this level, in the southern part of Helsingborg, lies generally at less than 100 m depth, often around 60 m. In northern Helsingborg the Rhaetian is locally found at shallower depths, <25 m.

In general the lithological succession in Köpinge-3 can be traced throughout the Helsingborg area. A few key beds including the Boserup, Fleninge "Slipsandstenen" and the Pullastra beds can used for correlation as they are identified at several locations in Helsingborg (Sivhed & Wikman 1986).

The composition of the Höganäs Formation is fairly consistent in the eastern part of the Danish Basin. Deep drillings in SW Skåne, e.g. Barsebäck-1, FFC-1, Höllviksnäs-1, have all verified very similar bedding sequences as the ones found in the Helsingborg area. Differences seen are mainly grain-size, and total thickness, which is related to a more proximal position of Helsingborg in the Danish Basin.

In summary the beds that constitute the bedrock surface in Helsingborg have been buried to >2 km depth prior to their uplift in Late Cretaceous times. Based on regional geological data a pre-existing and now removed overlying pre-uplift sequence of Middle Jurassic to Lower Cretaceous strata would amount to this estimate.

## 4.1 Upper Triassic – Lower Jurassic stratigraphy

The lithostratigraphic subdivisions spanning the Rhaetian-Pliensbachian/Toarcian interval in Skåne involve the Höganäs Formation and the Rya formation (**Figure 4**). These are very well known in NW Skåne, but not clearly defined in SW Skåne.

The Höganäs Formation, representing the Rhaetian–Hettangian interval in Skåne, has an approximate thickness of 250 m and is subdivided into three members. The Vallåkra and Bjuv members represent the Rhaetian part, and the Helsingborg Member represents the Hettangian part. The basal Vallåkra Member is regarded as the transition between the continental red beds of the Kågeröd Formation and the deltaic, coal bearing Bjuv Member. The Vallåkra Member is estimated to be c. 30 m thick in NW Skåne, and includes grey and variegated clays with sphaerosiderite and greenish sandstone lenses. The Bjuv Member is bounded by a coal seam (B-seam) marking its lower boundary to the Vallåkra Member, and an upper seam (A-seam) marking its boundary to the overlying Helsingborg Member, which is the Triassic–Jurassic transition in Skåne. The Bjuv Member has a thickness of approximately 25 m and is composed of sandstone, siltstone, claystone and paleosols with underclays and autochtonous coal-seams with interfingering channel-shaped sandstone stringers (Ahlberg 1994). The Helsingborg Member is the Hettangian part of the Höganäs Formation. It has a thickness of c. 215 m (Grigelis & Norling 1999) and includes floodplain strata similar to those of the Bjuv Member, however, with several marine incursions (Vossmerbäumer 1969; Ahlberg 1990, 1994; Pienkowski 1991).

The post-Hettangian Lower Jurassic sequence is in NW and W Skåne represented by the Rya Formation, subdivided into four members (**Figure 4**). The Döshult Member representing the Lower Sinemurian is characterized by coarse-grained, cross-bedded sandstones in the lower part, and clays and marls in the upper part (Grigelis & Norling 1999). The Pankarp Member representing the Upper Sinemurian consists of 60–75 m of variegated clay and shale in the lower part, a thin middle part of sand and sandstone with rootlet beds, and an upper part of variegated clay and shale (Grigelis & Norling 1999). The Katslösa Member represents the Upper Sinemurian and Lower Pliensbachian and consists of 30–40 m of greenish, brownish and dark grey claystones, siltstones, and sandstones with a varying content of iron and carbonate (Grigelis & Norling 1999). The Rydebäck Member represents the Upper Pliensbachian–Toarcian/Aalenian interval. The unit is known from boreholes only and varies in thickness between 50 m and 100 m. It includes sandy and silty, partly oolitic sediments with a varying content of clay and calcium carbonate (Grigelis & Norling 1999).

In the Danish Basin, the equivalent Upper Triassic–Lower Jurassic lithostratigraphic subdivision includes the Skagerrak, Vinding, Gassum, and Fjerritslev formations (**Figure 4**) (Nielsen 2003).

The Gassum Formation corresponds in Skåne to the Bjuv Member, Helsingborg Member and the Döshult Member. This interval is also where there are a relatively high amount of sandstone beds (aquifers) to be found.

Additional sandstone aquifers in the Jurassic of Skåne exist in the Middle Jurassic, i.e. the Glass Sand, likely being at least partly equivalent to the Haldager Sand in the Danish Basin. The 50–80 m thick Glass Sand is known, beside from outcrops in the Fyledalen Valley in SE Skåne, within the Romeleåsen Fault and Flexure Zone. This is verified by borehole data from Øresund (Larsen et al. 1968) and outside the town of Landskrona (Norling 1972; Norling & Grigelis 1999). It´s aquifer properties have, however, not been assessed.

## 4.2 Depositional setting

The deposition of Lower, Middle, and Upper Triassic strata (excluding Norian–Rhaetian) was restricted to the Höllviken Halfgraben. In the late Triassic (Rhaetian), a change from local graben development to a general lowering of the Danish basin (Norling & Bergström 1987), and a primarily eustatically controlled progressive overstepping of the Höllviken Halfgraben took place. This resulted in a wider deposition of the Rhaetian strata, contemporaneous with a climate change from seasonally arid to permanent humid conditions (Ahlberg et al. 2003). These were the main reasons for a very sharp change in the style of sedimentation at the onset of the Rhaetian. The texturally immature clastic sediments of the Norian Kågeröd Formation were followed by Rhaetian–Hettangian chemically and texturally mature quartz arenites deposited in turbulent lacustrine, alluvial, and deltaic environments (Norling et al. 1993; Ahlberg et al. 2003).

During the deposition of predominantly continental to deltaic sediments in the Rhaetian–Hettangian, several marine incursions invaded Skåne. However, the marine influence did not have an impact until the Early Sinemurian, with the deposition of the Döshult Member of the Rya Formation (Norling & Bergström 1987; Norling et al. 1993; Surlyk et al. 1999). The Lower Sinemurian is dominated by nearshore mature coarse-grained arenites with herringbone cross-bedding and an uppermost part composed of dark marine mudstone (Norling et al. 1993). The presence of several ammonites, large fossil logs, and coarse-grained arenites confirms the marine influence and indicates a nearshore high energy depositional environment (Troedsson 1951; Norling et al. 1993). The succeeding Upper Sinemurian deposits of the Pankarp Member are dominated by dull homogeneous mudstone with marine fossils, however, an intermittent proximity to shore is indicated by one coal-seam recorded from boreholes (Norling et al. 1993). Quiet marine environments persisted and muddy sediments were deposited in the Upper Sinemurian–Lower Pliensbachian forming the Katlösa Member, which is occasionally interrupted by sandy horizons and oolitic limestone intercalations (Norling et al. 1993). The Upper Pliensbachian–Toarcian Rydebäck Member is dominated by a series of arenites and wackestones rich in marine microfossils with minor intraformational conglomerates implying a regressional tendency emplaced by increased tectonic activity (Norling et al. 1993).

The Middle Jurassic is in NW Skåne represented by the Vilhelmsfält Formation. It is known from boreholes in the Romeleåsen Fault and Flexure Zone at Landskrona and in Øresund. It is dominated by mudstone and siltstone, however, with one exception being the Bathonian Glass Sand Member, deposited in high energy proximal coast environments such as delta front sands and beach–foreshore settings.

# 5 Distribution and proportion of sandstone beds in the cores from Helsingborg

## 5.1 Main sandstone lithofacies

The sandstone beds observed in the core material from Helsingborg and the Helsingborg Member can be classified into the following types:

### 5.1.1 Primary aquifers

1) Cross-bedded and wavy bedded sandstone composed of up to c.15 m thick units of fining upward sequences. The basal part composed of homogeneous, cross-bedded and medium-grained, quartz arenite grading into fine-grained arenite with increasing amount of thin clay laminae (flasers). The basal parts of these units have in general a very low GR-reading, high porosity and very high permeability (1–2 D). Thin carbonate cemented beds occur. Ahlberg (1990) interpreted these as large distributary sands followed by tidally and wave influenced shore line deposits (**Figure 5**).

2) Planar and low-angel cross-bedded, well-sorted sandstone, medium-grained: Very high permeability and uniform GR-reading, no grading, homogeneous beds with thickness between 5 and 10 meters. The good sorting and low-angle cross-bedding indicate foreshore and shoreface settings (Ahlberg 1990).

### 5.1.2 Secondary aquifers

3) Less than 1 m thick, fine-grained and matrix-rich sandstone sheets in mudstone dominated intervals. These were likely formed as isolated sand layers from wash over fans or overbank flooding. Medium high GR, permeability >200 mD.

4) 5–30 m thick units of fine-grained sandstone frequently interbedded by variably silty and sandy claystone. Dominated by very fine- and fine-grained sandstone, variably clayey. Interpreted as deposited in intertidal settings. Serrated GR-curve (**Figure 6**).

The relative occurrence of these two main groups of aquifers is mapped in all cored boreholes. These data are presented in **Table 1**. The results show that the drilled trough part of the Helsingborg Member consists on average of 22.5% of sandstone beds of type 1 and 2, and 14% of sandstone type 3 and 4. Considering a total thickness of c. 200 m for the Helsingborg Member it would mean that the Hettangian sequence is composed of c. 45 m of primary and 28 m of secondary aquifer beds in total.

**Table 1:** Distribution and proportion of the two main sandstone facies (aquifers) in cores in southern, central and northern parts of the town of Helsingborg.

| **Borehole** | **Primary aquifer Sandstone, fine- and medium-grained Type 1 & 2** | | **Secondary aquifer Fine-grained, laminated sandstone Type 3 & 4** | | **Total core ()** |
|---|---|---|---|---|---|
| ***Southern and central parts of Helsingborg*** | | | | | |
| **09.01.2001** | 6.5 m | 20.0% | 5.9 m | 18.0% | 33.0 m |
| **09.01.2009** | 10.1 | 31.0 | 0.0 | 0.0 | 32.4 |
| **09.01.2021** | 6.6 | 21.0 | 0.0 | 0.0 | 31.0 |
| **09.01.2026** | 1.7 | 6.0 | 2.5 | 10.0 | 25.8 |
| **09.01.2027** | 15.1 | 43.0 | 5.4 | 15.0 | 35.3 |
| **09.01.2029** | 23.2 | 74.0 | 5.1 | 16.0 | 31.4 |
| **09.01.2033** | 5.2 | 18.0 | 7.0 | 24.0 | 29.2 |
| **09.01.2035** | 6.4 | 19.0 | 4.5 | 13.0 | 33.3 |
| **09.01.2040** | 1.2 | 4.0 | 0.0 | 0.0 | 31.4 |
| **09.01.2044** | 4.4 | 17.0 | 7.2 | 28.0 | 25.9 |
| **06.1.2002** | 2.2 | 2.1 | 13.8 | 41.1 | 33.6 |
| **06.1.2005** | 4.0 | 10.9 | 0.5 | 1.3 | 36.5 |
| **06.1.2007** | 5.8 | 27.9 | 3.5 | 16.8 | 20.8 |
| **06.1.2009** | 0.2 | 1.0 | 0.0 | 0.0 | 20.0 |
| **Average** | 6.6 m | 21.1% | 4.0 m | 13.7% | 30.0 m |
| **Total** | 92.6 | 22.1 | 55.4 | 13.2 | 419.6 |
| ***Cored boreholes from the drilling campaign 2006 in northern part of Helsingborg, Tågaborg area.*** | | | | | |
| **06.1.1004** | 8.7 m | 32.9% | 5.8 m | 21.9% | 26.5 m |
| **06.1.1007** | 7.5 | 14.4 | 15.0 | 28.8 | 52.0 |
| **06.1.1008** | 10.2 | 24.3 | 4.0 | 9.5 | 42.0 |
| **06.1.1010** | 3.5 | 16.6 | 0.0 | 0.0 | 21.0 |
| **06.1.1011** | 9.0 | 36.7 | 2.0 | 8.2 | 24.5 |
| **Average/bh** | 7.8 m | 25.0 % | 5.4 m | 13.7 % | 33.2 m |
| **Total** | 38.9 | 23.4 | 26.8 | 16.1 | 166.0 |
| **Average (all wells)** | 6.9 m | **22.5 %** | 4.3 m | **13.1 %** | 30.8 m |
| **Total (all wells)** | 131.5 | **22.5** | 82.2 | **14.0** | 585.6 |

## 5.2 Hydrogeological assessment

The shallow wells in the Helsingborg area that are selected for this study provide some useful hydrogeological data. Flow logs exist in most wells, and these give information on the occurrence of water conductive zones and their relative contribution to the total obtained flow from each well. It is, however, not possible to calculate the transmissivity of the productive sandstones based on these data. There is, however, a good correlation between the results from the permeability analyses on cores and the observed relative flow from the individual sandstone beds. From this it can be concluded that most sandstone beds contribute significantly to the inflow of water to the wells, thus being conductive aquifers. Their lateral hydraulic continuity is, however, less well established.

There are beside the flow logs results from a few stepwise pump tests performed in 2006. These are presented in a report by Tyréns (2007). The pump tests were performed in five wells in the north, mid, central south and south parts of Helsingborg (**Table 2**). The results show that the tested sequences in the 30–50 m deep wells indicate both closed and open aquifer conditions with an evaluated transmissivity (calculated as *hydraulic conductivity* x *net sand thickness*) between $1 \cdot 10^{-4}$ and $1 \cdot 10^{-3}$ $m^2/s$.

The observed variations related to open and closed aquifer conditions are likely related to the geometry of the individual sandstone bodies, the block faulted geology in Helsingborg and the depositional setting of the Höganäs Formation. The proximal deltaic and marginal marine depositional setting resulted in a highly variable bedding succession, including both regional and local sandstone bodies of open and closed hydrogeological characteristics.

The results of the pump test can, thus, only be used as indicator of the hydraulic properties of the aquifer since they only represent scattered intervals of the total succession. Bearing this in mind as well as that the tests represent data from shallow groundwater wells it can still be concluded that the data indicate hydraulic properties of great similarity to results from flow test of the Lower Cretaceous–Lower Jurassic succession at 1615–1828 m depth in SW Skåne (Rosberg 2010, **Table 3**). The indications of a transmissivity in the range of $1 \cdot 10^{-4}$ to $1 \cdot 10^{-3}$ $m^2/s$ and hydraulic conductivity of give clearly an indication of good aquifer properties of the tested Lower Jurassic interval in Helsingborg (cf. **Table 4**)

**Table 2:** Compilation of data from pump tests in the Helsingborg shallow wells (Tyréns 2007). Transmissivity is calculated as *hydraulic conductivity* x *net sand thickness*.

| **Test wells** | **Screen length/Net sand** | **Transmissivity (*T*)** ($m^2$/s) | **Hydraulic conductivity (*K*)** cm/s |
|---|---|---|---|
| HB north (1001, 1002, 1012, 1016), | 20/15 m | $9.61 \cdot 10^{-4}$–$1.56 \cdot 10^{-3}$ | |
| HB south A (2002, 2003, 2001) | 20/17 m | $5.56 \cdot 10^{-4}$–$1.16 \cdot 10^{-3}$ | |
| HB south B (2005) | 20/8 m | $2 \cdot 10^{-4}$ | |

**Table 3:** Compilation of data from the FFC wells in Malmö (Rosberg 2010). ). Transmissivity is calculated as *hydraulic conductivity* x *net sand thickness*.

| **Well** | **Zone depth** (m)**, sl** | **Accumulated thickness of perforated beds** | **Stratigraphy** | **Transmissivity (*T*)** $m^2$/s | **Notes** |
|---|---|---|---|---|---|
| FFC-1, perforated casing | 1615–1828 (213 m) | 141.5 m | Lower Cretaceous sands + Rya and Höganäs formations (Pliensbachian-Rhaetian) | $1.3 \cdot 10^{-3}$ (flow test) Equals 7.8 D<br><br>$7.9 \cdot 10^{-4}$ (build up) Equals 4.8 D. | C. 10 m of Lower Cretaceous sands contribute 60–80% to the flow |

### 5.2.1 Definitions

#### Hydraulic conductivity, *K*

Hydraulic conductivity is a property that describes the ease with which a fluid (usually water) can move through pore spaces or fractures. It depends on the intrinsic permeability of the material and on the degree of saturation, and on the density and viscosity of the fluid.

#### Transmissivity, *T*

Transmissivity is a measure of how much water can be transmitted horizontally, such as to a pumping well.

**Table 4:** Values for typical fresh groundwater conditions — using standard values of viscosity and specific gravity for water at 20°C and 1 atm.

| *K* (cm/s) | $10^2$ | $10^1$ | $10^0$=1 | $10^{-1}$ | $10^{-2}$ | $10^{-3}$ | $10^{-4}$ | $10^{-5}$ | $10^{-6}$ | $10^{-7}$ | $10^{-8}$ | $10^{-9}$ | $10^{-10}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Aquifer | Good | | | | | Poor | | | None | | | | |
| Consolidated Rocks | Highly Fractured Rocks | | | Crs-m gr Sandstone | | | F. gr. Sandstone, siltstone | | Limestone, dolomite, claystone | | Granite | | |
| *K* (mD) | $10^{+8}$ | $10^{+7}$ | $10^{+6}$ | $10^{+5}$ | 10,000 | 1,000 | 100 | 10 | 1 | 0.1 | 0.01 | 0.001 | 0.0001 |

Source: modified from Bear (1972)

# 6 Biostratigraphic report on samples from selected cores from Helsingborg

## 6.1 Material and methods

Biostratigraphic (palynological) data has been obtained from 14 cored wells, drilled during 2006 and 2009 in the city of Helsingborg. Three of the wells are located in the northern part of Helsingborg, while the remaining 10 wells are from the southern part of the city. The data from one of the wells (06.1.1008), which encompass 39 samples across the Triassic-Jurassic boundary (Rhaetian–Hettangian) boundary, was already processed for another project. It is included in the dataset herein, as it represents the oldest part of the succession investigated herein, contains several important sequence stratigraphic surfaces, and is as such used as a base level reference. A total number of 35 samples were analyzed from the remaining 13 wells.

For the palynology, c. 20 g of bulk rock was treated in alternating steps with hydrochloric (38%) and hydrofluoric acid (40%) to remove carbonate and silicate mineral phases. After washing to neutrality, residues were sieved with 11 µm mesh-size sieves and mounted on strew slides. Between 200 and 300 palynomorphs were counted per slide with a compound microscope at 650x magnification. Abundance data were calculated as: a) for spores and pollen as the percentage of the spore/pollen assemblage, and b) for aquatic palynomorphs as percentage of the total palynoflora. The microscope slides were further checked for additional taxa not encountered during the counting.

The biostratigraphic analysis of the quantitative data consists of three parts: 1) recording first (FO) and last (LO) occurrences of stratigraphically important taxa, 2) quantitative analysis of the spore-pollen flora, i.e. vegetation signal, and 3) quantitative assessment of the aquatic palynoflora (marine phytoplankton vs freshwater microalgae), which gives an indication of the depositional setting. The results are shown in **Table 5**. Two sets of range charts will be produced for each well, one with the individual species arranged stratigraphically, and one where they are grouped into genera.

The biostratigraphic data, together with log responses and sedimentological information, is used to correlate between the wells, and the distribution the sand layers A–H are marked on the biostratigraphic charts.

**Table 5:** Preliminary results of the biostratigraphic analysis.

| Well/depth | Vegetation signal | Grp | Depositional environment | FS | Markers |
|---|---|---|---|---|---|
| **09.1.2001** | | | | | |
| 7.50m | D>>Pe>Pi>Co | 4 | marine | FS | |
| 11.50m | D>>Pe>Pi>Co | 4 | marginal marine | | |
| 13.32m | D>>Pe>Pi>Co | 4 | marine | (FS) | FO:*Cerebropollenites thiergartii* |
| 25.05m | D>>Pe>Pi | 2 | Marine | FS | LO:*Ricciisporites tuberculatus*<br>LO:*Semiretisporis gothae* |
| 26.90m | D>>Pe>Pi | 2 | Terrestrial | | LO:*Granuloperculatipollis rudis* |

| Well/depth | Vegetation signal | Grp | Depositional environment | FS | Markers |
|---|---|---|---|---|---|
| **09.1.2026** | | | | | |
| 13.65m | Pe>D>>Pi=Ch>Co | 1 | marginal marine | | |
| 19.90m | D>>Co≥Pe>Ch>Pi | 4 | near marine | | FO:*Cerebropollenites thiergartii*<br>LO:*Cingulizonates rhaeticus* |

| Well/depth | Vegetation signal | Grp | Depositional environment | FS | Markers |
|---|---|---|---|---|---|
| **09.1.2027** | | | | | |
| 31.40m | D>>Co≥Pe≥Pi | 3 | marginal marine | | FO:*Cerebropollenites thiergartii*<br>LO:*Ricciisporites tuberculatus*<br>LO:*Granuloperculatipollis rudis* |
| 34.75m | D>>Pi=Co≥Pe | 5 | marginal marine | | LO:*Rhaetogonyaulax rhaetica* |

| Well/depth | Vegetation signal | Grp | Depositional environment | FS | Markers |
|---|---|---|---|---|---|
| **09.1.2033** | | | | | |
| 30.70m | D>>Pe>Ch>Pi>Co | 10 | marginal marine | | |
| 35.00m | D>>Pe≥Pi | 3 | terrestrial | | LO:*Granuloperculatipollis rudis* |

| Well/depth | Vegetation signal | Grp | Depositional environment | FS | Markers |
|---|---|---|---|---|---|
| **09.1.2035** | | | | | |
| 11.55m | D>>Pe>>Co>Ch | 7 | marginal marine | | |
| 25.90m | D=Pe>>Co>Ch>Pi | 9 | marginal marine | | FO:*Cerebropollenites thiergartii*<br>LO:*Rhaetogonyaulax rhaetica*<br>LO:*Lunnomidinium scaniense*<br>LO:*Suessia swabiana*<br>LO:*Polypodiisporites polymicroforatus* |

| Well/depth | Vegetation signal | Grp | Depositional environment | FS | Markers |
|---|---|---|---|---|---|
| **09.1.2009** | | | | | |
| 10.78m | D>>Pe>>Co>Ch=Pi | 8 | near marine | | |
| 26.14m | Pe>D>>Ch>Pi | 2 | near marine | | LO:*Ricciisporites tuberculatus* |

| Well/depth | Vegetation signal | Grp | Depositional environment | FS | Markers |
|---|---|---|---|---|---|
| **09.1.2040** | | | | | |
| 11.30m | Pe>Co≥D>>Pi | 3 | marginal marine | | |

**Table 5** continued…

| Well/depth | Vegetation signal | Grp | Depositional environment | FS | Markers |
|---|---|---|---|---|---|
| **09.1.2021** | | | | | |
| 13.50m | D>Co=Pe>Pi | 5 | marginal marine | | |
| 19.60m | D>>Co>Pe=Pi | 2 | marginal marine | | LO:*Ricciisporites tuberculatus* |
| 19.87m | D>>Co>Pe>Pi | 1 | marginal marine | | FO:*Cerebropollenites thiergartii* |
| 27.25m | D>>Pe>>Co>Pi | 6 | marginal marine | | |

| Well/depth | Vegetation signal | Grp | Depositional environment | FS | Markers |
|---|---|---|---|---|---|
| **09.1.2044** | | | | | |
| 10.95m | Ma>D>Pe>Pi | | terrestrial | ?coal | |
| 29.48m | D>Pe>Ma>Pi | 5 | near marine | | |

| Well/depth | Vegetation signal | Grp | Depositional environment | FS | Markers |
|---|---|---|---|---|---|
| **06.1.2005** | | | | | |
| 22.30m | D>>Pi>Ch≥Pe≥Co | 6 | near marine | | ?FO:*Mendicodinium groenlandicum* |
| 23.93m | D>>Pi>Ch≥Pe≥Co | 6 | near marine | | ?LO:*Dapcodinium priscum* |
| 25.20m | D>>Pi≥Pe>>Ch | 7 | terrestrial | | |
| 25.78m | D>>Pi≥Pe>>Ch | 7 | nearmarine | | FO:*Cerebropollenites thiergartii*<br>LO:*Ricciisporites tuberculatus* |

| Well/depth | Vegetation signal | Grp | Depositional environment | FS | Markers |
|---|---|---|---|---|---|
| **06.1.1011** | | | | | |
| 31.38m | D>>Pi>>Ch>>Pe | 4 | marine | FS | LO:*Polypodiisporites polymicroforatus* |
| 34.70m | D>>Pi>>Ch≥Pe | 3 | near marine | | FO:*Cerebropollenites thiergartii*<br>LO:*Ricciisporites tuberculatus* |
| 34.90m | D>>Pi>>Ch≥Pe | 3 | near marine | | |

| Well/depth | Vegetation signal | Grp | Depositional environment | FS | Markers |
|---|---|---|---|---|---|
| **06.1.1007** | | | | | |
| 11.20m | D≥Pi>>Ch | 2 | near marine | | LO:*Ricciisporites tuberculatus* |
| 11.68m | D>>>> | | terrestrial | | |
| 12.37m | D>>Pi>>Ch | 1 | near marine | | |
| 29.80m | D>>Pi>>Ch | 1 | near marine | | LO:*Perinosporites thuringiacus* |
| | D>>Pi>>Ch | 1 | near marine | | FO:*Cerebropollenites thiergartii*<br>LO:*Limbosporites lundbladiae* |
| 35.68m | | | | | LO:*Densoisporites fissus* |
| 36.58m | D>>Pi>>Ch | 1 | near marine | | |

**Table 5** continued…

| Well/depth | Vegetation signal | Grp | Depositional environment | FS | Markers |
|---|---|---|---|---|---|
| **06.1.1008** | | | | | |
| 4.00m | D>>Ch>Pi | | near marine | | LO:*Ricciisporites tuberculatus* |
| | D>>Pi>>Ch | 1 | near marine | | LO:*Cingulizonates rhaeticus* |
| 5.50m | | | | | LO:*Polypodiisporites polymicroforatus* |
| 7.20m | D>>Pi>>Ch | 1 | near marine | | LO:*Densoisporites fissus* |
| 8.10m | D>>Pi>>Ch | 1 | near marine | | LO:*Limbosporites lundbladiae* |
| 9.00m | D>>Pi>>Ch | 1 | near marine | | |
| 11.68m | D>>Pi>>Ch | 1 | near marine | | |
| 14.33m | D>>Pi>>Ch | 1 | near marine | | LO:*Lunatisporites rhaeticus* |
| 15.60m | D>>Pi>>Ch | 1 | near marine | | |
| 16.28m | D>>Pi>>Ch | 1 | near marine | | FO:*Cerebropollenites thiergartii* |
| 16.44m | D>>Pi>>Ch | 1 | near marine | | |
| 16.54m | Rhaetian RDPi | | near marine | | |
| 16.56m | Rhaetian RDPi | | near marine | | |
| 16.75m | Rhaetian RDPi | | near marine | | |
| 17.20m | Rhaetian RP Zone | | near marine | | |
| 17.82m | Rhaetian RP Zone | | near marine | | |
| 18.30m | Rhaetian RP Zone | | near marine | | |
| 18.80m | Rhaetian RP Zone | | near marine | | |
| 19.44m | Rhaetian RP Zone | | near marine | | |
| 20.58m | Rhaetian RP Zone | | near marine | | |
| 22.61m | Rhaetian RP Zone | | near marine | | |
| 23.33m | Osmundaceae dominance | | near marine | | |
| 24.35m | Rhaetian RPeD | | near marine | | |
| 24.61m | Rhaetian RPeD | | near marine | | |
| 25.63m | Rhaetian RPeD | | near marine | | |
| 27.40m | Rhaetian RPeD | | near marine | | |
| 28.50m | Rhaetian RPeD | | marine | MFS7 | |
| 29.15m | Rhaetian RPeD | | marine | MFS7 | |
| 29.90m | Rhaetian RPeD | | marine | FS | |
| 30.50m | Rhaetian PDR = RL Zone | | marine | FS | |
| 36.90m | Rhaetian PDR = RL Zone | | marginal marine | | |
| 37.12m | Rhaetian PDR = RL Zone | | marginal marine | | |
| 37.52m | Rhaetian PDR = RL Zone | | marine | FS | |
| 37.78m | Rhaetian PDR = RL Zone | | marine | FS | |
| 38.74m | Rhaetian PDR = RL Zone | | marginal marine | | |
| 38.95m | Rhaetian PDR = RL Zone | | marginal marine | | |
| 42.68m | Rhaetian PDR = RL Zone | | marginal marine | | |
| 42.99m | Rhaetian PDR = RL Zone | | marginal marine | | |
| 44.34m | Rhaetian PDR = RL Zone | | marginal marine | | |
| 45.37m | Rhaetian PDR = RL Zone | | marginal marine | | |

**Table 5** continued…

| **Legend** | | | | | |
|---|---|---|---|---|---|
| | | | | **Deltoidospora-Corollina dominance** | |
| **Deltoidospora-Perinopollenites dominance** | | | | D>Co=Pe>Pi | 5 |
| D>>Pe>Ch>Pi>Co | 10 | | | D>>Co≥Pe>Ch>Pi | 4 |
| D=Pe>>Co>Ch>Pi | 9 | | | D>>Co≥Pe≥Pi | 3 |
| D>>Pe>>Co>Ch=Pi | 8 | **Deltoidospora-Pinuspollenites dominance** | | D>>Co>Pe=Pi | 2 |
| D>>Pe>>Co>Ch | 7 | D>>Pi≥Pe>>Ch | 7 | D>>Co>Pe>Pi | 1 |
| D>>Pe>>Co>Pi | 6 | D>>Pi>Ch≥Pe≥Co | 6 | | |
| D>Pe>Ma>Pi | 5 | D>>Pi=Co≥Pe | 5 | | |
| D>>Pe>Pi>Co | 4 | D>>Pi>>Ch>>Pe | 4 | **Perinopollenites dominance** | |
| D>>Pe≥Pi | 3 | D>>Pi>>Ch≥Pe | 3 | Pe>Co≥D>>Pi | 3 |
| D>>Pe>Pi | 2 | D≥Pi>>Ch | 2 | Pe>D>>Ch>Pi | 2 |
| D>>Pe>>Pi | 1 | D>>Pi>>Ch | 1 | Pe>D>>Pi=Ch>Co | 1 |
| **Others** | | Ch=Chasmatosporites | | Ma=Marattisporites | |
| D>>Ch>Pi | | Co=Corollina | | Pe=Perinopollenites | |
| D>>>> Ma>D>Pe>Pi | | D=Deltoidospora | | Pi=Pinuspollenites | |
| FS=flooding surface | | LO=last occurrence | | | |
| MFS=Maximum flooding surface | | FO=first occurrence | | | |

## 6.2 Biostratigraphic well descriptions

### Well 06.1.1008

(**Enclosure 3a:** species range chart; **Enclosure 3b**: genera range chart)

Forty samples from this well were analyzed palynologically in a different project but the results are presented briefly below.

The succession can be divided into three distinct palynological zones, in stratigraphical order:

#### The *Rhaetipollis–Limbosporites* Zone (Lund 1977)

lowermost part of the succession belongs to the *Rhaetipollis-Limbosporites* Zone, which possibly also encompasses the Rhaetian marine sandstone and parts of the black shale above. Below the Rhaetian marine sandstone (which was not sampled for palynology) this part of the succession is predominantly marginal marine with two episodes of fully terrestrial deposition marked by coal.

*Age:* middle Rhaetian

#### The *Ricciisporites–Polypodiisporites* Zone (Lund 1977)

transition between this zone and the preceding middle Rhaetian *Rhaetipollis-Limbosporites* Zone is a bit unclear in this succession, and the boundary is tentatively placed at 29.90 m. A black shale which was deposited during a late Rhaetian marine transgression, maximum flooding surface 7 (MFS7; Nielsen 2003), contains abundant dinoflagellate cysts and spore/pollen floras typical of the *Ricciisporites-Polypodiisporites* Zone.

The next interval uphole, 24.3-16.55 m, is a grey siltstone interval, which can also be recognized in the Stenlille succession (Lindström et al. 2012). This grey siltstone is the distal marginal marine equivalent of the Boserup beds, the coarse grained, poorly sorted unit that makes up the basal Helsingborg Member in many old wells (Troedsson 1951). The grey siltstone interval contains abundant reworked palynomorphs, primarily of Ordovician- Silurian, Carboniferous and Middle Triassic age.

*Age:* late Rhaetian

The Pinuspollenites–Trachysporites Zone (Lund 1977)

This zone encompasses the topmost part of the succession, between 16.54-4.00 m. The base of this zone is marked by an unconformity at 16.55 m.

*Depositional environment:* All samples contain marine phytoplankton in low numbers indicating a coastal (marginal marine) or deltaic (near marine) depositional environment. Rare freshwater algae indicate some freshwater influence.

*Age: Cerebropollenites thiergartii,* the accessory marker for the Triassic-Jurassic boundary, has its FO at 16.54 m, and this together the absence of younger markers, as well as the presence of rare typical Rhaetian palynomorphs (e.g. *Limbosporites lundbladiae, Cingulizonates rhaeticus* and *Ricciisporites tuberculatus*), indicate an early Hettangian age for this part of the succession.

*Correlation:* This part of the succession in 06.1.1008 is believed to represent the some of the oldest Hettangian sedimentary rocks within the Helsingborg composite succession. However, it should be noted that the topmost Rhaetian and the lowermost Hettangian might be missing in 06.1.1008 due to an unconformity at 16.55m.

## Well 06.1.1007

(**Enclosure 3c:** species range chart; **Enclosure 3d:** genera range chart)
Six samples were analyzed palynologically, and they all belong to:

The Pinuspollenites–Trachysporites Zone (Lund 1977)

The assemblages are typical for the *Pinuspollenites-Trachysporites* Zone (Lund 1977) in that they are dominated by fern spores assigned to *Deltoidospora* and the pinacean pollen *Pinuspollenites minimus.* In addition, *Trachysporites* fern spores are consistently present. The taxodiacean/cupressacean pollen *Perinopollenites elatoides* is rare.

*Depositional environment:* All samples contain marine phytoplankton in low numbers indicating a coastal (marginal marine) or deltaic (near marine) depositional environment. Rare freshwater algae indicate some freshwater influence.

*Age:* The consistent but rare presence of *Cerebropollenites thiergartii* (marker species for the Triassic–Jurassic boundary), and lack of *Cerebropollenites macroverrucosus* (marked species for the Hettangian–

Sinemurian boundary) confirm a Hettangian age from the sampled succession. Typical Rhaetian spores and pollen are present in low numbers. *Limbosporites lundbladiae, Densoisporites fissus* and *Perinosporites thuringiacus* are recorded in the lower part of the succession only, while rare fragments and tetrads of the enigmatic gymnosperm pollen *Ricciisporites tuberculatus* are recorded in almost all samples. The presence of these typical Rhaetian taxa may indicate an early Hettangian age (Koppelhus & Batten 1996; Batten & Koppelhus 1996; Lindström 2003; Lindström & Erlström 2006). The continuous presence of the dinoflagellate cyst *Dapcodinium priscum,* which has its LO at top early Sinemurian, further corroborates a Hettangian age (Poulsen & Riding 2003).

*Correlation:* The lower part (36.58-29.80m) of well 06.1.1007 correlates palynologically to the uppermost part (4.00-8.00m) of well 06.1.1008.

## Well 06.1.1011

(**Enclosure 3e:** species range chart; **Enclosure 3f:** genera range chart)

Three samples were analyzed palynologically, and they can all be assigned to:

### The Pinuspollenites–Trachysporites Zone (Lund 1977)

The assemblages are typical for the *Pinuspollenites-Trachysporites* Zone (Lund 1977) in that they are dominated by fern spores assigned to *Deltoidospora* and the pinacean pollen *Pinuspollenites minimus.* In addition, *Trachysporites* fern spores are consistently present. The taxodiacean/cupressacean pollen *Perinopollenites elatoides* is present but not abundant.

*Depositional environment:* The lower two samples contain rare *Dapcodinium priscum* (marine dinoflagellate cyst) which indicates deposition in a near marine environment. The uppermost sample contains abundant marine phytoplankton in indicating a marginal marine to marine depositional environment. Rare freshwater algae indicate some freshwater influence.

*Age:* The occurrence of *Cerebropollenites thiergartii* (marker species for the Triassic–Jurassic boundary) in the lowermost sample, and the lack of *Cerebropollenites macroverrucosus* (marked species for the Hettangian–Sinemurian boundary) confirm a Hettangian age from the sampled succession. The last occurrences of typical Rhaetian spores and pollen; the schizacean fern spore *Polypodiisporites polymircoforatus* and the enigmatic gymnosperm pollen *Ricciisporites tuberculatus* may indicate an early Hettangian age (Koppelhus & Batten 1996; Batten & Koppelhus 1996; Lindström 2003; Lindström & Erlström 2006). The continuous presence of the dinoflagellate cyst *Dapcodinium priscum*, which has its LO at top early Sinemurian, further corroborates a Hettangian age (Poulsen & Riding 2003).

*Correlation:* Palynologically the investigated samples form 06.1.1011 belongs to the same zone as the uppermost part (4.00-8.00m) of well 06.1.1008, and the lower part (36.58-29.80m) of well 06.1.1007, but is considered somewhat younger.

## Well 09.1.2001

(**Enclosure 3g:** species range chart; **Enclosure 3h:** genera range chart)
Five samples from this well were analyzed palynologically, and they all belong to:

### The Pinuspollenites–Trachysporites Zone (Lund 1977)

The assemblages are typical for the *Pinuspollenites-Trachysporites* Zone (Lund 1977) in that they are dominated by fern spores assigned to *Deltoidospora* and contain common fern spores of the genus *Trachysporites.* However, the pinacean pollen *Pinuspollenites minimus,* is less abundant than in the wells to the north. The taxodiacean/cupressacean pollen *Perinopollenites elatoides* generally occurs in somewhat higher frequencies in the samples than *P. minimus.*

*Depositional environment:* All samples except the lowermost one contain abundant marine phytoplankton marginal marine depositional environment. For the lowermost sample a near marine depositional environment is assumed based on low amounts of marine phytoplankton. Rare freshwater algae indicate some freshwater influence.

*Age: Cerebropollenites thiergartii* (marker species for the Triassic–Jurassic boundary) is first registered in the middle part of the investigated sequence, but this taxon is usually very rare when it first appears.  The lack of *Cerebropollenites macroverrucosus* (marked species for the Hettangian–Sinemurian boundary) confirm a Hettangian age from the sampled succession. Several typical Rhaetian spores and pollen are recorded in low numbers in the lowermost part of the sampled succession, namely *Granuloperculatipollis rudis, Semiretisporis gothae* and *Ricciisporites tuberculatus*. The presence of these typical Rhaetian taxa may indicate an early Hettangian age for the lower part of the sequence (Koppelhus & Batten 1996; Batten & Koppelhus 1996; Lindström 2003; Lindström & Erlström 2006). The continuous presence of the dinoflagellate cyst *Dapcodinium priscum,* which has its LO at top early Sinemurian, further corroborates a Hettangian age (Poulsen & Riding 2003).

*Correlation:* Although there is a difference in floral composition, the assemblages from the lower part of 09.1.2001 appear to correspond to those from 06.1.1007 and 06.1.1011.

## Well 09.1.2026

(**Enclosure 3i:** species range chart; **Enclosure 3j:** genera range chart)

Two samples from this well were analysed palynologically, and they both belong to:

### The Pinuspollenites–Trachysporites Zone (Lund 1977)

The assemblages are typical for the *Pinuspollenites*-*Trachysporites* Zone (Lund 1977) in that they are dominated by fern spores assigned to *Deltoidospora* and contain common fern spores of the genus *Trachysporites.* However, the pinacean pollen *Pinuspollenites minimus,* is less abundant than in the wells to the north. The taxodiacean/cupressacean pollen *Perinopollenites elatoides* is more abundant than *P. minimus*, and actually become dominant in the upper sample. Also abundant are cheirolepidiacean conifer pollen assigned to *Corollina.*

*Depositional environment:* The presence of marine phytoplankton indicates a near marine depositional environment.

*Age: Cerebropollenites thiergartii* (marker species for the Triassic–Jurassic boundary) is registered in the lower of the two samples, together with rare occurrences of the typical Rhaetian spores and pollen *Cingulizonates rhaeticus* and *Ricciisporites tuberculatus*, which may indicate an early Hettangian age for the lower part of the succession (Koppelhus & Batten 1996; Batten & Koppelhus 1996; Lindström 2003; Lindström & Erlström 2006). A single specimen of the Rhaetian dinoflagellate cyst *Suessia swabiana* is considered reworked. The lack of *Cerebropollenites macroverrucosus* (marked species for the Hettangian–Sinemurian boundary) confirms a Hettangian age from the sampled succession. The continuous presence of the dinoflagellate cyst *Dapcodinium priscum,* which has its LO at top early Sinemurian, further corroborates a Hettangian age (Poulsen & Riding 2003).

*Correlation:* Although there is a difference in floral composition, the assemblages correlate with those from 09.1.2001.

## Well 09.1.2027

(**Enclosure 3k:** species range chart; **Enclosure 3l:** genera range chart)

Two samples from the lower part of this well were analyzed palynologically, and they both belong to:

The Pinuspollenites–Trachysporites Zone (Lund 1977)

The assemblages are typical for the *Pinuspollenites-Trachysporites* Zone (Lund 1977) in that they are dominated by fern spores assigned to *Deltoidospora* and contain common fern spores of the genus *Trachysporites.* The pinacean pollen *Pinuspollenites minimus* and the taxodiacean/cupressacean pollen *Perinopollenites elatoides* are equally abundant, as are cheirolepidiacean conifer pollen assigned to *Corollina.*

*Depositional environment:* The common occurrence of marine phytoplankton indicates a marginal marine depositional environment.

*Age: Cerebropollenites thiergartii* (marker species for the Triassic–Jurassic boundary) is registered in the upper of the two samples, together with rare occurrences of the typical Rhaetian pollen *Granuloperculatipollis rudis* and *Ricciisporites tuberculatus*, which may indicate an early Hettangian age. A single specimen of the Rhaetian dinoflagellate cyst *Rhaetogonyaulax rhaetica* is considered reworked. The lack of *Cerebropollenites macroverrucosus* (marked species for the Hettangian–Sinemurian boundary) confirms a Hettangian age from the sampled succession. The continuous common presence of the dinoflagellate cyst *Dapcodinium priscum,* which has its LO at top early Sinemurian, further corroborates a Hettangian age (Poulsen & Riding, 2003).

*Correlation:* The assemblages correlate well with those from 09.1.2026.

## Well 09.1.2033

(**Enclosure 3m:** species range chart; **Enclosure 3n:** genera range chart)

Two samples from the lower part of this well were analyzed palynologically, and they both belong to:

The Pinuspollenites–Trachysporites Zone (Lund 1977)

The assemblages are typical for the *Pinuspollenites-Trachysporites* Zone (Lund 1977) in that they are dominated by fern spores assigned to *Deltoidospora* and contain common fern spores of the genus *Trachysporites. Pinuspollenites minimus* and *Perinopollenites elatoides* are common, and a little more abundant than cheirolepidiacean conifer pollen assigned to *Corollina.* Pollen assigned to *Chasmatosporites* are also common.

*Depositional environment:* The high abundance of spores (*Deltoidospora, Calamospora)* and virtual lack of marine phytoplankton in the lower sample indicate terrestrial deposition. The presence of marine phytoplankton indicates a near marine depositional environment for the upper sample.

*Age:* Neither *Cerebropollenites thiergartii* (marker species for the Triassic–Jurassic boundary), nor the marker for the Hettangian–Sinemurian boundary, *Cerebropollenites macroverrucosus,* were registered in the two samples. The only typical Rhaetian taxon encountered was a single specimen of *Granuloperculatipollis rudis* which may be reworked. The general lack of typical Rhaetian taxa may indicate a late Hettangian age. The presence of the dinoflagellate cyst *Dapcodinium priscum* in the lower assemblages indicates a Hettangian to early Sinemurian age (Poulsen & Riding 2003).

*Correlation:* The assemblages are interpreted as being a little younger than those from 09.1.2026 and 09.1.2027.

## Well 09.1.2035

(**Enclosure 3o:** species range chart; **Enclosure 3p:** genera range chart)

Two samples from the middle part of this well were analyzed palynologically, and they both belong to:

### The Pinuspollenites–Trachysporites Zone (Lund 1977)

The assemblages are not typical for the *Pinuspollenites-Trachysporites* Zone (Lund 1977). They are dominated by fern spores assigned to *Deltoidospora,* and fern spores of the genus *Trachysporites* are also present, but *Pinuspollenites minimus* are not abundant. Instead *Perinopollenites elatoides* dominate together with *Deltoidospora*.

*Depositional environment:* The presence of marine phytoplankton indicates a near marine depositional environment for these samples.

*Age: Cerebropollenites thiergartii* (marker species for the Triassic–Jurassic boundary) is present in both samples, but *Cerebropollenites macroverrucosus* - the marker for the Hettangian–Sinemurian boundary was not registered indicating a Hettangian age. Only one typical Rhaetian pollen is recorded, in the lower sample, together with single occurrences of typical Rhaetian dinoflagellate cysts *Lunnomidnium scanience*, *Rhaetogonyaulax rhaetica* and *Suessia swabiana*, and these are all considered reworked. The continued presence of the dinoflagellate cyst *Dapcodinium priscum* in the lower assemblages indicates a Hettangian to early Sinemurian age (Poulsen & Riding 2003).

*Correlation:* The assemblages are interpreted as being a little younger than those from 09.1.2033.

## Well 09.1.2040

(**Enclosure 3q:** species range chart; **Enclosure 3r:** genera range chart)

A single sample from the upper part of this well was analyzed palynologically, and assigned to:

### The Pinuspollenites–Trachysporites Zone (Lund 1977)

The assemblage is not typical for the *Pinuspollenites-Trachysporites* Zone (Lund 1977) in that it is dominated by *Perinopollenites elatoides, Corollina* and *Deltoidospora*. The nominate taxa, *Pinuspollenites minimus* and *Trachysporites* spp., are both common but less abundant than the previous three.

*Depositional environment:* The presence of marine phytoplankton indicates a near marine depositional environment for this sample.

*Age:* Neither *Cerebropollenites thiergartii* (marker species for the Triassic–Jurassic boundary) nor *Cerebropollenites macroverrucosus* - the marker for the Hettangian–Sinemurian boundary have been recorded, but the presence of the dinoflagellate cyst *Dapcodinium priscum* in the lower assemblages indicates a Hettangian to early Sinemurian age (Poulsen and Riding 2003). No typical Rhaetian taxa were recorded in this assemblage.

*Correlation:* The assemblage is interpreted as being a little younger than those from 09.1.2035.

## Well 09.1.2009

(**Enclosure 3s:** species range chart; **Enclosure 3t:** genera range chart)

Two samples from this well were analyzed palynologically, and they both belong to:

### The Pinuspollenites–Trachysporites Zone (Lund 1977)

The assemblages are dominated by *Perinopollenites elatoides* and *Deltoidospora*. The nominate taxa, *Pinuspollenites minimus* and *Trachysporites* spp., are common and present, respectively.

*Depositional environment:* The presence of marine phytoplankton indicates a near marine depositional environment for this sample.

*Age:* Neither *Cerebropollenites thiergartii* (marker species for the Triassic–Jurassic boundary) nor *Cerebropollenites macroverrucosus* - the marker for the Hettangian–Sinemurian boundary, have been recorded, but the presence of the dinoflagellate cyst *Dapcodinium priscum* in the lower assemblages indicates a Hettangian to early Sinemurian age (Poulsen and Riding 2003). The only Rhaetian taxon encountered was *Ricciisporites tuberculatus,* which is herein considered reworked.

*Correlation:* The assemblages correlate to those from 09.1.2035.

## Well 09.1.2044

(**Enclosure 3u:** species range chart; **Enclosure 3v:** genera range chart)
Two samples from this well were analyzed palynologically, and they are both assigned to:

### The Pinuspollenites–Trachysporites Zone (Lund 1977)

The lower assemblage is dominated by *Deltoidospora* and *Perinopollenites elatoides*. The nominate taxa, *Pinuspollenites minimus* and *Trachysporites* spp., are common and present, respectively. The upper assemblage is totally dominated by fern spores assigned to *Deltoidospora* and *Marattisporites scabratus.* Also abundant are caytonialean pollen assigned to *Vitreisporites.* The nominate taxa *Pinuspollenites minimus* and *Trachysporites* spp. are both present.

*Depositional environment:* The presence of marine phytoplankton indicates a near marine depositional environment for the lower sample. The upper sample clearly represents a coal mire flora and fully terrestrial conditions.

*Age:* Neither *Cerebropollenites thiergartii* (marker species for the Triassic–Jurassic boundary) nor *Cerebropollenites macroverrucosus* - the marker for the Hettangian–Sinemurian boundary, have been recorded, but log-correlation with nearby wells indicates a Hettangian age. The only Rhaetian taxon encountered was *Limbosporites lundbladiae,* and it is considered reworked.

*Correlation:* The assemblages are considered younger than those from 09.1.2009 and 09.1.2035. They are considered age equivalent to the lower two assemblages from 09.1.2021 but older to the upper two assemblages from that well.

## Well 09.1.2021

(**Enclosure 3w:** species range chart; **Enclosure 3x:** genera range chart)

Four samples from this well were analyzed palynologically, and they two biozones were recognized, in stratigraphic order:

### The Pinuspollenites–Trachysporites Zone (Lund 1977)

The two upper assemblages are assigned to this zone based on the absence of *Cerebropollenites macroverrucosus,* the nominate taxon for the succeeding zone. These two assemblages do not differ markedly from those above, and are as such non-typical for the *Pinuspollenites-Trachysporites* Zone. They are dominated by *Deltoidospora, Corollina* and *Perinopollenites elatoides. Pinuspollenites minimus* are still common and *Trachysporites* still present.

*Depositional environment:* The common presence of marine phytoplankton indicates a marginal marine depositional environment for these two samples.

*Age: Cerebropollenites thiergartii* (marker species for the Triassic–Jurassic boundary) is recorded in the upper of the two assemblages, but *C. macroverrucosus* was not encountered. The presence of the dinoflagellate cyst *Dapcodinium priscum* in the lower assemblages indicates a Hettangian to early Sinemurian age (Poulsen and Riding 2003). The only Rhaetian taxon encountered was *Cingulizonates rhaeticus,* which is here considered reworked, as are some typical Carboniferous spores.

*Correlation:* The assemblages correlate to those from 09.1.2044, although the palynofloral composition is somewhat different with much more abundant *Corollina* in the present assemblages.

### The Cerebropollenites macroverrucosus Zone (Dybkjær 1991)

The two upper assemblages are assigned to this zone based on the presence of the nominate taxon *Cerebropollenites macroverrucosus.* These two assemblages do not differ markedly from those below. They are dominated by *Deltoidospora, Corollina* and *Perinopollenites elatoides. Pinuspollenites minimus* are still common and *Trachysporites* still present.

*Depositional environment:* The presence of marine phytoplankton indicates a near marine to restricted marine depositional environment for these two samples.

*Age:* The presence of *Cerebropollenites macroverrucosus*, the marker for the Hettangian–Sinemurian boundary, indicates an early Sinemurian age for these assemblages. The continued presence of the dinoflagellate cyst *Dapcodinium priscum,* which has its LO at the top of the lower Sinemurian, corroborates an early Sinemurian age (Poulsen & Riding 2003). The only Rhaetian taxon encountered was *Ricciisporites tuberculatus,* which is herein considered reworked, as are some single occurrences of typical Carboniferous spores.

*Correlation:* The assemblages are considered younger than those from 09.1.2044.

## 6.3 Review of the stratigraphy of the Øresund cores

Biostratigraphic and sedimentological information from cores drilled in Øresund between the cities of Helsingør, Denmark, and Helsingborg, Sweden, have been presented in Larsen et al. (1968) and Koppelhus & Batten (1996). These papers show the presence of Lower to Upper Jurassic sedimentary rocks in the straight. The strata are generally dipping towards the west. Below is a short review of the sedimentary succession, which contains a more sandy Lower Jurassic (Hettangian–lower Sinemurian) succession and a more fine-grained (clay and silt dominated upper Lower Jurassic–Middle Jurassic succession (upper Sinemurian–Bajocian).

### 6.3.1 Lower Jurassic

*Höganäs Formation, Helsingborg Member*

Sedimentary rocks belonging to the lowermost Jurassic (Hettangian) Helsingborg Member were identified in boreholes 19, 18 and 13 (Larsen et al. 1968). Biostratigraphic data (palynology) further corroborate this as that these three boreholes all belong to the *Pinuspollenites–Trachysporites* Zone, which is Hettangian in age (Koppelhus & Batten 1996). The authors make the distinction that borehole 19 is somewhat older, early Hettangian, due to the sporadic presence of typical Rhaetian taxa e.g. *Ricciisporites tuberculatus, Limbosporites lundbladiae* and *Ovalipollis ovalis*, while the lack of these relict forms in boreholes 18 and 13 indicate a late Hettangian age (Koppelhus & Batten 1996).

Assemblages from the lower part of boreholes 8 and 9 are typical of the Hettangian *Pinuspollenites-Trachysporites* Zone (Koppelhus & Batten 1996).

Within the Helsingborg Member succession in the Øresund boreholes there are a number of fine- to medium-grained sandstone units.

*Rya Formation, Döshult member*

In boreholes 8 and 9 a fine- to coarse-grained sandstone unit with bivalves is identified as the lower part of the Döshult Member (Larsen et al. 1968; Ahlberg et al. 2003). In borehole 8 this sandstone unit is 15 m thick, and somewhat thinner in borehole 9 (Larsen et al. 1968). Below this unit the strata in boreholes 8 and 9 also contains fine- to coarse-grained sandstone units that were not included in the Pankarp sand by Larsen et al. (1968). In boreholes 8 and 9 the basal 37 m and 56 m, respectively, are dominated by these sandstones.

*Rya Formation, Pankarp member*

The topmost parts of boreholes 8 and 9 consist of grey-black mudstones which belong to the Pankarp Member (Larsen et al. 1968; Ahlberg et al. 2003). The first occurrence (FO) of *Cerebropollenites macroverrucosus* in the lowermost part of the Pankarp Member in borehole 9 confirms a Sinemurian age for this part of the succession (Koppelhus & Batten 1996). It should be noted that the boundary between the

Hettangian and the Sinemurian could be located lower in the succession, in the uppermost part of the Helsingborg Member, as Larsson (2009) identified *C. macroverrucosus* in both the heterolithic section at Kulla Gunnarstorp and a temporary excavation at Laröd. The clayey Pankarp Member is also present in boreholes 11, 10 and 14 which are all assigned to the Sinemurian-Pliensbachian *Cerebropollenites macroverrusosus* Zone by Koppelhus & Batten (1996). In Øresund the Pankarp Member is estimated to be 40 m thick (Larsen et al. 1968), but in Scania the estimated thickness is c. 70 m (Ahlberg et al. 2003). Pankarp Member is also present in the lower part of borehole 15 (below 68m; Grigelis & Norling 1999).

### *Rya Formation, Katslösa Member*

This unit is characterized by greenish, brownish and dark grey mudstones with shells and grey siltstones and fine-grained sandstones with shells, and various contents of iron and carbonate (Grigelis & Norling 1999). It is identified in the uppermost part of borehole 15, according to Grigelis & Norling (1999) from c. 68 m and upwards. A sample from 44.5 m in borehole 15, just below the succeeding Katslösa Member, was dated as early Pliensbachian by Koppelhus & Batten (1996), indicating a Pliensbachian age for the Katslösa Member.

### *?Rya Formation, Rydebäck Member*

Borehole 3 contains a c. 40 m thick siltstone succession (Larsen et al. 1968) which according to Koppelhus & Batten (1996) also belongs to the *Cerebropollenites macroverrusosus* Zone, but the presence of dinoflagellate cysts assigned to the genus *Nannoceratopsis* indicates a late Pliensbachian age for the succession.

A similar succession is encountered in borehole 2. The lower part of borehole 2 contained palynofloras typical of the *Spheripollenites–Leptolepidites* Zone and were assigned a Toarcian age (Koppelhus & Batten 1996).

### *Vilhelmsfält Formation*

In the upper part of borehole 2, as well as in borehole 7, Koppelhus & Batten (1996) typical Middle Jurassic (Aalenian–Bajocian) palynofloras of the *Callialasporites–Perinopollenites* Zone. The c. 30 m thick coal and clay dominated succession in borehole 7 is assigned to the Vilhelmsfält Formation by Grigelis & Norling (1996).

# 7 Identification of geological marker beds

The Lower Jurassic succession in the eastern parts of the Danish Basin is characterized by a number of repeatedly occurring similar lithologies reflecting shallow marginal marine and coastal depositional settings, including lagoonal, fluvial, estuarine, shoreline and marine facies associations. This facies framework results in frequent lateral as well as vertical shifts in lithological characteristics, which consequently delimits the occurrence of widely distributed marker beds.

The well data in Helsingborg including wire-line logs, core descriptions and core photographs have been examined for characteristic layers, e.g. sandstone and coal beds which could be intimately connected with construction of the vertical composite profile based on Helsingborg data.

The main regional marker found is a marine black clay (corresponding to the interval including the marked MFS7 surface of Nielsen 2003) close to the Rhaetian–Hettangian boundary, which marks a section with the oldest sequences found in the examined shallow wells in Helsingborg. The bed is well defined by palynomorphs and occurs at 30 metres depth in 06.1.1008 above a c. 5 m thick homogeneous cross bedded medium-grained sandstone on top of a sequence with claystone, thin coal seams and rootlet beds, typical for the Rhaetian Bjuv Member.

The construction of the overlying younger part of the composite section is based on the occurrence of a few important local marker beds and log motifs that makes it possible to build the succession laterally. Two minor coal beds found in connection to the D sand tie the correlation between the wells 09.1.2001, 09.1.2026 and 09.1.2027. The serrated log motif of the E sand and the G sand with a sharp base and fining upward trend are significant features used to combine the wells 09.1.21, 09.1.16 and 09.1.2044.

A general dip of the Lower Jurassic succession in south Helsingborg with successively younger strata to the south is shown in seismic lines 3 & 4. This does also, together with the lithological, wire-line logging and biostratigraphic information from wells along these lines, support the construction of the composite section.

# 8 Core analysis data: Porosity, permeability and grain density

Eleven wells, i.e. the wells 09-KB-2001, -2009, -2021, -2026, -2027, -2029, -2033, -2035, -2040, -2044 and Fleninge-1, have been cored, and in total 37 representative plug samples, covering the shallow depth interval 7–41 metres below surface, were taken and prepared for conventional core analysis (CCAL). The GEUS Core Laboratory analysed the plug samples (i.e. 30 horizontal and 7 vertical plugs), measuring helium-porosity, gas-permeability and grain density as listed in **Table 6** below. The corresponding porosity-permeability plot (**Figure 7**) provides a reasonable correlation between porosity and permeability, despite that outliers exist in the database (refer e.g. to data from Fleninge-1 and 09-KB-2026). **On <u>average</u>** the core analysis data point to reservoir sandstone porosities of c. 25% associated with gas-permeabilities in the range 100–4000 mD (laboratory data).

**Table 6:** List of core analysis data from the 09-KB-20xx wells drilled in the Helsingborg city area. The plug samples were analysed by the GEUS Core Analysis Laboratory in 2014. Horizontal & Vertical plugs.

| Plug GEUS ID | Well SGU ID | Plug SGU Lab no. | Depth [m] | Plug H/V | Por.(He) [%] | Gas perm. [mD] | Grain dens. [g/cc] | Comment |
|---|---|---|---|---|---|---|---|---|
| 1 | 2001 | 28B1 | 38.99 | Hori. | 28.51 | 1480 | 2.644 | |
| 1V | 2001 | 28B1 | 38.99 | Vert. | 28.70 | 1128 | 2.639 | |
| 2 | 2009 | 32B2 | 40.49 | Hori. | 27.65 | 4805 | 2.657 | |
| 3 | 2009 | 26B1 | 31.45 | Hori. | 28.28 | 4136 | 2.642 | |
| 4 | 2009 | 29A3 | 35.45 | Hori. | 29.29 | 1828 | 2.656 | |
| 5 | 2009 | 29 | 35.80 | Hori. | 25.03 | 1223 | 2.664 | |
| 5V | 2009 | 29 | 35.80 | Vert. | 26.96 | 1900 | 2.648 | |
| 6 | 2009 | 25B2 | 29.97 | Hori. | 27.36 | 3181 | 2.641 | |
| 7 | 2009 | 19B1 | 21.30 | Hori. | 14.12 | 0.81 | 2.653 | |
| 8 | 2009 | 16A1 | 17.01 | Hori. | 17.77 | 1.51 | 2.651 | |
| 9 | 2021 | 25B1 | 31.44 | Hori. | 23.90 | 262 | 2.641 | |
| 9V | 2021 | 25B1 | 31.44 | Vert. | 24.24 | 94.3 | 2.641 | |
| 10 | 2021 | 15A1 | 15.30 | Hori. | 24.48 | 471 | 2.652 | |
| 11 | 2021 | 26A1 | 31.82 | Hori. | 24.69 | 596 | 2.644 | |
| 12 | 2021 | 24B2 | 30.03 | Hori. | 26.40 | 1080 | 2.642 | |
| 13 | 2026 | 23A1 | 29.40 | Hori. | 24.72 | 236 | 2.667 | |
| 14 | 2026 | 14B1 | 16.27 | Hori. | 27.66 | 1511 | 2.640 | |
| 15 | 2026 | 10B1 | 10.03 | Hori. | 19.47 | 998 | 2.638 | |
| 15V | 2026 | 10B1 | 10.03 | Vert. | 19.27 | 946 | 2.641 | |
| 16 | 2026 | 22B1 | 28.50 | Hori. | 9.14 | 31.0 | 2.668 | |
| 17 | 2027 | 23A1 | 29.45 | Hori. | 25.87 | 385 | 2.642 | |
| 18 | 2027 | 20B2 | 25.38 | Hori. | 25.70 | 2111 | 2.642 | Fractured |
| 19 | 2029 | 24A1 | 30.30 | Hori. | 29.24 | #I/T | 2.639 | Plug conical |
| 19V | 2029 | 24A1 | 30.30 | Vert. | 29.33 | 3870 | 2.642 | |
| 20 | 2029 | 17B3 | 20.54 | Hori. | 29.35 | 3047 | 2.641 | |
| 21 | 2029 | 8C1 | 7.48 | Hori. | 24.12 | 1125 | 2.648 | |
| 22 | 2029 | 17B1 | 20.35 | Hori. | 27.72 | 1193 | 2.657 | |
| 23 | 2033 | 19B1 | 23.80 | Hori. | 24.49 | 1082 | 2.653 | |
| 24 | 2033 | 17B2 | 20.94 | Hori. | 23.02 | 238 | 2.632 | |
| 25 | 2035 | 17B1 | 19.80 | Hori. | 25.70 | 455 | 2.655 | Fracs; clay lam. |
| 25V | 2035 | 17B1 | 19.80 | Vert. | 25.25 | 30.6 | 2.644 | |
| 26 | 2035 | 24B1 | 30.14 | Hori. | 19.77 | 32.0 | 2.646 | |
| 27 | 2040 | 22C1 | 26.53 | Hori. | 3.05 | #I/T | 2.666 | Perm < 0.05 mD |
| 28 | 2044 | 29-3 | 32.90 | Hori. | 27.36 | 966 | 2.644 | |
| 29 | 2044 | 29-2 | 33.06 | Hori. | 26.10 | 1065 | 2.649 | |
| 30 | Fleninge | | | Hori. | 22.60 | 3982 | 2.644 | |
| 30V | FleningeV | | | Vert. | 22.45 | 3736 | 2.649 | |

# 9 Interpretation of well-log data from selected wells and evaluation of reservoir properties

A number of geotechnical test wells were drilled in the Helsingborg city area in 2006 and 2009 prior to planned construction works. Both geophysical logs and core material are available from these wells along with hydro-geological analyse, geological and geotechnical reports etc. A rather large geological database suitable for evaluating reservoir properties thus exists. Through SGU (Sveriges Geologiske Undersökninger) GEUS got access to core samples and well log data from selected wells located in the Helsingborg area. The wells drilled in 2006 and 2009 are named 06-HB-xxxx and 09-KB-xxxx, respectively, where xxxx is a serial number.

The wells were drilled in relation to geotechnical and hydro-geological investigations and consequently, only a limited number of log types were run in the boreholes, implying that a standard petrophysical evaluation, including e.g. porosity determination, cannot be performed. However, core analysis data from 11 wells located in the area of interest makes it possible to evaluate reservoir parameters of particular formations in selected wells. In relevant intervals the log data have been used to disseminate information from cored sections into un-cored parts.

The well-logs acquired in the 06-HB and 09-KB wells comprise caliper, natural gamma, conductivity, formation resistivity and flow. In addition, sonic logs of reasonably good quality are available from the 06-HB-1007, 06-HB-2002 and 06-HB-2009 wells. The log data form the basis of a standard lithological interpretation of the drilled sections, encompassing sandstone, shale/mudstone and occasionally calcite cemented layers. The lithological interpretation is followed by a quantitative reservoir analysis.

## 9.1 Combined analysis of log and core data

No density, neutron or sonic logs were acquired in the wells, meaning that a conventional petrophysical evaluation cannot be carried out. Instead the porosity was calculated from the resistivity and GR logs using the porosity data as calibration data. Potential reservoir intervals, being up to 10 metres thick, have been interpreted from the log data acquired in the 09-KB-2009, -2021, -2026, -2029, -2033, -2035, -2044 wells. Interpreted porosities are generally in the 23–30% range, and corresponding gas-permeabilities, being in the 200–4500 mD range, are interpreted from the porosity-permeability plot presented in **Figure 7**. Hence the combined analysis of log and core data indicates that potential reservoir sandstone layers exist in the Helsingborg city area and in several of the wells analysed, the sandstone layers are characterised by high porosity and high permeability. At reservoir scale (field scale) the permeability level is expected to be even higher than signified by the core analysis data. Data from areas outside the Helsingborg area point to reservoir permeabilities that may be at least 1.25 times higher than gas-permeabilities measured on core plugs in the laboratory (Nielsen et al. 2014).

### 9.1.1 Log interpretation procedure

A full log suite is not available from any of the study wells and thus a conventional petrophysical approach cannot be applied. GEUS suggests, however, an alternative approach to evaluate the porosity distribution on the basis of core data and resistivity logs. The log interpretation procedure is summarised below.

- The total porosity is calculated from Archie's Equation assuming that the water saturation is 100% (*Sw* = 1), and that the petrophysical parameters are standard values, i.e. *'a' = 1; 'm' = 'n' = 2*. Furthermore, it is assumed that true formation resistivity (*Rt*) equals the formation resistivity log readings ("Form.Res" log) and that the formation water resistivity ( *Rw*) equals 3.5 ohmm:

$$PHIT = \sqrt{aRw/Rt} = \sqrt{3.5/(Formation\ resistivity\ log)}$$

  The formation water resistivity ( *Rw* = 3.5 ohmm) is estimated from an iterative process using the core porosity data as calibration points. This *Rw* value is well specific, but herein it is considered valid (or partly valid) for the remaining Helsingborg-KB-wells drilled in 2009. This assumption introduces some uncertainty on the log-derived porosity estimates.

- Next the shale volume (*Vshale*) is calculated from the *Natural Gamma* log:

$$Vshale = Natural\ Gamma/150$$

- Finally, the effective porosity (*PHIE*) is calculated from total porosity and shale volume:

$$PHIE = PHIT - PHIT \cdot Vshale$$

The permeability is estimated from two porosity-permeability relationships:

- The regional GEUS model (PERM_log). Reference is made to **Figure 8**, which includes the regional Danish trend line based on various Danish onshore well. The Helsingborg data are plotted for comparison. It appears that on average, the Swedish data deviate from the regional Danish trend. **Figure 9** is a refinement of the regional porosity-permeability relationship (**Figure 8**) including only measurements on samples of Gassum Formation age.
- The local Helsingborg model (PERM_HBG), i.e. the porosity-permeability relation illustrated in **Figure 7.**

## 9.2 Results of the log interpretations, exemplified by representative well-log evaluations

The log analysis aims at assessing the porosity and permeability in the sandstone reservoirs, and results are presented in tables and plots. An example of such a result display is given in **Figure 10,** which show an evaluation of the 09-KB-2009 well. The lithological interpretation is plotted along with an evaluation of shale volume and the porosity distribution. In addition, a number of raw log curves are illustrated and the core porosity data are plotted as point data.

Two different permeability curves, based on the regional model and the Helsingborg model respectively, is plotted in **Figure 10** along with core permeability data (CPERM). It appears that the local permeability curve based on the Helsingborg data is more optimistic than the permeability curve calculated from the regional model. The higher permeability level at Helsingborg may be a consequence of shallow depth, but nevertheless the relatively late uplift of the (Höganäs Formation/Lower Jurassic Unit) sandstones at Helsingborg supports the idea of similar (or slightly lower) permeabilities to be present at Helsingør, despite the reservoir sandstones are buried deeper at Helsingør.

For the depth interval 28.7–38.7 m MD in the 09-KB-2009 well, an average gas-permeability of 470 mD is estimated from the regional GEUS model, but a significantly higher average permeability (1030 mD) is estimated from the Helsingborg model (see **Table 7** below). Due to the fact that a clear correlation porosity and permeability does not exist, a final average gas-permeability of 700 mD (range of 150–3500 mD) is suggested for this interval in order to account for the uncertainty. The reservoir permeability is, however, somewhat higher, as up-scaling is needed to account for the effect of changing scale from laboratory scale field scale. As previously described, a scaling factor of 1.25 is suggested.

The reservoir parameters for selected wells other than 09-KB-2009 have been calculated and tabulated in **Table 7**–**Table 11**. The uppermost parts of the well sections are generally not logged, meaning that the gross and net sand thicknesses usually are minimum values, which again affects the transmissivity assessments given in the tables (the transmissivities are thus also minimum values). Furthermore, the entire Höganäs Formation/Lower Jurassic Unit is not always fully drilled, which also affect calculation of formation specific parameters.

**Table 7:** Reservoir parameters for the Höganäs Formation/Lower Jurassic Unit reservoir sandstone(s) found in the 09-KB-2009 well. Result of log evaluation, cut-offs: Vshale <30% and porosity >15%.

| **Model:** | **Depth** | **Sand thickness** | | **N/G** | **Porosity** | **Est. Perm** | | **Transmissivity** | |
|---|---|---|---|---|---|---|---|---|---|
| | (m, MD) | **Gross** (m) | **Net** (m) | | (%) | **Gas** (mD) | **Reservoir** (mD) | (Dm) | **'range'** (Dm) |
| **Regional** | 28.7–38.7 | 10 | 9.5 | 0.95 | 24.8 | 470 | 585 | 6 | 1–28 |
| **Helsingborg** | 28.7–38.7 | 10 | 9.5 | 0.95 | 24.8 | 1030 | 1285 | 12 | 2–61 |
| **Combined** | 28.7–38.7 | 10 | 9.5 | 0.95 | 24.8 | 700 | 875 | 9 | 2–44 |

**Table 8:** Reservoir parameters for the Höganäs Formation/Lower Jurassic Unit reservoir sandstone(s) found in the 09-KB-2029 well. Result of log evaluation, cut-offs: Vshale <30% and porosity >15%.

| **Model:** | **Depth** | **Sand thickness** | | **N/G** | **Porosity** | **Est. Perm** | | **Transmissivity** | |
|---|---|---|---|---|---|---|---|---|---|
| | (m, MD) | **Gross** (m) | **Net** (m) | | (%) | **Gas** (mD) | **Reservoir** (mD) | (Dm) | **'range'** (Dm) |
| **Regional** | 8.5–34.8 | 24.8 | 24.2 | 0.98 | 22.2 | 305 | 380 | 9 | 2–46 |
| **Helsingborg** | 8.5–34.8 | 24.8 | 24.2 | 0.98 | 22.2 | 555 | 700 | 17 | 3–85 |
| **Combined** | 8.5–34.8 | 24.8 | 24.2 | 0.98 | 22.2 | 450 | 570 | 14 | 3–69 |

**Table 9:** Reservoir parameters for the Höganäs Formation/Lower Jurassic Unit reservoir sandstone(s) found in the 09-KB-2033 well. Result of log evaluation, cut-offs: Vshale <30% and porosity >15%.

| **Model:** | **Depth** | **Sand thickness** | | **N/G** | **Porosity** | **Est. Perm** | | **Transmissivity** | |
|---|---|---|---|---|---|---|---|---|---|
| | | **Gross** | **Net** | | | **Gas** | **Reservoir** | | **'range'** |
| | (m, MD) | (m) | (m) | | (%) | (mD) | (mD) | (Dm) | (Dm) |
| **Regional** | 15.3–29.1 | 10.7 | 10.2 | 0.95 | 20.8 | 220 | 275 | 3 | 1–14 |
| **Helsingborg** | 15.3–29.1 | 10.7 | 10.2 | 0.95 | 20.8 | 285 | 360 | 4 | 1–18 |
| **Combined** | 15.3–29.1 | 10.7 | 10.2 | 0.95 | 20.8 | 260 | 320 | 3 | 1–16 |

**Table 10:** Reservoir parameters for the Höganäs Formation/Lower Jurassic Unit reservoir sandstone(s) found in the 09-KB-2035 well.

| **Model:** | **Depth** | **Sand thickness** | | **N/G** | **Porosity** | **Est. Perm** | | **Transmissivity** | |
|---|---|---|---|---|---|---|---|---|---|
| | | **Gross** | **Net** | | | **Gas** | **Reservoir** | | **'range'** |
| | (m, MD) | (m) | (m) | | (%) | (mD) | (mD) | (Dm) | (Dm) |
| **Regional** | 31.7–38.1 | 6.0 | 6.0 | 0.99 | 26.5 | 625 | 780 | 5 | 1–23 |
| **Helsingborg** | 31.7–38.1 | 6.0 | 6.0 | 0.99 | 26.5 | 1925 | 2400 | 14 | 3–72 |
| **Combined** | 31.7–38.1 | 6.0 | 6.0 | 0.99 | 26.5 | 1350 | 1700 | 10 | 2–51 |

**Table 11:** Reservoir parameters for the Höganäs Formation/Lower Jurassic Unit reservoir sandstone(s) found in the 09-KB-2044 well.

| **Model:** | **Depth** | **Sand thickness** | | **N/G** | **Porosity** | **Est. Perm** | | **Transmissivity** | |
|---|---|---|---|---|---|---|---|---|---|
| | | **Gross** | **Net** | | | **Gas** | **Reservoir** | | **'range'** |
| | (m, MD) | (m) | (m) | | (%) | (mD) | (mD) | (Dm) | (Dm) |
| **Regional** | 16.7–33.2 | 8.5 | 8.3 | 0.98 | 19.3 | 160 | 200 | 2 | 1–8 |
| **Helsingborg** | 16.7–33.2 | 8.5 | 8.3 | 0.98 | 19.3 | 175 | 220 | 2 | 1–9 |
| **Combined** | 16.7–33.2 | 8.5 | 8.3 | 0.98 | 19.3 | 170 | 212 | 2 | 1–9 |

# 10 Composition and petrographic description of the sandstone beds

Previous studies of the petrography of the Höganäs Formation have been presented by Ahlberg (1994). His study is here supplemented by a microscopy study on 25 thin sections of sandstone samples from cores in the southern part of Helsingborg. These samples were examined regarding texture, detrital components, matrix, cement and porosity. This was done by a statistic evaluation of 500 data points on each thin section. These new results as well as the data from Ahlberg (1994) are compiled in **Table 12** and **Table 13**. An overview microphotograph of each sample is presented in **Enclosure 1**.

On many of the samples a corresponding laboratory measurement was performed on porosity and permeability.

Examples of composition for two common types of sandstone are displayed as pie diagrams in **Figure 11**.

## 10.1 Texture

The texture of the examined sandstone samples ranges from very fine-grained poorly sorted to medium-grained sorted types. The fine-grained moderately sorted sandstone beds dominate the Höganäs Formation. Medium- and coarse-grained beds are less frequent. The bulk of the investigated sandstone beds have grain-sizes between 0.1 and 0.2 mm. Coarser intervals are mainly found in the Rhaetian, the basalmost Hettangian and Uppermost Hettangian, i.e. the Bjuv Member, the Boserup beds and in the Fleninge beds.

The finer sandstone beds are commonly cross-bedded, wavy bedded or associated with thin clay flasers or laminae, which commonly gives anisotropic vertical and physical properties such as permeability.

## 10.2 Detrital components

The detrital components are dominated by quartz which makes up more than 85% of the framework grains. Beside quartz, K-feldspars are the most dominating component. Only a few grains of plagioclase have been identified. The feldspars are normally severely weathered, showing selective solution. Authigenic kaolinite is found associated to these grains. In medium- and coarse-grained sandstone beds there are occasional polycrystalline quartz grains and grains composed of shale (Palaeozoic?). Scattered grains of heavy minerals (ilmenite, rutile and zircon) were found in most samples. Carbonate shell fragments was not identified in the examined samples.

## 10.3 Matrix

The matrix observed is mainly composed of a mixture of detrital clay, fine organic detritus and authigenic kaolinite and to a minor extent chlorite.

**Table 12:** Results from modal analyses of sandstone samples from the tunnel walls and three boreholes associated to the Knutpunkten project. Data from Ahlberg (1990). Höganäs Formation. Helsingborg Member, Lower Jurassic, Hettangian.

| Sample ID. | Location | Quartz (%) | Rock frag. (%) | Organic Material (%) | Clay Matrix (%) | Cement (%) | Grain size (mm) | Primary porosity (%) | Remaining porosity (%) |
|---|---|---|---|---|---|---|---|---|---|
| T-1 | Tunnel wall | 63.6 | 4.0 | 8.3 | 9.0 | 9.3 | 0.2 | 0 | 5.6 |
| T-7 | Tunnel wall | 51.6 | 4.6 | 1.0 | 1.3 | 41.3 | 0.2 | 41.3 | 0 |
| T-14 | Tunnel wall | 60.3 | 3.9 | 2.0 | 3.0 | 30.0 | 0.1 | 30.3 | 0.3 |
| T-16 | Tunnel wall | 50.3 | 1.3 | 2.3 | 3.3 | 46.0 | 0.2 | 46.0 | 0 |
| T-17 | Tunnel wall | 55.9 | 1.6 | 8.0 | 0.2 | 0.6 | 0.2 | 31.2 | 4.6 |
| T-25 | Tunnel wall | 62.7 | 9.2 | 0.0 | 0.7 | 0.0 | 0.3 | 26.9 | 26.9 |
| T-28 | Tunnel wall | 60.2 | 2.6 | 13.5 | 0.3 | 0.0 | 0.2 | 22.9 | 22.9 |
| T-29 | Tunnel wall | 61.6 | 9.9 | 1.6 | 8.0 | 0.0 | 0.1 | 18.3 | 18.3 |
| T-33 | Tunnel wall | 53.0 | 2.9 | 1.0 | 1.3 | 42.0 | 0.3 | 42.0 | 0 |
| T-34 | Tunnel wall | 68.3 | 7.5 | 6.0 | 0.0 | 0.0 | 0.3 | 15.3 | 15.3 |
| T-50 | Tunnel wall | 58.6 | 6.3 | 0.3 | 1.3 | 33.6 | 0.3 | 33.6 | 0 |
| T-51 | Tunnel wall | 58.3 | 10.2 | 4.0 | 0.6 | 0.0 | 0.4 | 26.0 | 26.0 |
| T-52A | Tunnel wall | 56.6 | 8.0 | 0.6 | 0.3 | 33.0 | 0.4 | 33.0 | 0 |
| T-52B | Tunnel wall | 60.0 | 10.9 | 1.6 | 2.3 | 0.0 | 0.4 | 25.3 | 25.3 |
| T-54 | Tunnel wall | 55.2 | 3.6 | 1.6 | 1.0 | 35.6 | 0.2 | 37.9 | 2.3 |
| T-56 | Tunnel wall | 64.0 | 5.2 | 5.0 | 3.3 | 0.0 | 0.3 | 21.2 | 21.2 |
| T-66U | Tunnel wall | 48.3 | 3.3 | 8.3 | 0.0 | 40.3 | 0.3 | 40.3 | 0 |
| T-72 | Tunnel wall | 55.5 | 8.0 | 1.3 | 2.3 | 0.0 | 0.4 | 23.9 | 23.9 |
| VBB-1 | BH 88, -15.5 m | 75.0 | 1.2 | 1.6 | 1.3 | 0.0 | 0.5 | 20.3 | 20.3 |
| VBB-2 | BH 103, -7 m | 77.6 | 0.9 | 1.3 | 0.3 | 0.0 | 0.6 | 19.0 | 19.0 |
| VBB-3 | BH 88,-17.0 m | 78.3 | 0.0 | 6.0 | 0.0 | 0.0 | 0.6 | 16.0 | 16.0 |
| VBB-6 | BH 73, -17 m | 73.3 | 0.9 | 4.6 | 0.3 | 0.0 | 0.6 | 20.3 | 20.3 |
| VBB-7 | BH 73, -16.5 m | 75.0 | 0.9 | 11.3 | 1.0 | 0.0 | 0.5 | 11.3 | 11.3 |
| VBB-10 | BH 4, -19 m | 63.6 | 2.9 | 13.3 | 0.3 | 0.0 | 0.3 | 19.3 | 0 |
| Average | | 62,0 | 4.6 | 4.4 | 1.7 | 13.0 | 0.3 | 25.9 | 11.6 |

**Table 13:** Results from modal analyses performed on thin sections from cored boreholes located in the southern part of Helsingborg, H+ project. Höganäs Formation, Helsingborg Member, Lower Jurassic, Hettangian.

| **Borehole** | **Depth** (m GL) | **Quartz** (%) | **Rock frag.** (%) | **Clay matrix/ org. material** (%) | **Cement** (%) | **Grain size**[1] (mm) | **Primary porosity** (%) | **Remaining porosity** (%) |
|---|---|---|---|---|---|---|---|---|
| 2001 | 19.90 | 64.8 | 5.8 | 13.2 | 0.8 | 0.06-0.1 | 16.2 | 15.4 |
| 2001 | 38.90-39.08 | 60.0 | 5.8 | 9.4 | 0.4 | 0.1-0.15 | 24.8 | 24.4 |
| 2009 | 35.66 | 62.0 | 5.8 | 2.8 | 6.8 | 0.1-0.15 | 29.4 | 22.6 |
| 2009 | 29.90-30.03 | 60.4 | 5.2 | 1.6 | 6.8 | 0.2-0.3 | 32.8 | 26.0 |
| 2009 | 40.24 | 58.6 | 7.2 | 4.2 | 5.8 | 0.1-0.2 | 30.0 | 24.2 |
| 2009 | 16.98-17.04 | 52.6 | 3.8 | 34.4 | 3.2 | 0.2 | 9.2 | 6.0 |
| 2009 | 34.95 | 63.0 | 5.4 | 4.0 | 7.4 | 0.1-0.3 | 27.6 | 20.2 |
| 2009 | 40.43-40.54 | 61.0 | 3.2 | 1.4 | 11.2 | 0.2-0.4 | 34.4 | 23.2 |
| 2021 | 31.34-31.53 | 59.8 | 4.0 | 9.6 | 0.8 | 0.1-0.2 | 26.6 | 25.8 |
| 2026 | 9.91-10.16 | 58.8 | 7.8 | 2.8 | 7.6 | 0.2-0.3 | 30.6 | 23.0 |
| 2026 | 16.17-16.33 | 55.0 | 3.6 | 12.4 | 9.8 | 0.1-0.2 | 29.0 | 19.2 |
| 2026 | 28.37-28.67 | 53.6 | 3.2 | 6.6 | 28.8 | 0.06-0.1 | 36.6 | 7.8 |
| 2027 | 15.00 | 59.0 | 8.0 | 1.7 | 5.7 | 0.2-0.3 | 31.4 | 25.7 |
| 2029 | 7.40-7.55 | 60.0 | 4.0 | 1.7 | 14.3 | 0.2 | 34.3 | 20.0 |
| 2029 | 9.37-9.42 | 64.3 | 5.7 | 0.7 | 7.0 | 0.2 | 29.3 | 22.3 |
| 2029 | 24.29-24.38 | 53.0 | 5.7 | 2.0 | 38.3 | 0.1-0.2 | 39.3 | 1.0 |
| 2033 | 29.30 | 61.3 | 5.7 | 3.0 | 27.7 | 0.06-0.1 | 30.0 | 2.3 |
| 2033 | 14.29-14.32 | 63.3 | 6.3 | 1.0 | 8.3 | 0.2 | 29.3 | 21.0 |
| 2033 | 18.40 | 56.7 | 2.7 | 2.3 | 26.0 | 0.3-0.5 | 38.3 | 12.3 |
| 2033 | 17.65 | 58.3 | 7.3 | 0.0 | 10.7 | 0.2 | 34.4 | 23.7 |
| 2033 | 14.06-14.17 | 54.7 | 3.7 | 7.0 | 14.0 | 0.2-1.5 | 34.7 | 20.7 |
| 2035 | 19.75-19.85 | 55.7 | 4.3 | 8.7 | 12.3 | 0.1-0.2 | 31.3 | 19.0 |
| 2035 | 30.43-30.46 | 52.7 | 5.3 | 5.3 | 21.7 | 0.1-0.2 | 36.7 | 15.0 |
| 2035 | 39.26-39.35 | 54.0 | 7.7 | 5.7 | 31.0 | 0.2 | 32.7 | 1.7 |
| 2040 | 26.45-26.60 | 55.0 | 4.7 | 6.0 | 34.3 | 0.2 | 34.3 | 0.0 |
| 2044 | 32.88-33.00 | 58.0 | 5.7 | 4.7 | 7.3 | 0.1-0.2 | 31.6 | 24.3 |
| Average | | 58.3 | 5.3 | 5.8 | 13.4 | | 30.6 | 17.2 |

[1] Estimated predominant grain-size in thin sections.

## 10.4 Cement

The L. Jurassic sandstones in the Helsingborg area are predominantly poorly cemented. Well indurated and cemented sandstone beds are few and generally <1 m thick. These are mainly cemented with carbonates. The amount of cement varies in the examined samples between 0 and 40% with an average of c. 10%. Three types of cement are found, i.e. quartz overgrowth on detrital grains, pore filling calcite and micronodules of iron-carbonate (siderite).

Authigenic pyrite was occasionally observed in the very fine-grained and matrix rich sandstone samples.

### 10.4.1 Quartz cementation

Most detrital grains in the examined sandstone samples have a thin overgrowth of quartz (cf. Bh 2035: 30.43 m and Bh 2009: 40.24 m; **Figure 12**). Interlocking grain to grain cementation with quartz is frequently found, especially in the finer grained sandstone samples. Burial related pressure solution in grain contacts is not observed.

The thin overgrowth of quartz is in occasional samples corroded due to either secondary dissolution. However, a primary uneven growth of quartz crystals on the grain surface could also in some cases be mistaken as caused by dissolution (Ahlberg 1994).

The overgrowths of silica was found in two varieties, either as a thin irregular coating, where a dust rim of the original grain surface is often seen, or as euhedral growth of silica commonly resulting in angular crystal surfaces bounding the pore space. No completely silica cemented sandstones was observed.

### 10.4.2 Calcite cementation

Occasional sandstone beds are more or less completely cemented by calcite. These beds are found to be between 0.1 and 1.0 m thick. Thicker calcite cemented beds have not been found. These beds are often found scattered within thick porous sandstone sequences or as isolated thin sand sheets or channel sand in clay-mudstone dominated sequences.

In most cases the calcite cement is pore filling and poikilotopic, i.e. totally embedding the detrital grains giving a microscopic texture where the grain contacts are few and the cement is the dominating framework.

### 10.4.3 Siderite cementation

Siderite is commonly found in the Rhaetian–Hettangian strata in Skåne. Most commonly as disc shaped nodules in mudstone dominated deposits, however, also commonly occurring in sandstone beds as microcrystals ranging in size from a few to 10 µm in diameter. In the investigated samples siderite is only found in very small amounts as brownish scattered microcrystals.

## 10.5 Diagenetic history and evolution of cementation

Ahlberg (1994) describes a burial diagenesis of the Höganäs Formation in the Helsingborg area that reflects low to moderate maximum burial temperatures (70–90 °C). Ahlberg suggests a maximum burial depth of 1000–2000 m based on a Late Cretaceous inversion of c. 1000–1500 m and a Neogene uplift of c. 500 m of the Sorgenfrei-Tornquist Zone in Skåne. However, vitrinite reflectance measurements (discussed in **Section 12**) indicate maximum burial depths of 2000–3000 m. Further, maximum burial depths of 1000–2000 m imply a geothermal gradient exceeding 50 °C/km (theoretically) which is highly unlikely unless the Helsingborg area has been hydrothermally influenced by tectonic activities related to the Sorgenfrei-Tornquist Zone.

Most of the silica precipitated as overgrowth cement on the detrital grains is interpreted to be formed by very early phases of fresh water flushing of permeable sandstone beds at less than 600 m burial depths. The main source for the silica is interpreted to derive externally from release of silica due to extensive chemical weathering of Precambrian rocks in the hinterland terrain. Internal release of silica from compaction of mudstones and in situ weathering of feldspars is not a sufficient source (cf. Ahlberg 1994).

The precipitation of silica was followed by early diagenetic calcite cementation, commonly very early prior to any major compaction occurred. Completely calcite cemented sandstone beds have a cement proportion of 30–40%, which is close to the maximum initial porosity of these beds. To some extent the carbonate cement has corroded the earlier formed silica cement (eg. Bh 2033; 29.30 m; **Figure 12**). The main source for the carbonates are a redundancy of Ca, Mg and Fe deriving from weathering of feldspars and the $CO_3$ either coming from dissolution of fossil shells or associated to saline and carbonate enriched formation fluids introduced in the deposits during transgressive phases in the Jurassic.

Late diagenetic dissolution and destruction of calcite cements due to uplift, primarily Late Cretaceous inversion, cannot be excluded, especially in permeable sandstone beds, which could have been subject to flushing of meteoric water. This has, however, not been possible to validate in the studied samples. However, Ahlberg & Ohlsson (2001) describe the same cement types and porosity values for Rhaetian–Lower Jurassic sandstones in drill cores at c. 1250–1500 m depths in Svedala-1 and Höllviken-2 in SW Skåne.

The siderite micronodules were formed after the silica overgrowths. They are merely found in samples without any calcite cement and in very porous and permeable samples.

## 10.6 Porosity

Porosity estimations on thin sections show values ranging from 0 to 26%. The most commonly occurring fine-grained sandstone beds with a low amount of cement yields values in the range of 20 to 25% in the point counting data. Laboratory measurements give even slightly higher values in general, see **Section** 8. A dominating reservoir value slightly above 20% is thus likely.

# 11 Seismostratigraphic framework – support to the correlation of boreholes

Most of the boreholes used to construct the composite log for the Höganäs Formation in Helsingborg are located along two seismic profiles in south central Helsingborg, i.e. line 3 and 4 (**Figure 13**). The seismic survey, performed by Ramböll A/S, was conducted as a pulled array with a seismic vibrator as the energy source. The survey was part of the geoscientific investigations during 2009 on behalf of Helsingborg Stad and gives valuable information on the subsurface bedrock framework even though the quality varies due to the town infrastructure. The best results were obtained along lines 1, 2, 3 and 4.

The seismic data in these lines display a gently southward dipping sequence of strata where successively younger strata sub-crop the soil layers in the same direction. The bedrock layering is, especially in line 3, clearly visualized down to depths of 200–300 ms TWT, corresponding to about the same metric depths. The seismograms reflect a Lower Jurassic bedding sequence which is composed of strata with frequently changing acoustic impedance, interpreted as alternating beds of poorly consolidated sandstone and indurated beds of claystone/mudstone. The maximum total thickness of c. 200 m for the Höganäs Formation correlates well with the seismostratigraphic display in the southern parts of profile 3 and in profile 4.

The correlation of the 30–50 deep wells along the two lines is in addition to the seismic data supported by biostratigraphic information that give an Early–Middle Hettangian age in the north (09.1.2026 and 06.1.1008) and a Sinemurian age in the upper parts of the southernmost well (09.1.2021).

# 12 Correlation between the Helsingborg composite succession and the Danish wells

## 12.1 Background and rationale

The assessment of the geothermal potential in the Helsingør area is hampered by a lack of deep well-sections in the vicinity of Helsingør. The available deep wells on Zealand are located at some distance to the west, southwest and south of Helsingør (**Figure 1**). In an attempt to produce a dataset closely east of Helsingør, GEUS in cooperation with SGU have performed a study to utilize available geodata from the Rhaetian–Lower Jurassic strata in the Helsingborg area. Owing to Late Cretaceous–Early Cenozoic inversion movements in the Sorgenfrei-Tornquist Zone (e.g. Michelsen & Nielsen 1991, 1993; Erlström et al. 1997), the deeply buried Mesozoic succession was uplifted and deeply eroded, and the present day bedrock in the greater Helsingborg area corresponds to a part of the succession that is expected to be present in the Helsingør area within the geothermal depth window. The strata in the two areas were once forming a coherent succession, but are today separated by major faults in the Øresund area.

The thermal maturity of Hettangian coals in the Helsingborg beds and Hettangian–Sinemurian coals in the Øresund wells BH 13 and BH18 (**Figure 2**) drilled along the tunnel line between Helsingør and Helsingborg show vitrinite reflectance of c. 0.48–0.57 % Ro and 0.46–0.51% Ro, respectively (Larsen 1968; Ahlberg 1994; Petersen et al. 2003). Based on the measured maturity values, it is estimated that the Helsingborg coals once were buried between 2.250–3.050 m while the Øresund-13 and -18 coals were buried between 2.100–2.440 m (Petersen et al. 2003). Although estimates of maximal burial depths based on vitrinite reflectance data are somewhat uncertain, the measured values indicate that the strata in the Helsingborg area prior to the Late Cretaceous–Early Cenozoic uplift were buried to depths closely comparable to the present day depth of c. 2.500 m of the mapped Top Gassum Formation in the Helsingør area (Hjuler et al. 2013).

The Top Gassum Formation reflector is assumed to correspond fairly close to the Hettangian–Sinemurian boundary (i.e. the top of the Helsingborg Member) and corresponds therefore closely to the stratigraphic level of the investigated coal beds. Therefore, it is likely that the strata in the Helsingør and Helsingborg area have been subjected to comparable compaction and diagenetic processes thus making data on reservoir properties from Helsingborg highly relevant for the assessment of the Helsingør area. This statement is corroborated by the petrographic analyses that do not indicate significant occurrence of secondary porosities or fractures related to the uplift (see **Section 10**).

## 12.2 Constructing the Helsingborg composite succession

The Upper Triassic–Lower Jurassic strata in the Helsingborg area generally show a weak tilting accompanied by faults that divides the strata into separate fault blocks. Therefore various parts of the succession form the local bedrock and are reached in shallow boreholes. The boreholes have been drilled as part of larger construction works in Helsingborg and supplement data obtained from previous outcrops (see

**Section 3**). The data comprises a number of 30–50 m deep borehole sections, which provide well-logs, cores, cuttings samples and information on the hydraulic properties.

Together, the various borehole data provide important information of the composition of the upper Rhaetian–Hettangian succession, which in Skåne belongs to the Höganäs Formation consisting of the Vallåkra, Bjuv and Helsingborg Members.

The Vallåkra Member is estimated to be c. 30 m thick mainly consisting of non-reservoir facies, while the c. 25 m thick Bjuv Member consists of sandstones, siltstones, mudstones and coals. The two Rhaetian members correspond time-wise to the principal part of the Gassum Formation in central parts of the Danish Basin. The two members were primarily formed in near-coastal terrestrial environments governed by the numerous sea-level changes that influenced the deposition of the shallow marine–coastal sandstones and interbeds of marine mudstones of the Rhaetian Gassum Formation (Nielsen 2003).

The upper part of the Höganäs Formation consists of the up to c. 215 m thick Hettangian Helsingborg Member which comprises floodplain strata interbedded with marine strata (Ahlberg 1994). It corresponds to the upper part of the Gassum Formation, which along the northeastern basin margin in North Jutland, Kattegat and northeast Zealand shows a gradual backstepping pattern of shallow marine and coastal deposits through the Hettangian–lowermost Sinemurian (Michelsen & Nielsen 1991; Nielsen 2003). Despite uncertain seismic ties to the wells Stenlille-1, Lavø-1, Karlebo-1A and Margretheholm-1 and recognition of reflector patterns, the mapped Top Gassum Formation reflector (Hjuler et al. 2013) is interpreted to correspond fairly close to the Hettangian–Sinemurian boundary. Therefore, the Helsingborg beds correspond time-wise to the mid–upper parts of the Gassum Formation, and in the following the studied units from Helsingborg is included in the Gassum Formation to ease communication and comparison to the Danish well-sections. An interpretation of the relation between the 06.KB1008 well and the Danish wells is presented in **Figure 14** and **Figure 15**.

Above the Helsingborg Member follows the Rya Formation with Döshult Member being the lower sandstone-dominated part of the formation. The Döshult sandstone beds constitute a potential reservoir and correspond probably to the topmost part of the Gassum Formation in proximal wells in North Jylland (Børglum-1 and Flyvbjerg-1; see Nielsen 2003).

## 12.3 The stratigraphic building blocks

In order to establish a dataset from Helsingborg that can be used for comparison and correlation to the nearest relevant deep well-sections, a composite Helsingborg succession is constructed displaying an imaginary well-section. The composite succession is built by comparing the shallow well-sections by estimating the age of the drilled sections, their orientation, composition and characters by means of biostratigraphy, log-patterns, marker beds and dominant lithology. Based on a number of biostratigraphic events, a few significant marker beds and characteristic well log-patterns, a series of borehole sections have been selected for the construction of the composite succession (**Figure 16**). When combined in the correct stratigraphic order, the selected borehole sections together form a c. 180 m thick upper Rhaetian–Hettangian succession containing prominent sandstone units separated by finer-grained, non-reservoir strata. The constructed succession thus contains 10 prominent sandstone units of which the lowermost belongs to the Rhaetian followed by 8 Hettangian units, here informally named A through H of the Hettangian Helsingborg Member. In addition to these 9 units, data from outcrop sections north of Helsingborg (Kulla, Gunnarstorp and Laröd) and boreholes (8 and 9) in Øresund show the presence of a tenth potential reservoir unit (I) of early Sinemurian age, namely the lower part of the Döshult Member. The hydrogeological tests that were performed in the boreholes indicate good hydraulic properties of the tested sandstones (see **Section** 5 in upcoming report). All 10 sandstone units are considered potential reservoir units, in particular the two thick sandstones E and B that probably constitute shoreface sandstones and channel sandstones, respectively. The proximal deltaic and marginal marine depositional setting resulted in a highly variable succession, including both regional and local sandstone bodies of open and closed hydrogeological characteristics.

## 12.4 Comparison of the Helsingborg composite succession with the Danish wells

The cumulative thickness of c. 150 m of the Helsingborg Member in the Helsingborg composite succession (**Figure 16**) seems very plausible compared to the generally accepted thickness of up to 215 m that is based old continuous well-sections and outcrops in Skåne (Pienkowski 1991; Ahlberg et al. 2003). In the Øresund wells 13, 18 and 19 a succession belonging to the Helsingborg Member of a minimum thickness of c. 159 m was encountered. The cumulative thickness of c. 150 m indicated in fig. 3 is thus well-constrained. In Karlebo-1A the Rhaetian–Hettangian Gassum Formation is c. 132 m thick, while it is 135 m in the Margretheholm-1 well. In both wells the Hettangian part of the Gassum Formation constitutes c. 72 m based on available biostratigraphic data (Nielsen et al. 2007) and using the sequence stratigraphic surface SB 8 and TS 11 of Nielsen (2003) as approximate delineations of the base and top of the Hettangian. The c. 72 m of succession in the two wells is to be compared to c. 150 m of Hettangian strata in the Helsingborg composite succession. The well sections of Karlebo-1A and Margretheholm-1 contain 7–8 prominent sandstone units and an attempt to correlate these to the 8 Hettangian sandstones in the Helsingborg composite succession has been performed. Using the same criteria for the Lavø-1 well, the Hettangian has a similar thickness of c. 71 m, but contains only 3–4 prominent sandstone units and a few thinner sandstone beds which clearly reflect its more distal position. Farther into the basin, the Hettangian of the Stenlille-1 well is c. 90 m thick and dominated by marine mudstones of the Fjerritslev Formation containing 3–4 thin shoreface sandstones of which some have been tested with good reservoir properties (**Table 7** in **Section 14**).

The general depositional environment of the Helsingborg Member is interpreted as coastal plain and deltaic with several sub-environments where sandstones accumulated, such as fluvial and tidal channels, foreshore–shoreface, washover fans etc., In contrast, the more marine influenced environment of the Gassum Formation is more likely to have formed fairly widely distributed shoreface sandstone units (Nielsen 2003). It is thus unlikely that the individual sandstone units form continuous sheet-like layers distributed from the Helsingborg area to the deeper parts of the basin where the Danish well- sections are located. However, the Gassum sandstones were formed as responses to frequent sea-level fluctuations, and these probably also affected the more coastal environments of the proximal Helsingborg Member; therefore it is plausible that the deposition of the thicker sandstone units is at least partly controlled by a common cause and corresponds stratigraphically. The presence of similar numbers of pronounced sandstones in the Hettangian of Helsingborg and Karlebo-1A and Margretheholm-1 thus give confidence to the assumption that similar sandstones are present in the Helsingør area.

## 12.5 Additional potential reservoirs

As mentioned in Hjuler et al. (2013) additional potential reservoirs may be found in the Chalk Group and the Middle Jurassic. In the lowermost part of the Chalk Group occurs c. 9 m of sandstones and siltstones referred to the Upper Cretaceous Lunda Sandstone. This unit is utilized for production in the Lund geothermal plant. The potential of this unit in Helsingør is poorly constrained from the presently available data.

Additional potential may be found in Middle Jurassic sandstones, which form important reservoirs in northern Jylland and parts of Skåne. The Øresund wells indicate the presence of a thick Middle Jurassic succession, possibly up to 200 m, but core material is only available from a minor part, less than 15% of this succession (Larsen et al. 1968). In wells located along structural strike in Kattegat (Terne-1) and Northern Jylland (Haldager-1 and Vedsted-1) very thick reservoir sandstones are known (Nielsen 2003). Thus, the Middle Jurassic may constitute an important reservoir possibility in the Helsingør area; the present seismic data, however, seems not to indicate the presence of this unit.

# 13 Reservoir parameters from selected Danish wells and the Helsingborg composite succession

The Mesozoic succession in the area of interest contains several sandstone units of Lower Cretaceous and Lower Jurassic age, but also the Gassum and Bunter Sandstone formations include sandstone layers that possess a geothermal potential. For the Lower Cretaceous and Lower Jurassic successions, which contain parts dominated by claystones and parts dominated by sandstones; only sandstone intervals are selected for reservoir analyses (these intervals are named “selected int.” in **Table 14–Table 17**). As merely sparse geological and petrophysical data are available from the North Sjælland area, a precise evaluation of the geothermal potential at Helsingør is complicated.

The **Table 14–Table 17** below present the results of a standard GEUS analysis of core data and well-logs acquired at Karlebo, Margretheholm, Lavø and Stenlille, Sjælland and Helsingborg, Skåne. The core data include permeability and porosity measurements primarily from the Stenlille-1 and -19 wells along with the Swedish wells, whereas the log database includes logs from all study wells. The log analyses are based primarily on the SP, gamma-ray, density, resistivity and sonic log readings, if available. Core permeabilities are normally measured using gas (helium or nitrogen), and in the **Table 14–Table 17**, the “Avg. gas perm.” term denotes an average permeability derived from core and log data using a relationship between **gas permeability and core porosity** (see **Section 13.1**). In this context the term ‘gas permeability’ equals ‘core permeability’. In some cases, a particular parameter cannot be calculated due to missing log data, poor log quality or a full suite of logs is not available (marked by a “-“ in the tables). The Karlebo-1A well is slightly deviated, which has been taken into account when calculating thicknesses etc.

**Table 14:** Reservoir parameters for the **Lower Cretaceous unit** drilled in nearby deep wells relevant for assessing the geothermal potential in the Helsingør area. Cut-offs applied for defining net reservoir: Vshale < 30% and Porosity > 15%. The Net sand thickness corresponds to the accumulated thickness of potential reservoir sandstone layers within a particular unit. The log analysis focuses on selected sand-bearing intervals (selected int.). The Lower Cretaceous unit was not tested in any of wells listed in the table.

| **Sandstone unit: *Lower Cretaceous*** | **Top - Base of unit** (m MD) | **Unit thick.** (m) | **Sst. thickness** | | **Avg. Por.** (%) | **Average gas perm.** (mD) | **Average reservoir perm.** (mD) | **Reservoir transmissivity** [1)] (Dm) |
|---|---|---|---|---|---|---|---|---|
| | | | **Gross Sand** (m) | **Net Sand** (m) | | | | |
| Karlebo-1A | 1794 - 1870 | 76 | 27 | | | | | |
| -Selected int. | 1840 - 1870 | 30 | 25 | 21 | 20.7 | 245 | 310 | 6.5 |
| Lavø-1 | 1999 - 2073 | 74 | 32 | | | | | |
| -Selected int. | 2058 - 2073 | 15 | 15 | - | - | - | - | - |
| Margretheholm-1 | 1623 - 1643 | 20 | 1.5 | | | | | |
| -Selected int. | 1630 - 1632 | 2 | 1.5 | 1 | 17.5 | 100 | 125 | 0.1 |
| Stenlille-1 | 1200 - 1248 | 48 | 2 | | | | | |
| -Selected int. | 1219 - 1221 | 2 | 2 | 2 | 23.2 | 180 | 225 | 0.5 |
| Stenlille-19 | No data | - | - | - | - | - | - | - |
| Helsingborg composite | No data | | | | | | | |

1) At reservoir scale (field scale)

**Table 15:** Reservoir parameters for the **Lower Jurassic unit** drilled in nearby deep wells relevant for assessing the geothermal potential in the Helsingør area. Cut-offs applied for defining net reservoir: Vshale < 30% and Porosity > 15%. The Net sand thickness corresponds to the accumulated thickness of potential reservoir sandstone layers within a particular unit. The Lower Jurassic unit contains 7 sandstone beds, up to few meters thick in Stenlille-1 and at least 4 sandstone beds in Margretheholm-1, but only the accumulated sandstone thicknesses are tabulated. Some of the sandstone beds were tested in Stenlille-1 and -3.

| **Sandstone unit:** ***Lower Jurassic*** | **Top - Base of unit** (m MD) | **Unit thick.** (m) | **Sst. thickness** | | **Avg. Por.** (%) | **Average gas perm.** (mD) | **Average reservoir perm.** (mD) | **Reservoir transmissivity** [1)] (Dm) |
|---|---|---|---|---|---|---|---|---|
| | | | **Gross Sand** (m) | **Net Sand** (m) | | | | |
| Karlebo-1A | 1946 - 2136 | 170 | 72 | | | | | |
| -Selected int. | 1946 - 2036 | 81 | 60 | 44 | 20.6 | 310 | 390 | 17 |
| Lavø-1 | 2134 - 2293 | 159 | 44 | - | - | - | - | - |
| Margretheholm-1 | 1713 - 1842 | 129 | 28 | 22.0 | 22.3 | 325 | 406 | 9 |
| Stenlille-1 | 1368 - 1506 | 139 | 20 | 19.5 | 24.2 | 240 | 300 | 6 |
| Stenlille-19 | No data | - | - | - | - | - | - | - |
| Helsingborg composite | No data | | | | | | | |

[1)] At reservoir scale (field scale)

**Table 16:** Reservoir parameters for the **Gassum Formation** drilled in nearby deep wells relevant for assessing the geothermal potential in the Helsingør area. Cut-offs applied for defining net reservoir: Vshale < 30% and Porosity > 15%. The Net sand thickness corresponds to the accumulated thickness of potential reservoir sandstone layers within a particular unit. The Gassum Formation was tested at Stenlille.

| **Sandstone unit:** ***Gassum Formation*** | **Top - Base of unit** (m MD) | **Unit thick.** (m) | **Sst. thickness** | | **Avg. Por.** (%) | **Average gas perm.** (mD) | **Average reservoir perm.** (mD) | **Reservoir transmissivity** [1)] (Dm) |
|---|---|---|---|---|---|---|---|---|
| | | | **Gross Sand** (m) | **Net Sand** (m) | | | | |
| Karlebo-1A | 2132 - 2279 | 132 | 60 | 40 | 19.7 | 290 | 360 | 15 |
| Lavø-1 | 2293 - 2368 | 75 | 50 | - | - | - | - | - |
| Margretheholm-1 | 1842 - 1977 | 135 | 63 | 53.5 | 21.7 | 300 | 375 | 20 |
| Stenlille-1 | 1506 - 1650 | 144 | 124 | 122.5 | 27.1 | 725 [2)] | 900 [2)] | 110 |
| Stenlille-19 | 1561 - 1706 | 145 | 99 | 98.0 | 27.3 | 1000 [3)] | 1250 [3)] | 123 |
| Helsingborg composite | _ | 200 | 76 | 57 | 25 | 1250 | 1560 | 99 |

[1)] At reservoir scale (field scale). [2)] Core analysis data from the upper part of Gassum Fm point to permeabilities lower than the average perm. 3) Estimated from core and log data representative of the entire Gassum Fm. (i.e. averaged for the entire Gassum Fm.).

**Table 17:** Reservoir parameters for the **Bunter Sandstone Formation** drilled in nearby deep wells relevant for assessing the geothermal potential in the Helsingør area. Cut-offs applied for defining net reservoir: Vshale < 30% and Porosity > 15%. The Net sand thickness corresponds to the accumulated thickness of potential reservoir sandstone layers within a particular unit. The Bunter Sandstone Formation was tested at Margretheholm.

| **Sandstone unit: *Bunter Sandstone Fm*** | **Top - Base of unit** (m MD) | **Unit thick.** (m) | **Sst. thickness** | | **Avg. Por.** (%) | **Average gas perm.** (mD) | **Average reservoir perm.** (mD) | **Reservoir transmissivity** [1)] (Dm) |
|---|---|---|---|---|---|---|---|---|
| | | | **Gross Sand** (m) | **Net Sand** (m) | | | | |
| Karlebo-1A | No data | - | - | - | - | - | - | - |
| Lavø-1 | No data | - | - | - | - | - | - | - |
| Margretheholm-1 | 2385 - 2682 | 297 | 137 | 48.3 | 19.7 | 320 | 400 | 19 |
| Stenlille-1 | - | - | - | - | - | - | - | - |
| Stenlille-19 | 2320 - 2534 | 214 | 52 | 15.9 | 20.2 | 300 | 375 | 6 |
| Helsingborg composite | No data | | | | | | | |

1) At reservoir scale (field scale)

The reservoir parameters of the Helsingborg composite succession (**Table 16**) are calculated from log and core analysis data from 9 sandstone beds, either as accumulated values (unit thickness, gross sand, net sand) or average values (porosity, permeability). In **Table 18** the reservoir parameters of the single sand beds are summarized.

**Table 18:** The calculation of the average reservoir parameters for the 'Helsingborg composite' succession is based on log data and core analysis data from a number of shallow wells. The interpreted log porosities are calibrated core porosity data, if possible. A subdivision into 9 sandstone units forms the basis of calculating the reservoir parameters for the Gassum Formation equivalent at Helsingborg as summarized below:

| **SAND Unit** | **Unit thickness** (m) | **Gross sand** (m) | **Net sand** (m) | **Porosity** % | **N/G** | **Gas PERM** (mD) | **Res. PERM** (mD) | **Well/source 2009-20-** |
|---|---|---|---|---|---|---|---|---|
| H | 2 - 5 | 5 | 4 | 25 | 0.80 | 500 | | 21 |
| G | 5 - 7 | 5 | 4 | 26 | 0.80 | 1500 | | 21 & 44 |
| F | 7 - 10 | 8 | 6 | 28 | 0.75 | 1000 | | 44 |
| E | 15 - 30 | 27 | 25 | 25 | 0.93 | 1400 | | 27,29,33 |
| D | 2 - 5 | 3 | 2 | 26 | 0.67 | 2000 | | 26 |
| C | 2 - 5 | 4 | 3 | 26 | 0.75 | 2000 | | 01 & 26 |
| B | 10 - 15 | 10 | 5 | 23 | 0.50 | 700 | | 01 |
| A | 5 - 7 | 7 | 4 | 23 | 0.57 | 700 | | Estimated |
| Rhät | 5 - 7 | 7 | 4 | 25 | 0.57 | 1500 | | Estimated |
| **All units** [1)] | | **76** | **57** | **25.0** | | **1250** | **1560** | |

**1)** See **Figure 16** for vertical position of the sandstone units.

## 13.1 Reservoir parameters

The procedure of deriving reservoir parameters for the various units and formations (Lower Cretaceous unit, Lower Jurassic unit, Gassum Formation and Bunter Sandstone Formation) is described in the following text. The shale content and the average porosity are interpreted from wireline log data acquired in the studied wells, primarily the gamma-ray, density and sonic logs, if available. A permeability log does not exist and consequently, permeability estimates must be based on logs combined with core analysis data. Drill cores were cut in the Lavø-1 and the Stenlille wells; the Stenlille core material is, in general, of good quality, whereas the density of Lavø-1 core material is rather poor and furthermore, the Lavø-1 cores were not taken from the sandstone intervals and the available shaly samples are not suitable for porosity and permeability measurements. No conventional cores were cut in the Karlebo-1A and Margretheholm wells and in these cases, the permeability may be assessed using a general porosity-permeability relationship derived from core material from various wells located outside the North Zealand area (**Figure 17–Figure 20**). A small number of porosity and permeability measurements are, however, available from Margretheholm-2 side wall cores (SWC).

With respect to North Zealand, the permeability is herein estimated on the basis of poro-perm plots focusing on the Gassum Formation (**Figure 19–Figure 20**). Especially the poro-perm plot dealing with medium-grained Gassum Formation sandstones is utilized (**Figure 20**); this plot includes data from selected Danish onshore wells supplemented by poro-perm data from shallow wells drilled in the Helsingborg area, despite that the additional Swedish data represent sandstones that are fine- to medium-grained. It is thus assumed that the Gassum Formation equivalent in the Helsingborg area is representative of the North Zealand area due to similar geological settings and (initially) similar depths of burial, but the sandstones of the two localities may differ slightly with respect to grain size and sorting (see **Section 13.2**). It should be noted that the Helsingborg sandstone layers are exposed to later uplift of significant magnitude. Data points related to high clay content, pronounced cementation or presence of fractures have been removed prior to plotting the data. Most of the plotted Gassum Formation data from Thisted-3 and Stenlille-19 are considered to signify elevated permeabilities relative to the Gassum Formation sandstones found in the North Zealand area due to e.g. sedimentological differences and different depositional environments. The present study focuses on reservoir sandstones and consequently, only sandstone layers with a minimum porosity of 15% and shale content less than 30% are taken into account. Cut-off values are, therefore, applied.

The drill-core sections from the Helsingborg railway tunnel indicate that the sandstones of the Gassum Formation equivalent are dominated by fine to medium-grained sandstones that are moderately to well-sorted (Ahlberg 1990). The sandstones of the Gassum and Fjerritslev formations are also characterized by fine to medium-grained sandstones in the Karlebo-1A well (Nielsen et al. 2014), but sorting is apparently poorer. In order to account for these differences in grain size and sorting, it is suggested to consider two different poro-perm relationships in order to supply a reasonable average permeability for each reservoir. Hence, it has been assumed that the sandstones of the Gassum and Fjerritslev formations in the North Zealand area consist of

2/3 medium-grained sandstone that is moderately to well-sorted (**cf. Figure 20**) ***plus*** 1/3 fine-grained sandstone with various degrees of sorting (**cf. Figure 19**). A separate plot focusing on the Helsingborg core analysis data is presented in **Figure 20**.

## 13.2 Examination of the Stenlille core analysis data

The objectives of including and examining Stenlille core analysis data in the present Helsingør study are twofold: (1) to allocate a local, good-quality core analysis database containing a large amount of data and (2) to elaborate on the uncertainty range connected to the permeability estimates.

Apart from the Margretheholm-2 data (**Figure 17**), the plot also includes data from the Gassum Formation in the Stenlille wells, and it is noteworthy that the Stenlille data do not fit the suggested poro-perm trend line (black) that is based primarily on core analysis data from selected wells located in Jylland. The latter core analysis data are largely measured on plug samples of medium-grained sandstones, where-as the Stenlille samples primarily consist of fine-grained sandstone. In order to refer all data to the same grain size class (medium-grained), the permeability data from the Stenlille wells were modified by applying a correction factor of 2.5 to fit the trend line (**Figure 18**). The determination of this correction factor (multiplying by 2.5) is not a straightforward task, but further details are given below.

Acknowledging that the grain size distribution of the upper part of the Gassum Formation is dominantly fine-grained at Stenlille, but presumably fine- to medium-grained at Helsingør like in the Karlebo-1 well, it was decided to multiply Stenlille permeabilities by a factor of 2.5 in order to balance this dissimilarity in grain size. In this way the modified Stenlille core analysis data may be used for permeability prediction at Helsingør (**Figure 18**). However, only core analysis data from Stenlille-1 to -15, representing the upper part of the Gassum Formation, have been modified, whereas the core analysis data from Stenlille-19 are kept unchanged, because these data already originate from medium-grained (and coarser-grained) sandstones discovered in the lower part of the Gassum Formation (Zone 6). These Zone 6 sandstones, which are characterized by excellent reservoir properties, are presumably not to be found at Helsingør due to different geological settings (see later). These Zone 6 sandstones have only been cored in Stenlille-19, but they are expected to be present in most parts of the Stenlille area, except in an area close the Stenlille-15 well (DONG 2001).

## 13.3 Assumed porosity-permeability relationship for the Helsingør area

A large amount of core material is available from the Stenlille area (central Zealand), but the amount of core data covering the North Zealand area is very limited, and to account for this limitation, the database is expanded by core analysis data from selected Swedish wells located in the Helsingborg area (**Figure 20**). For the wells analyzed, the expected maximum burial depth of the Gassum Formation is rather similar and accordingly, it is assumed that the relationships presented in **Figure 19** and **Figure 20** also are valid for Helsingør-Karlebo area, where the sandstones of the Gassum and Fjerritslev formations are fine- to medium-grained (Nielsen et al. 2014). A combined use of these relationships is used for predicting permeability throughout the Gassum and Fjerritslev formations. Generally, a permeability value is calculated from the log-porosity for each ½ feet, resulting in a computed permeability curve. The produced permeability curves (consult **Figure 19–Figure 20**) form the basis of calculating average permeabilities as listed in **Table 14–Table 17**. Two different permeability estimates (gas and reservoir permeability) are listed in the tables, and details on the different permeability columns are given below. As outlined above, it has been assumed that the sandstones of the Gassum and Fjerritslev formations in the North Zealand area consist of 2/3 medium-grained sandstone that is moderately to well-sorted (cf. **Figure 20**) ***plus*** 1/3 fine-grained sandstone with various degrees of sorting (cf. **Figure 19**).

The permeability distribution within the Lower Cretaceous unit is based on the regional porosity-permeability relationship presented in **Figure 17**.

## 13.4 Permeabilities and scaling factors

Gas permeabilities are normally measured on core plugs at laboratory conditions and consequently, up-scaling is needed prior to estimating reservoir permeabilities at field scale. GEUS suggests applying a permeability enhancement factor of 2.5 in order to up-scale from laboratory to reservoir level (i.e. multiply by 2.5). Furthermore, the gas permeabilities must be converted into liquid permeabilities prior to up-scaling (i.e. divide by 2). The combined scale factor is then 1.25. The scaled permeabilities (refer to the "Avg. reservoir perm." column in the **Table 14–Table 17**) are considered to be comparable with test permeabilities, i.e. permeabilities interpreted from an analysis of well test data (e.g. pumping test data). Further details on the scaling factors are given below.

The up-scaling from core plugs measurements (i.e. laboratory scale) to reservoir scale is not trivial. As a first step, log-derived permeabilities were generated on the basis of a general porosity-permeability relationship that has been established from cross-plotting core porosity data versus core permeability data. GEUS is currently carrying out an internal study, aiming at comparing these log-derived permeabilities with test permeabilities. The initial results of this study have indicated the log-based permeabilities to be somewhat conservative. In order to solve the issue of up-scaling along with the challenge of converting gas permeabilities into liquid permeabilities, GEUS suggests applying a scale factor of 1.25 as described above. The derivation of this factor is based on an analysis of a limited dataset, since both core analysis data and corresponding well test data are needed for the analysis. This database includes e.g. data from the Gassum Formation in the Stenlille-1, -2, -3, -4, -5 and -19 wells, and these data allows a direct comparison between test permeabilities derived from analysis of well test data and core permeabilities originating from intervals that match the tested intervals. So far, the examination of this limited database indicates that multiplying the gas-permeability by 1.25 provides a reasonable estimate of the actual reservoir permeability.

The combined scale factor of 1.25 accounts for the up-scaling from laboratory to field scale and it also incorporates the effect of converting gas permeability into liquid permeability. However, the value of 1.25 may be discussed and is likely to be changed somewhat, when more data and analyses become available. The scaling factor is thus associated with uncertainty, and it may turn out that the “final” scaling factor ranges between 1 and 2. Hence, the current scaling factor of 1.25 could be a conservative estimate, and a higher factor (e.g. 1.5) would also be possible.

# 14 Assessment of the reservoir parameters for the Helsingør area

With the constructed Helsingborg composite succession located closely east of Helsingør and the five deep Danish wells, Karlebo-1A, Lavø-1, Margretheholm-1 and Stenlille-1 & -19 located west, southwest and south of Helsingør, a relatively robust stratigraphic-sedimentological dataset is established for the assessment of the geothermal potential in Helsingør. Due to the poor coverage and quality of the seismic data and the absence of velocity data from the local area, the depths to and thickness of the stratigraphic units are uncertain; it is estimated that uncertainty on the depth and thickness figures may be up to 15%. Furthermore, the presence in Helsingør of the Lower Cretaceous and Lower Jurassic potential reservoir sandstones identified in the Danish well-sections cannot be verified by the seismic data, as the ties to the well-sections are uncertain. In comparison, the uncertainty regarding the Gassum Formation is much reduced because the comprehensive dataset from Helsingborg clearly demonstrates the presence of lateral equivalent Rhaetian–Hettangian–Lower Sinemurian strata – the Höganäs Formation and the Döshult Member. Further, the interpreted seismic data suggest a relatively uniform thickness of c. 100–170 msec. of the Gassum Formation in the greater Helsingør area probably corresponding to 175–300 m assuming an interval velocity of 3500 m/s. The low end of this thickness span corresponds very well to the thickness of the Helsingborg composite succession, while the upper end corresponds well to the Gassum thickness in the wells Hans-1 and Terne-1 located in the Kattegat (Nielsen & Japsen 1991).

The interpretation of the seismic line R29, which is placed close to the AOI-2 and- 3 suggests a thickness of c. 400 m of the base Gassum Formation to the base Upper Cretaceous succession using velocity data from Margretheholm-1. This thickness is used as input and basis for the prognosis shown in **Table 19–Table 21** by calculating the depth to the base Upper Cretaceous and adding estimated formation and unit thicknesses. The estimated thickness of 400 m is very small compared to a thickness of c. 1 km estimated for the Jurassic in the Øresund wells (Larsen et al. 1968). In addition to the 1 km, another 200 m of the Rhaetian–Hettangian is anticipated from the Helsingborg data. Therefore, a large discrepancy between the Øresund well data and the seismic data seems to be present, and it is not possible from the presently available seismic data to analyze this further.

## 14.1 Low and high case – a way to handle the geological uncertainty

In order to deliver figures that can be applied in economical calculations, the geological uncertainties are best illustrated and handled in a robust and sound geological manner by providing a low case and a high case.

The seismic line, R29, indicates that c. 400 m of sediments is available for distribution between the Lower Cretaceous unit, the Fjerritslev Formation, the Lower Jurassic unit and the Gassum Formation. Formation tops and bases within this 400 m succession remain unidentified due to the poor quality of the seismic line, and solely rely on extrapolated information from the closest Zealand wells and information from the Helsingborg and Øresund wells. In order to account for the limited amount of precise geological data from the Helsingør area minimum and maximum values of the depths and thicknesses are derived based on the presently available data, i.e. based on the current geological knowledge it is assumed unlikely that values fall outside the low and high cases (**Table 19–Table 21**). However, true formation depths and thicknesses are not expected to coincide exactly with neither the minimum nor the maximum values. Thus, an average of the low and high cases is calculated with the expectation to represent the best assessment until new seismic data is available (**Table 21**).

### 14.1.1 The Lower Cretaceous and Lower Jurassic units

The low case, which probably is rather pessimistic, assumes that both the Lower Cretaceous *and* the Lower Jurassic successions are missing in Helsingør *or* are dominated by mudstones and siltstones lacking sandstones with a reservoir potential.

For the high case, it is assumed that the Karlebo-1A reservoir figures for the Lower Cretaceous and the Lower Jurassic are directly applicable (see Hjuler et al. 2013). For both units, as discussed below, this approach may be regarded as somewhat conservative as the regional trend for both units point toward increasing grain size and thickness of the sandstones toward Helsingør.

Thus, both the low and the high case may be considered to be very pessimistic. If new seismic data with tie to Karlebo-1A make it possible to follow reflectors, which correspond to the Lower Cretaceous and Lower Jurassic in the well, from the well to the area of interest, then the units are "proved" to be present in Helsingør. If the new data further suggest the presence of sand-dominated intervals, then both the maximum and minimum values need to be revaluated and probably increased considerably.

### 14.1.2 The Gassum Formation

For the Gassum Formation the uncertainty is mainly related to the Helsingborg dataset – the Helsingborg composite succession. Despite that: 1) the available maturity data from vitrinite reflectance measurements on coal beds indicate a burial depth comparable to the mapped depth of the Gassum Formation in Helsingør; 2) that the petrographic-diagenetic study does not indicate significant effects on porosity and permeability related to uplift, and 3) the measured porosity and permeability on core samples plot as expected on the Danish porosity-permeability trend, it cannot be completely ruled out, that minor differences in maximal burial depths and minor effects from the uplift phase exist. In addition, the Helsingborg Member was deposited in a highly variable environment, where the sandstones accumulated in tidal and fluvial channels, as wash over fans, shorefaces, mouth bars and bay head deltas, whereas the Gassum Formation in general was formed in a more open and wave-influenced environment (Ahlberg 1994; Nielsen 2003). Therefore, the Helsingborg Member sandstones probably constitute more hydraulically isolated reservoir bodies compared to the Gassum Formation sandstones. This difference in geometry and distribution of the sandstones probably occurs over a laterally wide zone, and it is not possible to pinpoint where in the subsurface this transition occurs. Therefore, for the low case the Helsingborg composite succession is giving the same weight as the selected Danish wells. In the high case, the Helsingborg composite succession is given a double weight.

In the following the data and criteria for the assessment of the various reservoir parameters are described for the Lower Cretaceous unit, the Lower Jurassic unit and the Gassum Formation. For the deep Bunter Sandstone Formation the data from the Margretheholm plant is referred to.

## 14.2 Lower Cretaceous

A Lower Cretaceous succession of interbedded mudstones and sandstones was encountered in all four wells. No information on the Lower Cretaceous is available from Helsingborg or the Øresund wells as the succession probably was eroded during the Late Cretaceous–Early Cenozoic uplift phase. In the Margretheholm-1 and Stenlille-1 wells only 1–2 m of net sand is found in the Lower Cretaceous. In the Lavø-1 and Karlebo-1A wells the lower part of the Lower Cretaceous comprises thick sandstones and 15–30 m thick sandstone-dominated intervals have been identified for the evaluation (**Table 14**). The four wells thus indicate a distinct trend of increasing content of Lower Cretaceous sandstones toward the northeast. Based on GEUS´ standard cut-off values, 21 m of net sand is present in the Karlebo-1A well, while the net sand value cannot be determined in Lavø-1 due to an incomplete log-suite; assuming a similar ratio between gross sand and net sand in the two wells, a net sand of 10.5 m may be estimated in Lavø-1. The grain size of the sandstones in Karlebo-1A is dominantly fine-grained.

### 14.2.1 Input to the prognosis

Based on the fairly limited dataset and GEUS´ general geological model it is assumed that both the thickness of the sandstones and their grain size are increasing from the Karlebo-1A well toward the Helsingør area. Thus the reservoir parameters obtained from the evaluation of the Karlebo-1A well may be regarded as minimum values for the Lower Cretaceous in the Helsingør area in the high case. It is thus considered likely that the calculated transmissivity of 6.5 Dm (**Table 14**) from Karlebo-1A is a conservative value for Helsingør; however, the conservative estimate may be considered balanced by a larger burial depth of c. 2.2 km at Helsingør (**Table 20**).

However, as emphasized in Hjuler et al. (2013) it is not possible to map the presence and thickness of the Lower Cretaceous interval from the presently available seismic data. The presence of the Lower Cretaceous in Helsingør is thus primarily based on the data from the Lavø-1 and Karlebo-1 well sections and need to be confirmed by new seismic data from the Helsingør area. In the low case, no reservoir sandstones are assumed in this part of the Mesozoic (**Table 19, Figure 21**).

## 14.3 Lower Jurassic

In the Danish Basin the Lower Jurassic (post-Gassum Formation) mainly consists of claystones belonging to the Hettangian–lowermost Aalenian Fjerritslev Formation. However, along the northeastern basin margin in

North Jutland, Kattegat and Northeast Zealand the number, thickness and grain size of interbedded sandstones increase significantly. The lowermost part of these Lower Jurassic sandstones is traditionally included in the time-transgressive Gassum Formation, which is defined to include Hettangian–lowermost Sinemurian sandstones along the margin of the basin (see Nielsen 2003 for details). These Gassum Formation sandstones include the contemporaneous Helsingborg Member from Skåne as discussed in the section on the Gassum Formation below.

All five wells included in this study have encountered a Lower Jurassic succession, 129–170 m thick showing a dominance of claystones (**Table 15**). Both the total thickness of the succession and the gross and net sandstone thickness show a distinct increasing trend toward the northeast with the largest values found in the Karlebo-1A well. From the Helsingborg area information on the Lower Jurassic succession above the Hettangian Helsingborg Member is very limited due to erosion during the Late Cretaceous–Early Cenozoic uplift phase.

While claystones with thin siltstones and sandstones dominate the Fjerritslev Formation in the Danish Basin, the post-Hettangian Lower Jurassic sequence in NW and W Skåne consists of the Rya Formation subdivided into four members (Grigelis & Norling 1999). The Lower Sinemurian Döshult Member consists of coarse- to medium-grained sandstones (sandstone I, herein) in the lower part and clays and marls in the upper part. The Pankarp Member represent the Upper Sinemurian  and consist of 60–70 m of variegated clay and shale in the lower part overlain by sand and sandstones in the middle part overlain by clay and shale. The Katslösa Member represents the Upper Sinemurian and Lower Pliensbachian and consists of 30–40 m of claystones, siltstones and sandstones. The Rydebäck Member represents the Upper Pliensbachian–Toarcian/Aalenian interval and comprises 50–100 m of sandy, silty oolitic sediments with clay and carbonate. A similar succession was drilled in parts by the Øresund wells (see **Section 6.3**). Based on the available information from these well (Larsen et. al.1968), it is difficult to assess the amount of sandstones in the Lower Jurassic and thus the reservoir potential. The Döshult Member seems to form a potential reservoir in the post-Hettangian Lower Jurassic succession, and is included in the Gassum Formation as discussed below.

### 14.3.1 Input to the prognosis

Based on the information from the Danish wells it is reasonable to assume that the NE-ward trend of increasing net sandstone thickness continues into the Helsingør area. Thus the reservoir parameters obtained from the evaluation of the Karlebo-1A well may be regarded as minimum values for the Lower Jurassic in the Helsingør area. It is thus considered possible that the calculated transmissivity of 17 Dm for Karlebo-1A (**Table 15**) is a conservative value for Helsingør. The conservative estimate may be considered balanced by a larger burial depth of c. 2.3 km (**Table 20**).

However, as emphasized in Hjuler et al. (2013) it is not possible to map the presence and thickness of the Lower Jurassic interval from the presently available seismic data. The presence of the Lower Jurassic in Helsingør is thus primarily based on the data from the five well sections and the Øresund wells; new seismic data from the Helsingør area is needed to confirm the presence and depth of the succession. Furthermore, it has not been possible from the present data and knowledge within GEUS and SGU to correlate and compare in sufficient detail the Danish well-sections to the data from Skåne and the Øresund wells for a thorough evaluation of the apparently large differences in sedimentary development between the Danish well sections and the successions in Skåne and in the Øresund wells. Therefore, the low case assumes no reservoirs to be present in this part of the Mesozoic (**Table 19, Figure 21**). It has also to be born in mind that the Øresund wells did not cover the entire Lower Jurassic succession, and occurrence of sandstones in the undrilled sections is possible.

## 14.4 Gassum Formation

The Gassum Formation is present in most Danish wells within the geothermal depth window and constitutes a good reservoir in large parts of Denmark (Mathiesen et al. 2009). It is utilized for geothermal production in the Thisted and Sønderborg plants, and for storage of natural gas in the Stenlille structure. Four of the five investigated wells have penetrated a thick Gassum Formation of 132–145 m, while 75 m was encountered in the Lavø-1 well (**Table 16**). The constructed composite Helsingborg succession encompassing an upper Rhaetian sandstone and 8 overlying Hettangian sandstones is c. 180 m thick (**Figure 16**).

The Rhaetian sandstone is almost 6 m thick in the cored succession from borehole 06.1.1008. The succession below the sandstone consists of a heterogeneous succession of coal and clay and thinner sandstone beds. Ahlberg (1990) reports that this unit is present in three separate cores that were drilled during the railway tunnel construction in Helsingborg in the late 1980ies. He states that this unit differs from the Hettangian sandstone units in that it is a medium- to coarse-grained beach sand, very poor in feldspar and with rounded to spherical quartz grains. The thickness of this unit may be variable. Based on core material and wireline logs Ahlberg (1990) estimated its thickness to 10–15 m. Point counting data from Ahlberg (1990) suggest porosities of 11–20%. In most cases point counting estimates a lower porosity compared to measurement, and these values seem to be far too low when the grain size and grain shape is considered; thus a porosity of 25% is assumed in **Table 18**.

The Hettangian sandstones identified in the available core material from the Helsingborg area are classified into two main types – primary aquifers and secondary aquifers (see **Section 4**). The primary aquifers constitute 22.5% and the secondary aquifers constitute 14% of the investigated core material corresponding to c. 34 m and 21 m, respectively if the estimated cumulative thickness of 150 m of the Helsingborg Member is used. The combined thickness of the aquifers is thus 55 m plus 6 m of Rhaetian sandstones totaling 61 m, which is closely comparable to the results of the evaluation of the petrophysical logs that resulted in c. 76 m gross sand and 57 m of net sand (**Table 18**). Based on descriptions by Ahlberg (1990) the primary aquifer sandstones occur in two groups reflecting their depositional environments. The first group forms up to c. 15 m thick units of homogenous, medium-grained sandstones fining-upward into fine-grained sandstones with an upward increase of clay laminae. These units show high porosity and very high permeability (1–2 D) in their basal parts and were formed in large distributaries followed by tidal and wave influenced shoreline deposits. The second group forms 5–10 m thick, well-sorted, homogeneous and medium-grained sandstones with very high permeabilities. The sandstones represent foreshore and shoreface deposits very similar to many of the sandstones in the Gassum Formation (Ahlberg 1990; Hamberg & Nielsen 2000; Nielsen 2003). The secondary aquifers are typically fine-grained sandstones commonly interbedded with sandy and silty claystones.

In addition to the upper Rhaetian–Hettangian reservoir sandstones, the overlying lower Sinemurian Döshult Member contains sandstones that may form a significant reservoir. The Döshult sandstone was encountered in the Øresund wells BH8 and BH9 (**Figure 16**), where it forms an up to 15 m thick, fine and medium- to coarse-grained, coastal-marine sandstone overlain by mudstones (Larsen et al. 1968).

### 14.4.1 Input to the prognosis

The Stenlille wells are located at great distance from Helsingør (**Figure 1**) and in a different geological position in the Danish Basin, which is clearly reflected in the composition of the Gassum Formation. The Lavø-1 well is located closer to Helsingør, but still in the Danish Basin. The Karlebo-1A and the Margretheholm-1 wells are both located in the Höllviken Graben, and together with the Helsingborg composite succession they are considered as most relevant for the preliminary prognosis for Helsingør. As Margretheholm-1 is situated at greater distance to Helsingør compared to the two others, the three data points are balanced by weighing the Karlebo-1A and Helsingborg composite two each and Margretheholm-1 one for the high case (**Table 20**). As the presence of the Gassum Formation sandstones is well constrained by the Danish wells and the Helsingborg composite succession, the low case is reduced by down-grading the Helsingborg composite succession by giving it a weight of one out of five successions and by including the thinner succession encountered in the Lavø-1 well (**Figure 21**).

## 14.5 Bunter Sandstone Formation

The Bunter Sandstone Formation is well-known in the North German Basin and in the southern–central part of the Danish Basin, but is very poorly known from Zealand. The Stenlille-19 well drilled only the uppermost, sandstone-poor part of the formation. It is thus primarily known from the Margretheholm wells where it is used for geothermal production. A few wells in Sweden have encountered comparable units (e.g. the Ljunghusen Formation), and the Hans-1 and Terne-1 in the southern part of Kattegat have penetrated a c. 1 km thick Skagerrak Formation of which the lower part probably is time equivalent to the Bunter Sandstone Formation (Michelsen & Nielsen 1991). The information on the formation is thus very scattered in the greater vicinity of Helsingør. The preliminary mapping of a seismic reflector assumed to correspond to the Top Bunter Formation shows a depth of more than 3000 m in Helsingør when velocity data from Margretheholm-1 is used for depth conversion.

### 14.5.1 Input to the prognosis

As the data on the Bunter Sandstone Formation/Skagerrak Formation is very limited, it is suggested to use information from the Margretheholm plant corrected for a larger burial depth of c. 3100 m (**Figure 21**) compared to the 2600 m in Margretheholm.

## 14.6 Assessing the reservoir parameters of the Helsingør area

Predicted reservoir parameters, i.e. reservoir parameters expected to be valid for the Helsingør area, are listed in **Table 19–Table 21**. The prognosis is based on depth converted seismic data combined with well data, primarily wireline logs from the Helsingborg composite well section, Karlebo-1A, Lavø-1 and Margretheholm-1, along with core analysis data from wells located outside the North Zealand area, including the Helsingborg area. A low and a high case are suggested, because the presumed presence of Lower Cretaceous and Lower Jurassic strata cannot be confirmed from the existing seismic data.

**Lower Cretaceous:** Gross sand thicknesses are based on Karlebo-1 and Lavø-1 data, whereas the remaining parameters are derived primarily from the Karlebo-1 data, as the net sand thickness, porosity and permeability cannot be interpreted from the Lavø-1 log data. Weight factors: 1 x Karlebo-1 and 1 x Lavø-1. The basic reservoir data for the analyzed wells are tabulated in **Table 14**. It may turn out that the Lower Cretaceous unit is not present at Helsingør or if present do not contain sandstones; consequently, a zero sandstone thickness is given for the low case **(Figure 21)**.

**Lower Jurassic Reservoir (res.):** The reservoir parameters are based on data from the Karlebo-1, Margretheholm-1 and Lavø-1 wells. With respect to the net sand, porosity and permeability data, it has been assumed that the Lavø data equals the Karlebo data. Weight factors: 2 x Karlebo-1 and 2 x Lavø-1, and 1 x Margretheholm-1. The basic reservoir data for the analyzed wells are tabulated in **Table 15**. It may turn out that the Lower Jurassic reservoir is not present or if present do not contain sandstones at Helsingør; consequently, a zero sandstone thickness is given for the low case **(Figure 21)**.

**Gassum Formation:** The reservoir parameters are based on the Karlebo-1, Margretheholm-1 and 'Helsingborg composite'. In the low case, the following weight factors have been applied: 2 x Karlebo-1 and 1 x 'Helsingborg composite' and 1 x Margretheholm-1 (1 x Lavø-1 with respect to unit thickness). In the high case, the following weight factors have been applied: 2 x Karlebo-1 and 2 x 'Helsingborg composite' and 1 x Margretheholm-1. The basic reservoir data for the analyzed wells are tabulated in **Table 16**. Notice: The expected thickness of the Gassum Formation (i.e. the "Gassum Formation equivalent") is about 200 meters in the Helsingborg area.

**Bunter Sandstone Formation:** The parameters are based on data from the Margretheholm-1 well. These data have been adjusted for a greater depth, it is thus expected that top Bunter Sandstone Formation is situated c. 700 meters deeper at Helsingør compared to Margretheholm. The permeability may, however, be significantly reduced due to diagenesis. The basic reservoir data for the analyzed wells are tabulated in **Table 17**.

**Table 19:** Assessed depths and thicknesses of potential reservoirs in the Helsingør area: **Low case**. Based on information from well data and the GEUS geological model set up for the North Zealand area. Data from Karlebo-1/1A, Margretheholm-1/1A, and Lavø-1 along with the Helsingborg wells ('Helsingborg composite') have been utilized.

| **Formation/unit** | **Top – Base of unit** (m TVDss) | **Unit thickness** (m) | **Thickness Gross sand** (m) | **Thickness Net sand** (m) |
|---|---|---|---|---|
| Lower Cretaceous | 2130 – 2200 | 70 | 0 | 0 |
| Fjerritslev | 2200 – 2395 | 195 | 0 | 0 |
| Lower Jurassic reservoir | 2395 – 2395 | 0 | 0 | 0 |
| Gassum | 2395 – 2530 | 135 | 60 | 43 |
| Bunter Sandstone | 3100 – ? | 300* | 140* | 48* |

*: Parameters from Margretheholm 1A and -2.

**Table 20:** Assessed depths and thicknesses of potential reservoirs in the Helsingør area: **High case**. Based on information from well data and the GEUS geological model set up for the North Zealand area. Data from Karlebo-1/1A, Margretheholm-1/1A, and Lavø-1 along with the Helsingborg wells (Helsingborg composite') have been utilized.

| **Formation/unit** | **Top – Base of unit** (m TVDss) | **Unit thickness** (m) | **Thickness Gross sand** (m) | **Thickness Net sand** (m) |
|---|---|---|---|---|
| Lower Cretaceous | 2130 – 2200 | 70 | 25 | 20 |
| Fjerritslev | 2200 – 2220 | 20 | 0 | 0 |
| Lower Jurassic reservoir | 2220 – 2370 | 150 | 52 | 35 |
| Gassum | 2370 – 2530 | 160 | 67 | 50 |
| Bunter Sandstone | 3100 – ? | 300* | 140* | 48* |

*: Parameters from Margretheholm 1A and -2.

**Table 21:** Assessed depths and thicknesses of potential reservoirs in the Helsingør area: Average of **Low case** (**Table 19**) and **High case** (**Table 20**).

| **Formation/unit** | **Top – Base of unit** (m TVDss) | **Unit thickness** (m) | **Thickness Gross sand** (m) | **Thickness Net sand** (m) |
|---|---|---|---|---|
| Lower Cretaceous | 2130 – 2200 | 70 | 13 | 10 |
| Fjerritslev | 2200 – 2308 | 108 | 0 | 0 |
| Lower Jurassic reservoir | 2308 – 2383 | 75 | 26 | 18 |
| Gassum | 2383 – 2530 | 148 | 64 | 47 |
| Bunter Sandstone | 3100 – ? | 300 | 140 | 48 |

*: Parameters from Margretheholm 1A and -2.

**Table 22:** Prognosis for the Helsingør area: Depths and thicknesses are **average values** of **Low case** (**Table 19**) and **High case** (**Table 20**). Averaged (Avg.) reservoir parameters are listed in columns. Based on information from well data and the GEUS geological model set up for the North Zealand area. Data from Karlebo-1/1A, Margretheholm-1/1A, and Lavø-1 along with the Helsingborg wells ('Helsingborg composite') have been utilized. The reservoir parameters (including permeability estimates) are based primarily on the poro-perm relations presented in **Figure 19–Figure 20** along with the data and parameters listed in **Table 14–Table 17**. Weight factors applied as outlined above.

| **Prognosis; Helsingør area Res. Parameter** | **Top - Base of unit** (m MD) | **Unit thick.** (m) | **Sst. thickness** **Gross Sand** (m) | **Net Sand** (m) | **Avg. Por.** (%) | **Avg. gas perm.** (mD) | **Avg. reservoir perm.** [1)] (mD) | **Reservoir transmissivity** [1)] (Dm) |
|---|---|---|---|---|---|---|---|---|
| Lower Cret. | 2130 – 2200 | 70 | 13 | 10 | 20 | 250 | 300 | 3 |
| Fjerritslev Fm | 2200 – 2308 | 108 | 0 | 0 | - | - | - | 0 |
| L. Jurassic res. | 2308 – 2383 | 75 | 26 | 18 | 20 | 315 | 395 | 7 |
| Gassum Fm | 2383 – 2530 | 147 | 64 | 47 | 22 | 603 | 755 | 36 |
| Bunter Sst. Fm | 3100 – ? | 300 [2)] | 140 [2)] | 48 [2)] | 17 | 40 | 50 | 3 |

[1)]: At reservoir scale (field scale). [2)]: Parameters from Margretheholm 1A and -2.

The estimated reservoir parameters at Helsingør are associated with large uncertainty, primarily because the permeability is estimated on the basis of core analysis data originating from areas outside the North Zealand area. Core analysis data and well test data are not available from the nearest deep well (Karlebo-1/1A), but information about permeability can be extracted from shallow wells drilled in the Helsingborg area, but also the Stenlille wells and wells located elsewhere in DK provide information about permeability. The reservoir parameters listed in **Table 22** address the geothermal potential at Helsingør, and the expected geothermal potential is also associated with uncertainty, however, and the following items should also be considered prior to discussing development plans and drilling options.

So far a scaling factor of 1.25 is suggested for up-scaling from laboratory scale to reservoir level, but it may turn out that a somewhat higher factor (1.5?) should be applied for estimating reservoir permeabilities. This work is in progress.

The porosity-permeability relation used for assessing the permeability may be somewhat conservative, because it is average curve and it does not account for local permeability enhancements, i.e. minor intervals having significantly higher permeabilities than indicated by the general porosity-permeability curve.

The reservoir parameters presume a vertical well, but a deviated well will increase the contact area between the well bore and the reservoir formation, most likely leading to higher water production rates.

### 14.6.1 Water production tests

The various formations and reservoir units relevant for assessing the geothermal potential at Helsingør have been tested in a number of wells located on Zealand (**Table 23**). The test data have also been considered prior to calculating reservoir parameters.

**Table 23:** Relevant well tests; water production tests conducted in selected intervals.

| well | Unit or formation tested | Estimated test perm. (mD) | Comments Source |
|---|---|---|---|
| Stenlille-1 | Lower Jurassic Sand-1 | 1500 | Dansk Naturgas (1989) |
| Stenlille-3 | Lower Jurassic Sand-5 | 50 | Dansk Naturgas (1989) |
| Stenlille-3 | Lower Jurassic Sand-7 | 250 | Dansk Naturgas (1989) |
| Stenlille-1 to -5 | Gassum Fm, Zones 1–3 | 100–750 | Dansk Naturgas (1989) |
| Stenlille-19 | Gassum Fm, Zone 6 | 6300 | DONG (2001) |
| Margretheholm-1/2 | Bunter Sandstone Fm | 420 | DONG (2003,2004) |

### 14.6.2 Reducing the uncertainty range connected to the porosity-permeability correlation

Not that much good-quality core material is available from the North Zealand area, but despite of a limited database, a reliable poro-perm relation may be established on the basis of data from the Stenlille wells supplemented with core data from areas outside Sjælland and a few side wall core samples from Margretheholm-2. However, the reservoir sandstones at Stenlille are predominantly fine-grained, whereas the assumed reservoir sandstones at Helsingør are expected to be somewhat coarser grained, most likely fine- to medium-grained and comparable to the Karlebo-1A and Helsingborg sandstones as described above. This difference in grain size means that the Stenlille permeabilities are not representative of the Helsingør area. GEUS suggests multiplying the Stenlille permeabilities by a factor of 2.5 in order to compensate for effect of differences in grain size (cf**. Figure 19–Figure 20**), hereby making the Stenlille data comparable to permeabilities measured on core material representing the fine- to medium-grained Gassum Formation sandstones found in the Margretheholm-2, Års-1, Gassum-1 and Farsø-1 wells (**Figure 22**). The use of primarily Stenlille data, i.e. data from a local and restricted area, means that the accompanying uncertainty band becomes narrower (**Figure 22**) than the uncertainty band connected to the regional database.

### 14.6.3 Transmissivity

The transmissivity is calculated as flow weighted transmissivity based on the estimated gas permeability log and net sand thickness, followed by up-scaling as described above. The results of the transmissivity calculations are listed in **Table 24**. The uncertainty on the transmissivity is related primarily to the uncertainty on the permeability estimate, and in previous studies GEUS suggested setting up a permeability envelope defined by multiplying (and dividing) the permeability by a specific factor. This range is defined via cross-plotting core porosity and core permeability data from a number of wells as described above and in this context, the analysis of the Stenlille data have been utilized for defining an appropriate uncertainty range (**Figure 22**).

A similar methodology is suggested for addressing the uncertainty on the transmissivity, i.e. the transmissivity range is likewise defined by multiplying (and dividing) by the same factor, because the uncertainty on the transmissivity is related primarily to the uncertainty on the permeability estimate. Nevertheless, the intention of presenting a transmissivity range is to account for the “total” uncertainty, i.e. the accumulated uncertainty connected to permeability, net sand thickness and up-scaling (**Table 24**).

**Table 24:** Estimated reservoir transmissivity based on an average min and max value and associated range (uncertainty band).

| **Transmissivity Prognosis; Helsingør area** | **Top and Base of unit** (m) | **Reservoir Transmissivity** (Dm) | **Specific factor for multiplication, and division** | **Transmissivity range at reservoir cond.** (Dm) |
|---|---|---|---|---|
| Lower Cretaceous | 2130 – 2200 | 3 | 3 | 1 – 9 |
| Lower Jurassic res. | 2308 – 2383 | 7 | 3 | 2 – 21 |
| Gassum Formation | 2383 – 2530 | 36 | 3 | 12 – 107 |
| Bunter Sandstone Fm | 3100 – ? | 3 | 3 | 1 – 8 |

It is emphasized, that the relatively low transmissivity range for the Lower Cretaceous and Lower Jurassic units is related to the assumed low case of no sandstones being present in these units or the absence of the two units in Helsingør.

If new seismic data with tie to Karlebo-1A allow identification of the Lower Cretaceous and Lower Jurassic units in the area of interest, then the low case needs to be reconsidered.

If the new seismic data further provide support to GEUS´ regional geological model that assumes increasing sand content from the present well-sections toward the northeast, then both the high and low values need to be revaluated and probably increased considerably.

# 15 Temperature assessment for the Helsingør area

Based on the temperature data from the Höllviken Graben weighting the test-temperature highest, a temperature prognosis for the Helsingør area is compiled resulting in a general temperature gradient of 25 ºC /km and a mean annual surface temperature of 8 ºC. The equation describing this relation (0.025 x depth + 8) based on data from the Sjælland area has been used for assessing the temperature at the centre of potential geothermal formations (**Table 25**). This relation may be regarded as a conservative estimate when comparing with the general relation of 0.028 x depth + 8 (Hjuler et al. 2013). The uncertainty for the temperature estimates is ±10%.

**Table 25:** Assessed temperature of potential geothermal reservoirs.

| Formation / unit | Formation interval (m MD) | Depth of temperature assessment (m) | Temperature (°C) |
|---|---|---|---|
| Lower Cretaceous | 2130 – 2200 | 2165 | 62 |
| Lower Jurassic | 2220 – 2370 | 2295 | 65 |
| Gassum (min case) | 2395 – 2530 | 2463 | 70 |
| Gassum (max case) | 2370 – 2530 | 2450 | 69 |
| Bunter Sandstone | 3100 – ? | 3250 | 89 |

# 16 Conclusions

The objective of this study is to improve the understanding of the geothermal potential of sandstone formations in the Helsingør area by including geological data from the Helsingborg area and Øresund. These new data has been evaluated in order to identify and characterize lithostratigraphic units corresponding to the Lower Cretaceous unit, Lower Jurassic unit and Gassum Formation in the Danish wells of Zealand. A composite well profile of the Helsingborg area has been constructed based on well log and core data from a number of geotechnical wells located onshore close to the Helsingborg coastline. Several sandstone beds have been identified within the composite profile. Available cores from these sandstone beds have been dated biostratigraphically, described petrographically and analysed with respect to porosity and permeability.

- Integration of analyses results from the Helsingborg area and data from Øresund with data presented in Hjuler et al. (2013) and Nielsen et al. (2014) has strengthened the reservoir quality assessments in the Helsingør area as described below.

- The Helsingborg composite profile is of Late Triassic–Lower Jurassic age (Rhaetian–lowermost Sinemurian) and corresponds to the Danish Gassum Formation. The Maximum burial depth is estimated to 2000–3000 m corresponding well with the burial depth of Gassum Formation on Zealand. The composite profile of Helsingborg is c. 200 m thick (see **Figure 16**) with 57 m of net sand, an average porosity of 25%, estimated average reservoir permeability of 1560 mD and a transmissivity of 99 Dm.

- With highly prosperous reservoir parameters present in the Helsingborg area the uncertainty of assessing the geothermal potential of the Gassum Formation in the Helsingør area is reduced significantly. Thus the following reservoir parameters are assessed: a formation thickness of 157 m with 47 m of net sand, an average porosity of 22%, estimated average reservoir permeability of c. 750 mD and a transmissivity of 36 Dm (**Table 22**).

- With respect to the potential of Lower Cretaceous and Lower Jurassic (post Lower Sinemurian) units the uncertainty remains significant. The presently available seismic data seems to suggest the occurrence of both Lower Cretaceous and Lower Jurassic in the Helsingør area, but the data is of poor quality. As the lowermost Lower Jurassic strata equivalent to the Gassum Formation constitute the bedrock in the Helsingborg area it is not certain that younger Lower Jurassic and Lower Cretaceous sediments have been present in the area. However, as the Gassum Formation equivalent strata have been deeply buried and thus overlain by thick strata, it is very likely that younger Lower Jurassic and Lower Cretaceous have been present prior to uplift and erosion. In addition, Lower, Middle and Upper Jurassic sediments are known from wells located in the Øresund area between Helsingør and Helsingborg (Larsen et al. 1968). To clarify whether Lower Cretaceous and Lower Jurassic strata are present in Helsingør acquisition of new seismic data is necessary. If new seismic data indicate that the units are present with reasonable thicknesses comparable to the Danish well data, the low case presented here will probably be adjusted considerably (**Table 19**).

- Assessed temperatures for the potential reservoirs are indicated in **Table 25**.

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# 18 Figures

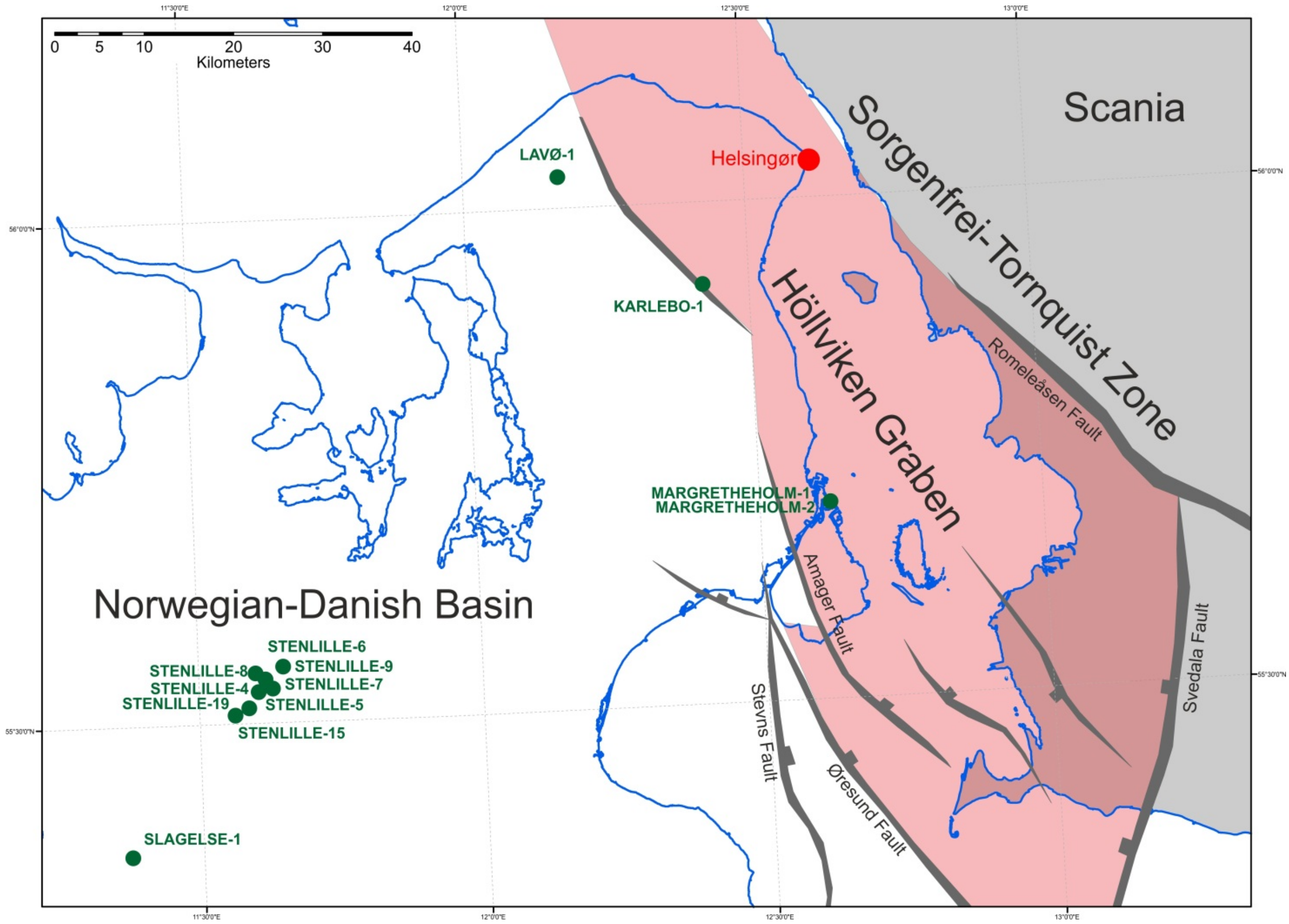



**Figure 1:** Map showing major structural elements in the East Sjælland-West Skåne area. Note the location of the downfaulted Höllviken Graben between the Norwegian-Danish Basin and the Sorgenfrei-Tornquist Zone and how the graben is bounded by faults. The Karlebo-1/1A and Margretheholm-1/1A wells are situated within the Höllviken Graben and expectedly provide the best well data for describing the subsurface of the Helsingør area.

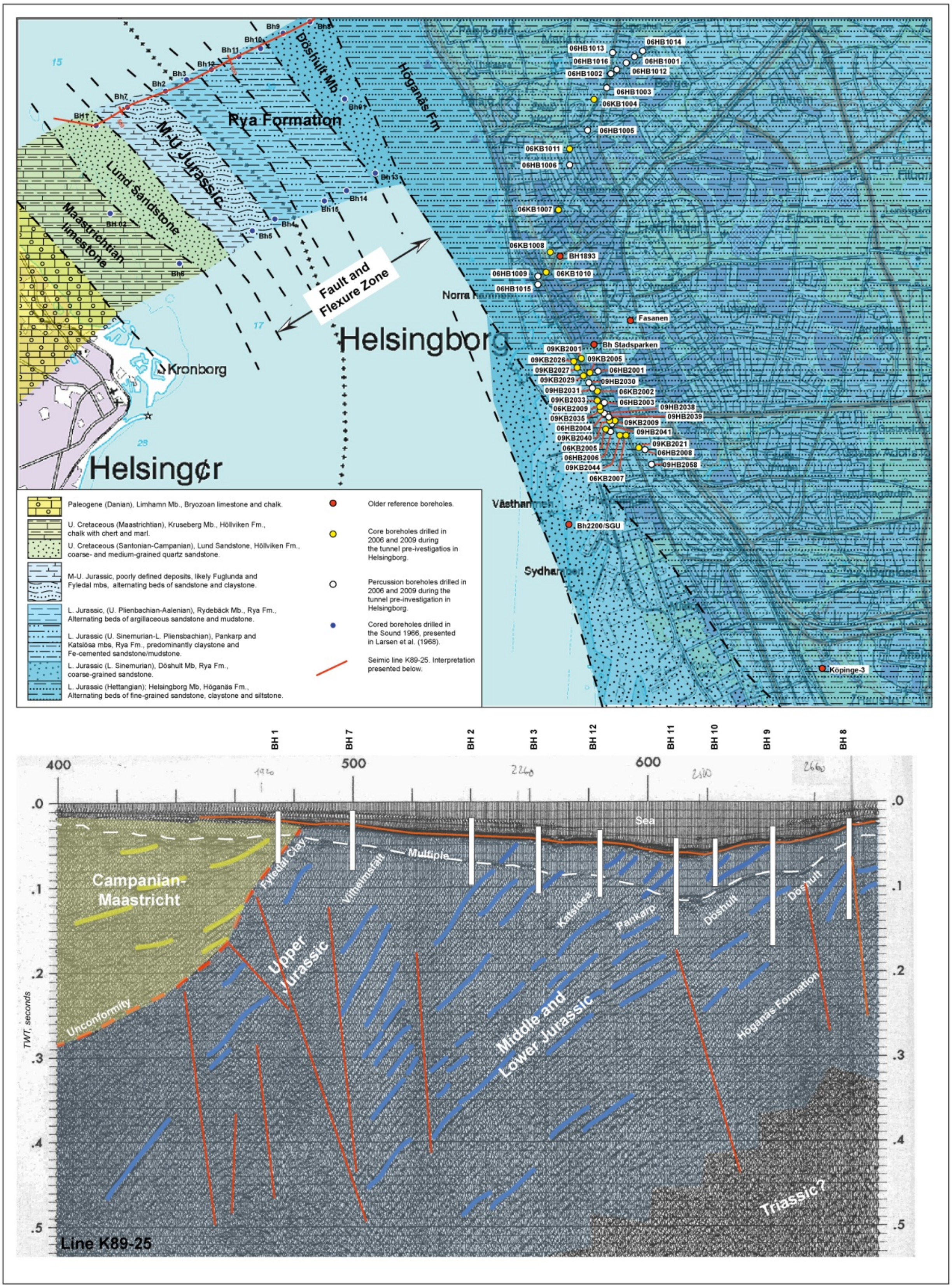



**Figure 2:** Map of the Helsingør-Helsingborg area with bedrock geology and the location of boreholes and schematic interpretation of the K89-25 seismic profile across Øresund.

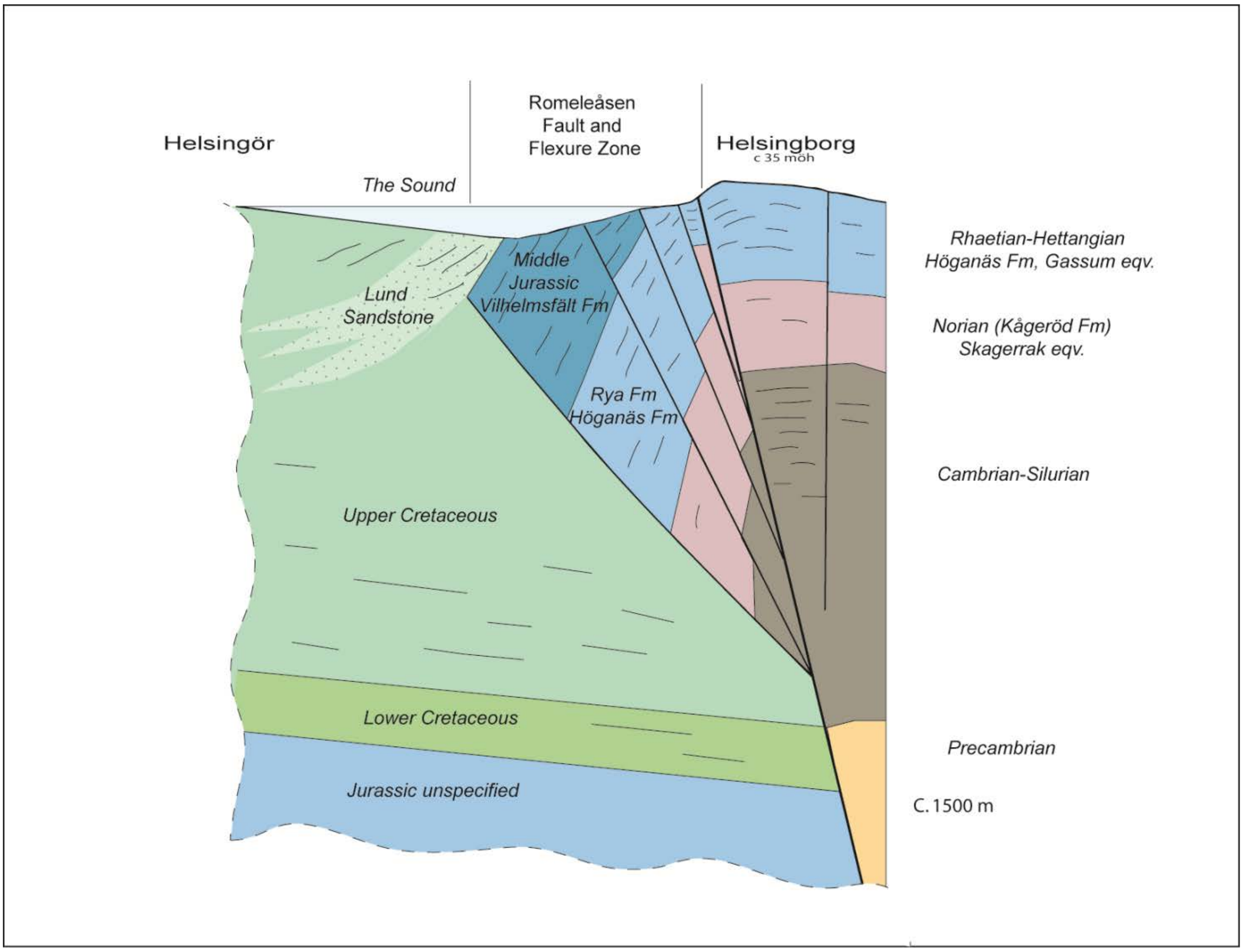



**Figure 3:** Conceptual geological cross section of the Romeleåsen Fault Zone.

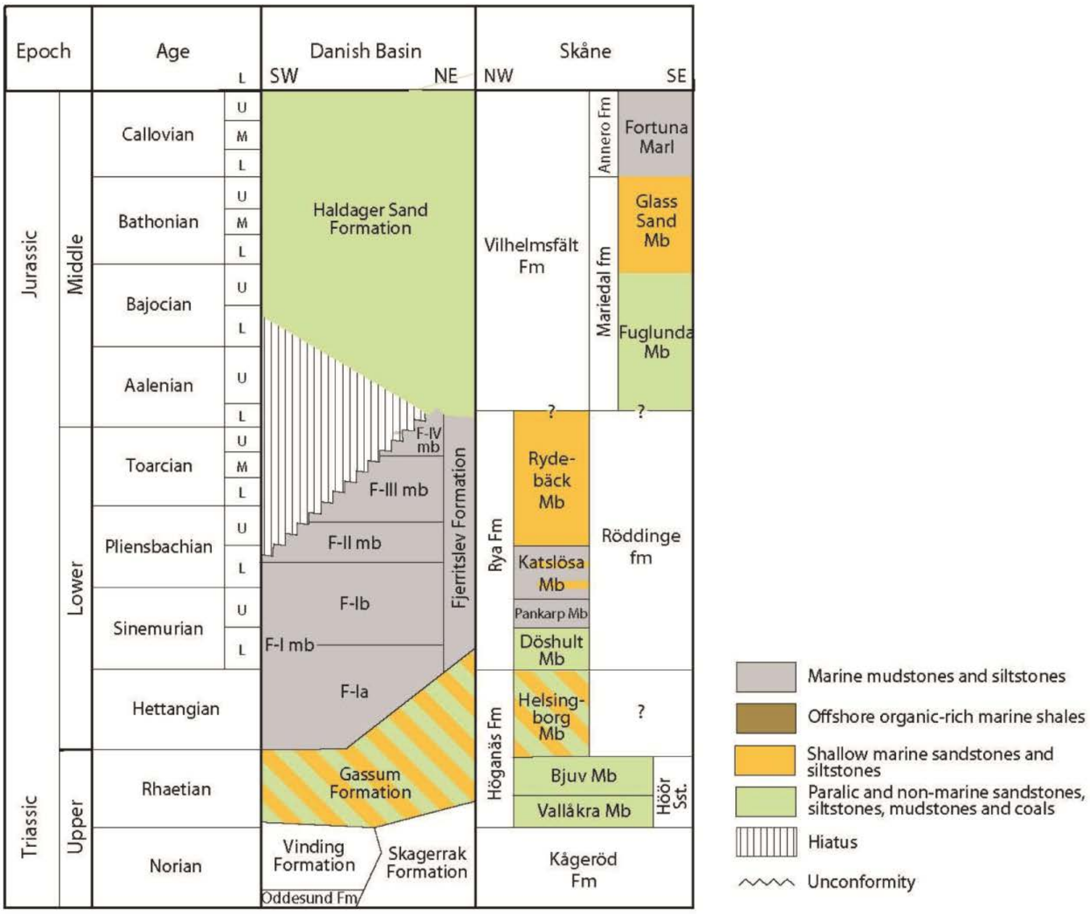



**Figure 4:** Stratigraphic scheme of the Upper Triassic and Jurassic in Skåne and Danish Basin. Modified after Nielsen (2003) and Lindström and Erlström (2011).

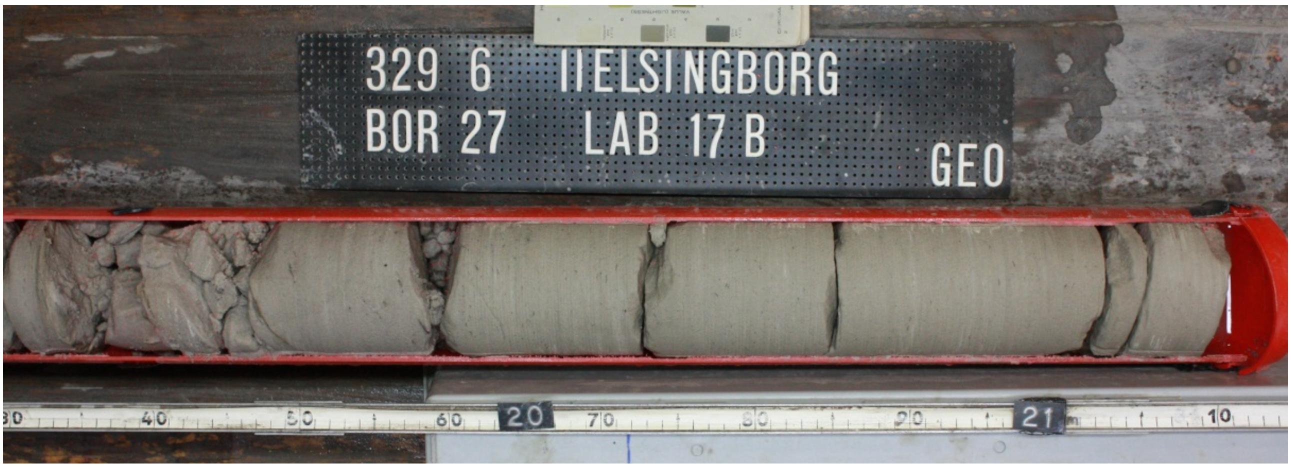



**Figure 5:** Core photograph showing an example of sandstone type 1.


**Figure 6:** Core photograph showing an example of sandstone type 4.

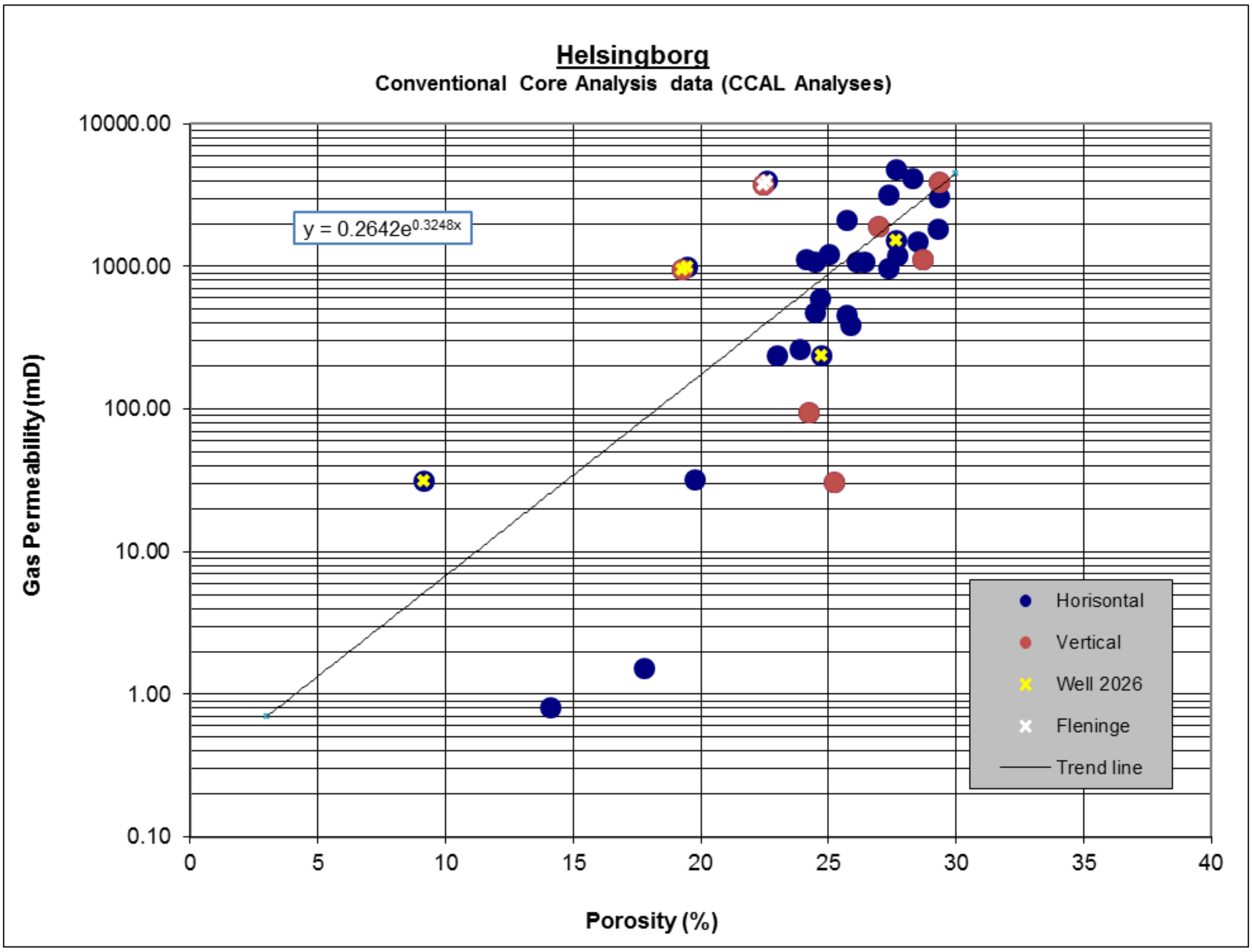



**Figure 7:** Porosity-permeability relationship. The plot is based on conventional core analysis data (CCAL) from the wells 09-KB-2001, -2009, -2021, -2026, -2027, -2029, -2033, -2035, -2040, -2044 and Fleninge-1. The core data are laboratory data. See legend for colour coding etc. The low porosity/low permeability data points are considered to be clay points and they are not included in the regression analysis. For further details, reference is made to the core analysis report (GEUS Core Laboratory 2014).

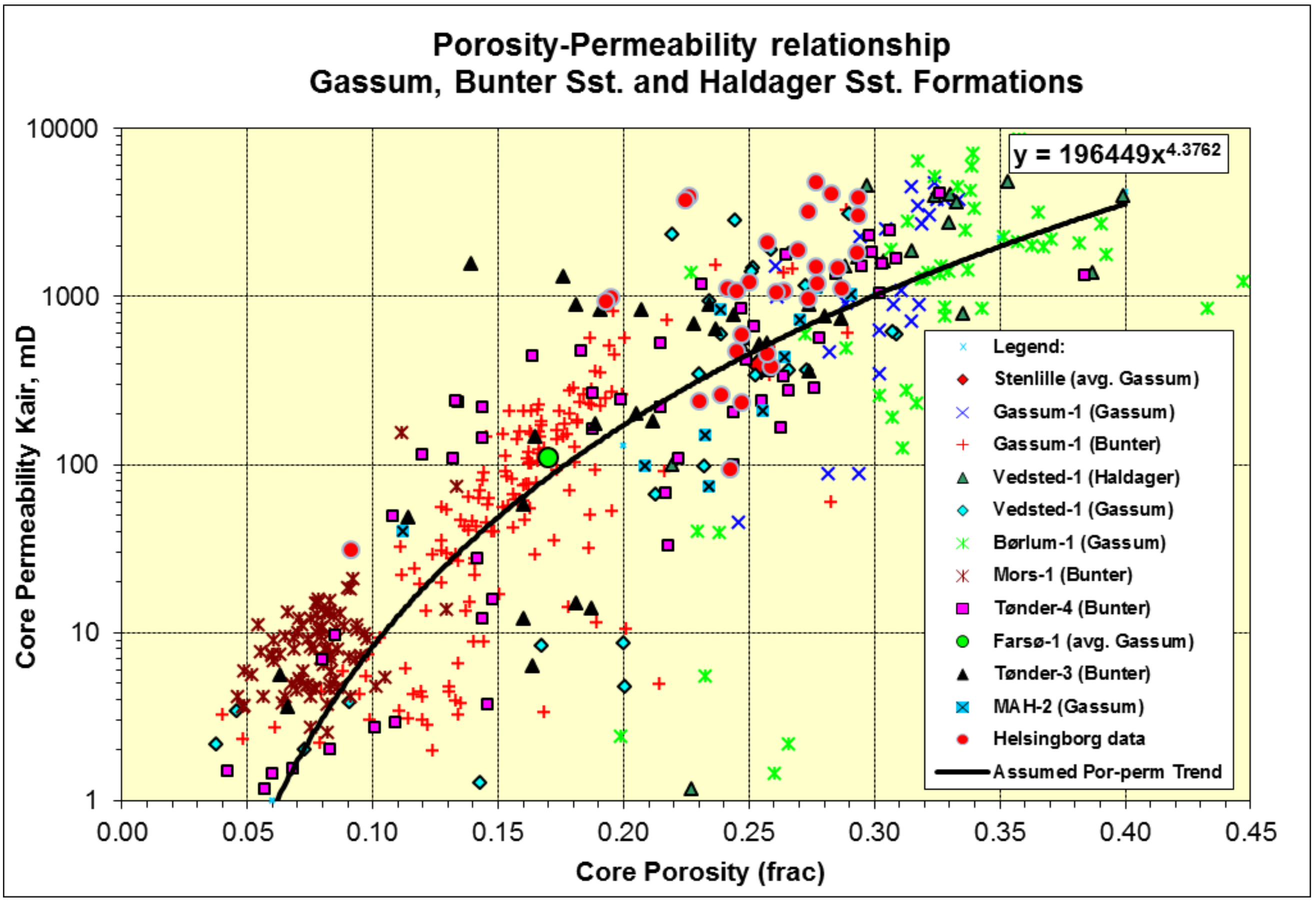



**Figure 8:** The regional GEUS porosity-permeability model (black trend line); based on laboratory (core) data from various Danish onshore wells. The Helsingborg core analysis data are plotted for comparison (red dots).

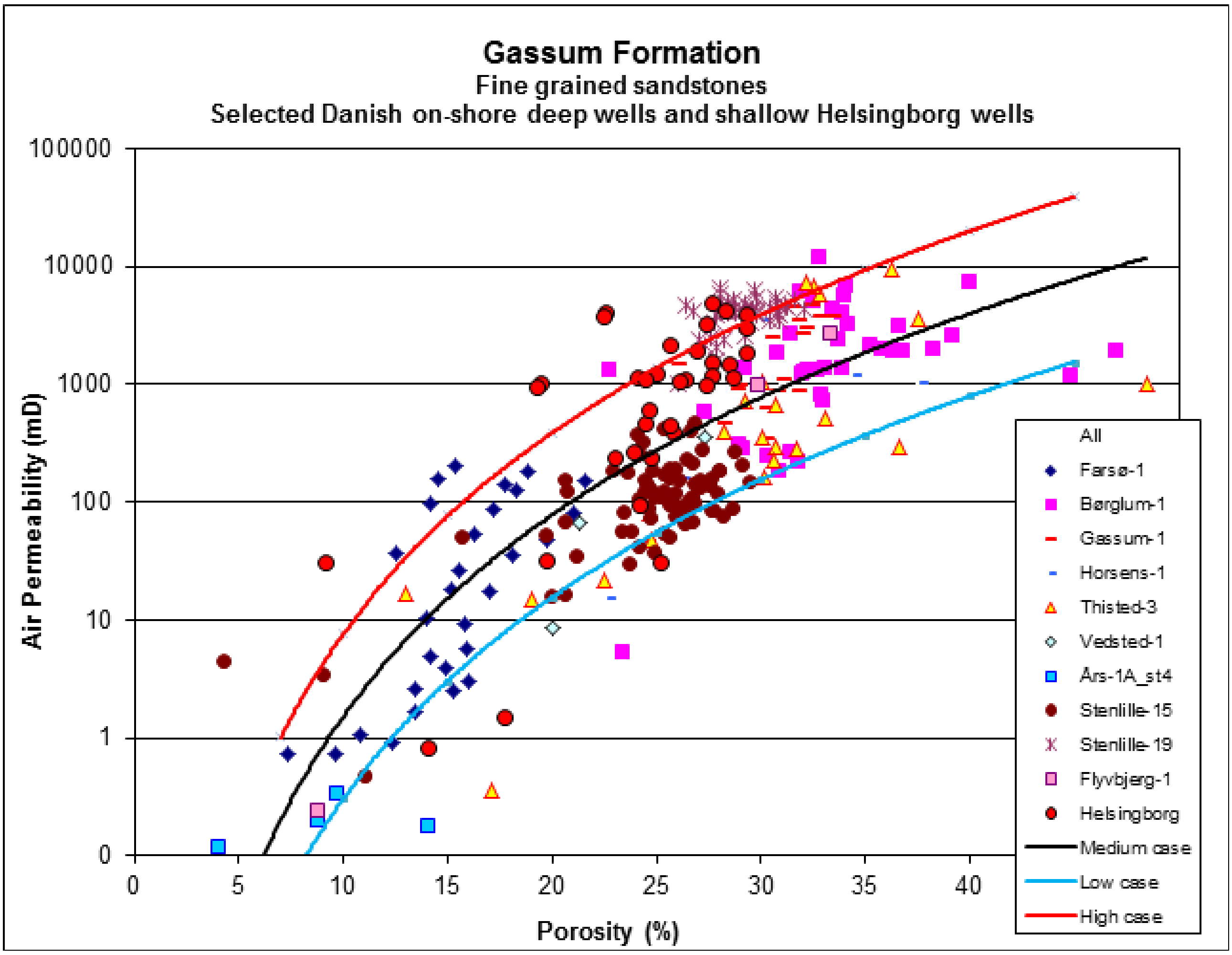



**Figure 9:** The GEUS porosity-permeability model for fine-grained sandstones of the Gassum Formation, (black trend line); based on laboratory (core) data from various Danish onshore wells penetrating the Gassum Formation. Note that data from two Stenlille wells are included, i.e. Stenlille-15 representative of the upper parts of the Gassum Formation and Stenlille-19 representative of deeper parts of the Gassum Formation. The Helsingborg core analysis data are plotted for comparison (red dots).

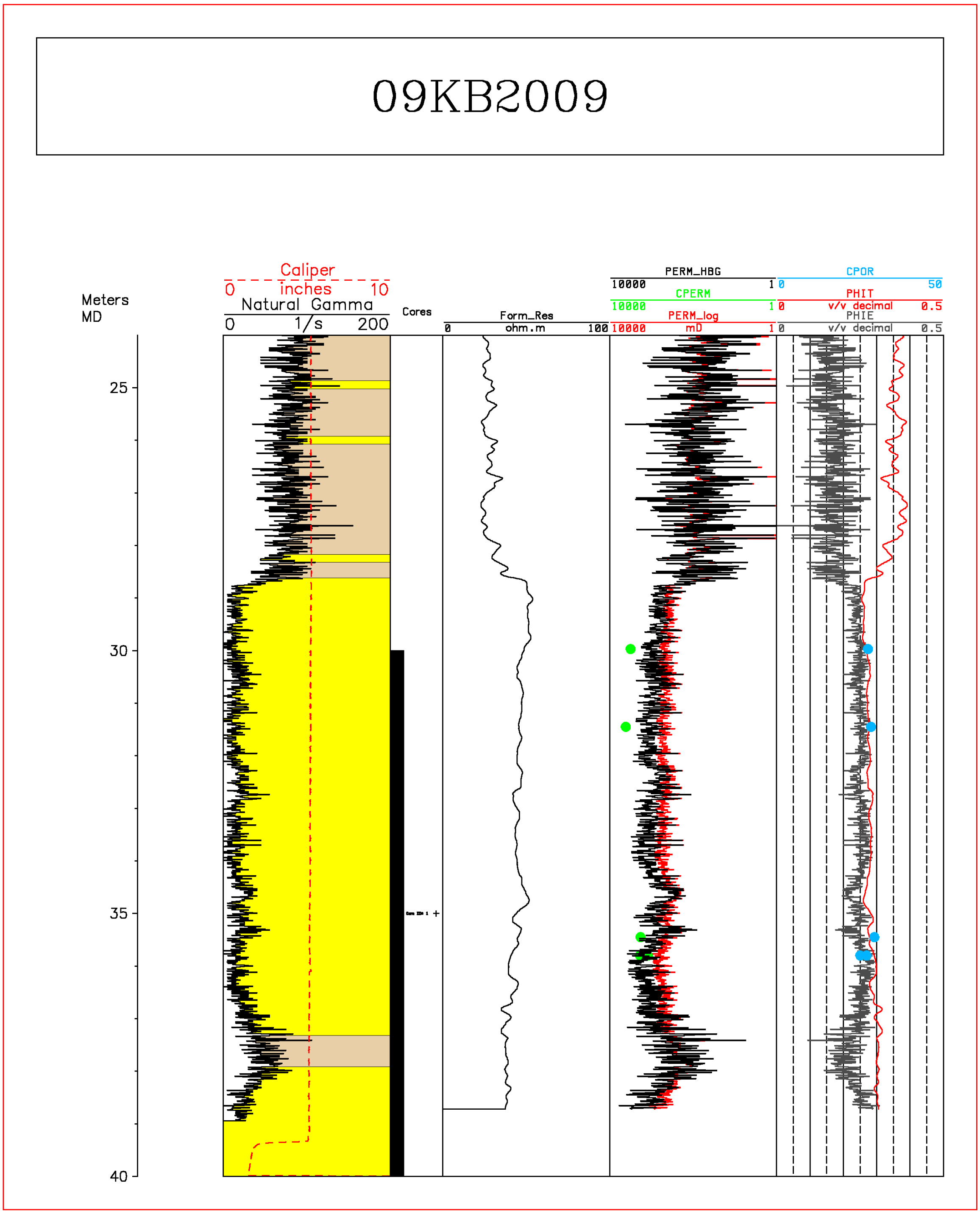



**Figure 10:** Example of log interpretation results prepared for this study. Interpreted lithologies: Sandstone (yellow), mudstone (light brown). Raw log curves: Caliper (red, track 1), Natural gamma-ray (black, track 1), Formation resistivity (black, track 2); Interpreted log curves: PERM_log and PERM_HBG (Permeability estimates, red/black, track 3), Core permeability (CPERM, green, track 3) PHIT (total porosity, red, track 4), PHIE (effective porosity, dark grey, track 4), Core porosity (CPOR, blue dots, track 4). The porosity curves in track 4 are scaled 0–50%. Cored interval indicated by a black bar.

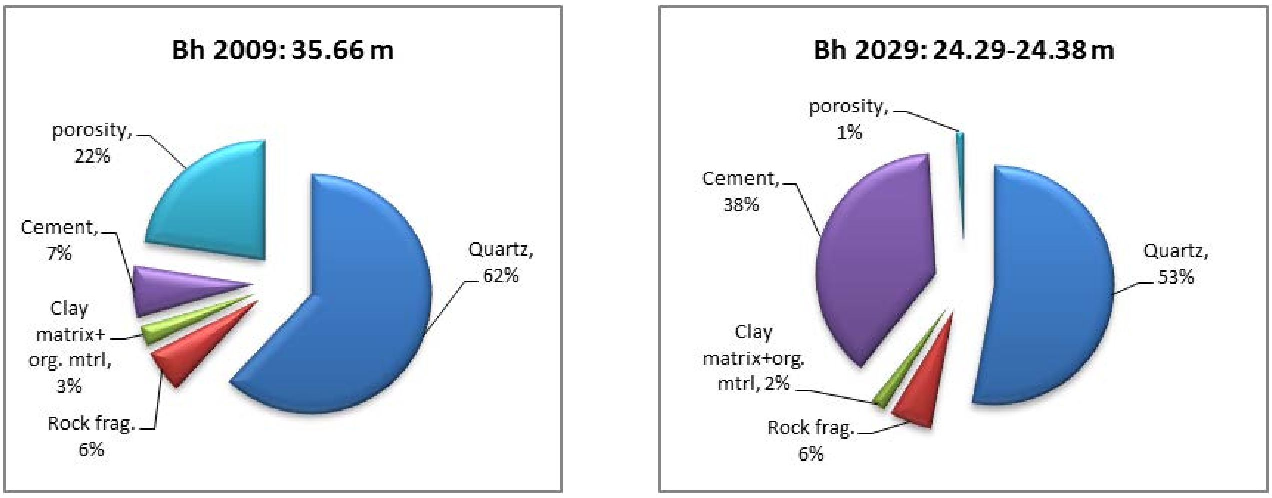



**Figure 11:** Pie diagrams showing the modal composition of two typical sandstone types occurring in the Höganäs Formation. To the left the dominating, porous and uncemented fine-grained sandstone type, and to the right the less frequently occurring calcite cemented and dense sandstone.

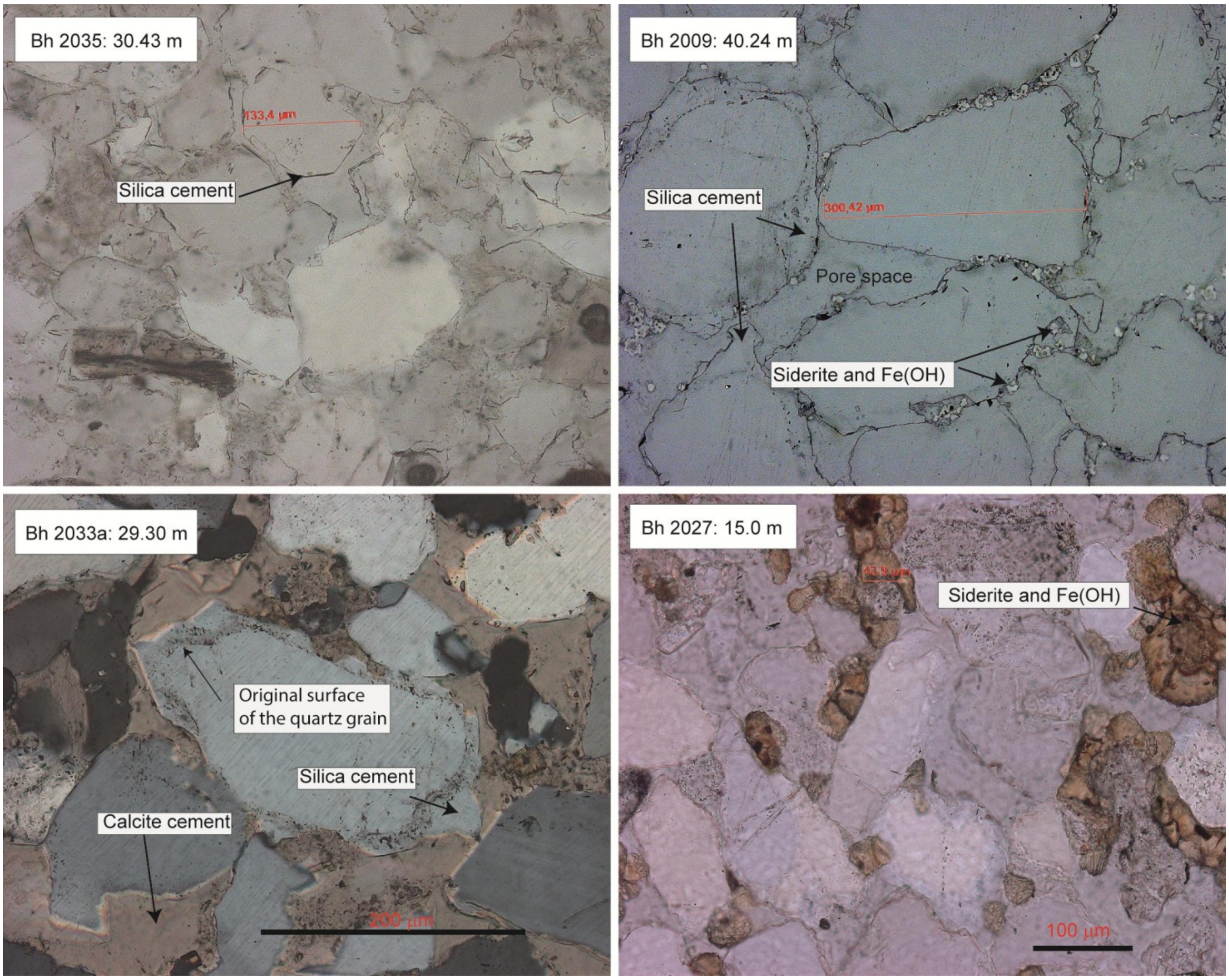



**Figure 12:** Microphotographs on thin sections illustrating different types of cements in various types of sandstone.

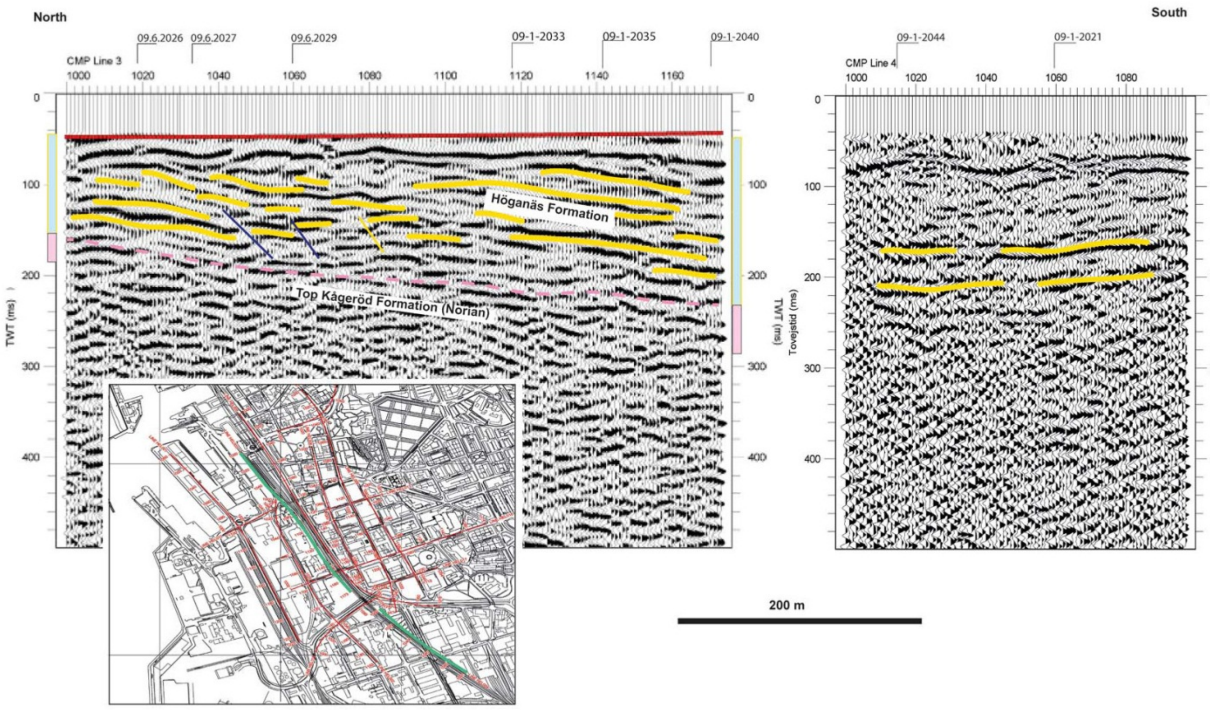



**Figure 13:** The two seismic profiles in south central Helsingborg, line 3 and 4, along which most of the boreholes used to construct the composite log for the Höganäs Formation in Helsingborg are located.

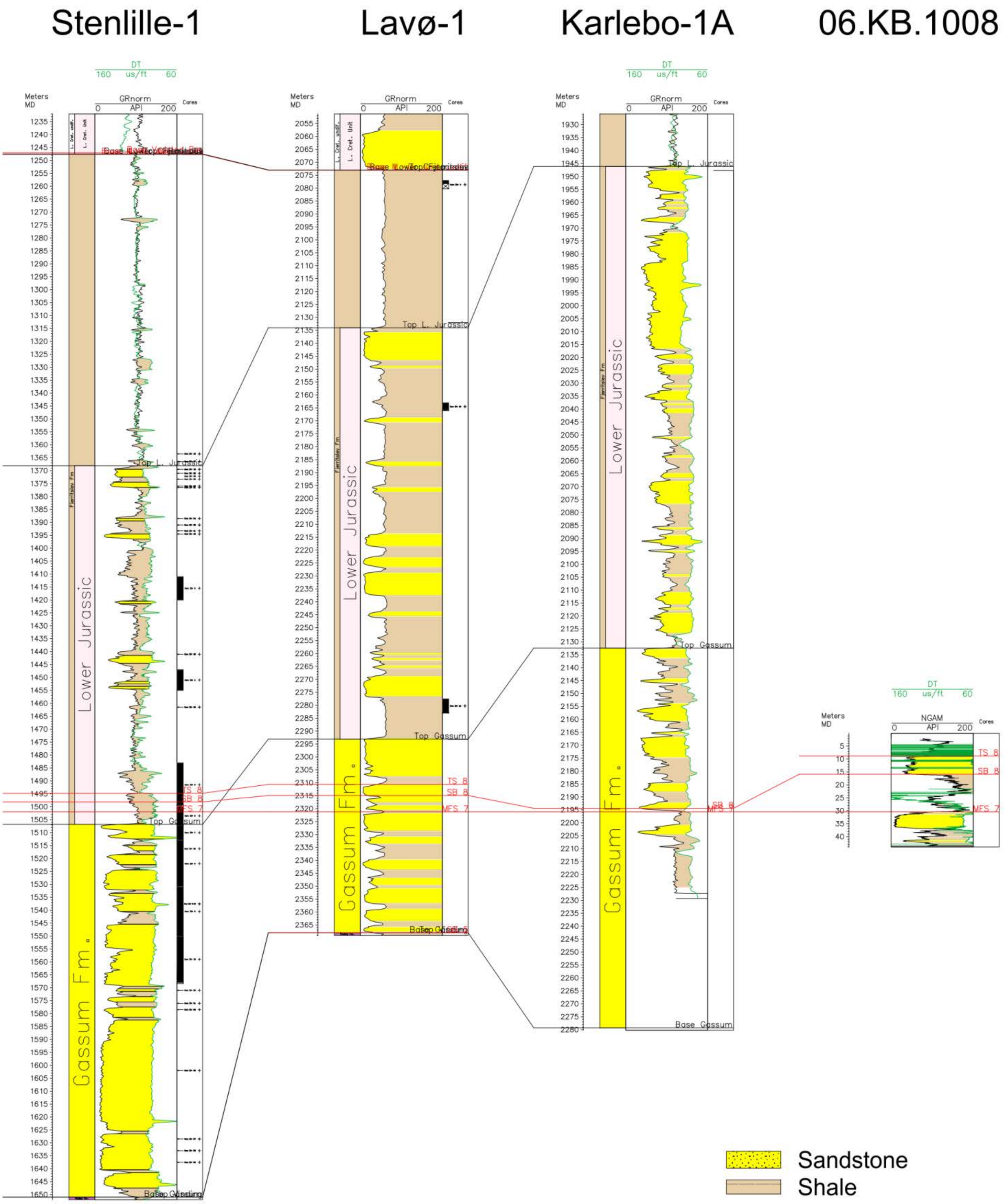



**Figure 14:** Correlation between the Danish wells Stenlille-1, Lavø-1 and Karlebo-1A and the Scanian well 06.KB.1008.

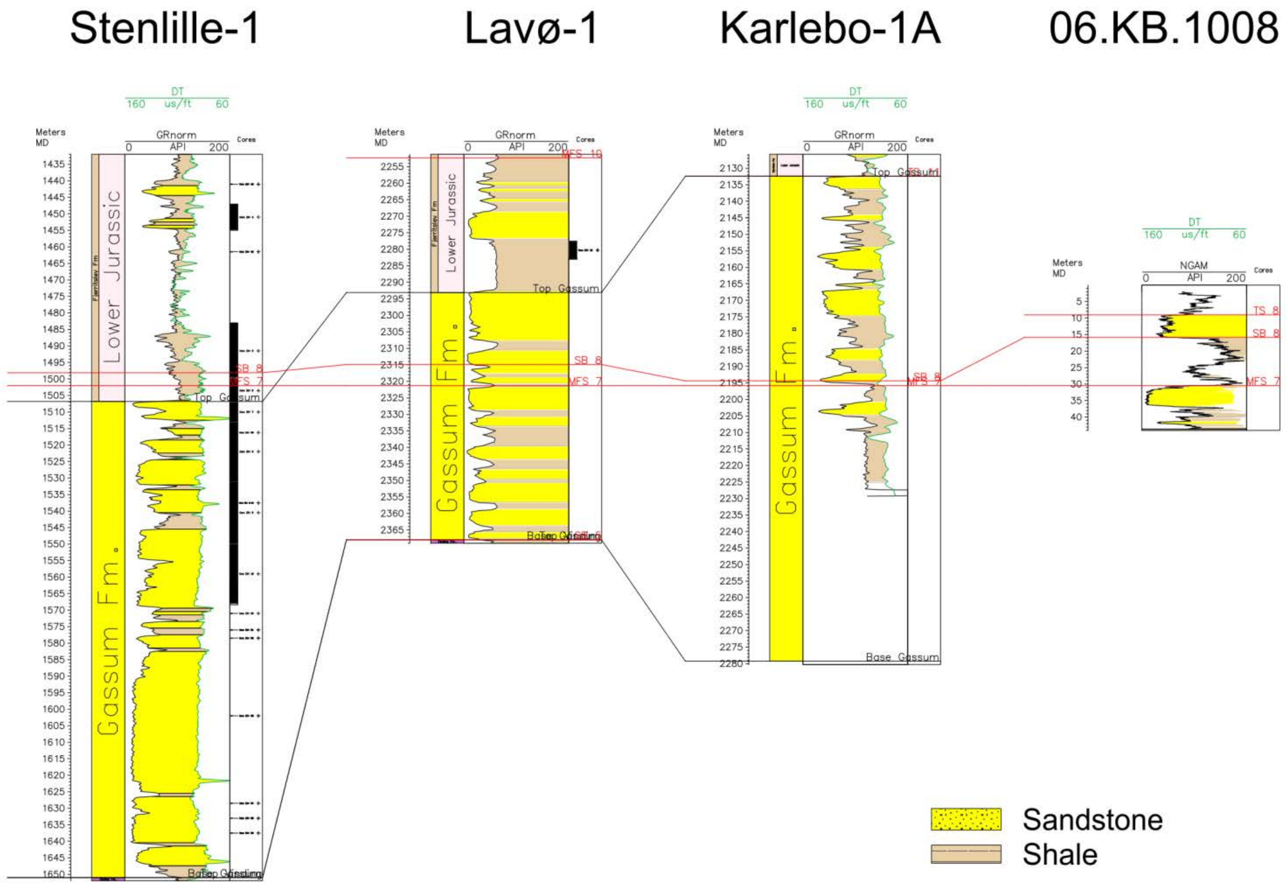



**Figure 15:** Correlation between the Danish wells Stenlille-1, Lavø-1 and Karlebo-1A and the Scanian well 06.KB.1008. Excerpt of **Figure 14** focusing on the Gassum Formation. The sonic log has been removed from well 06.KB.1008 for better visualization of the gamma log.

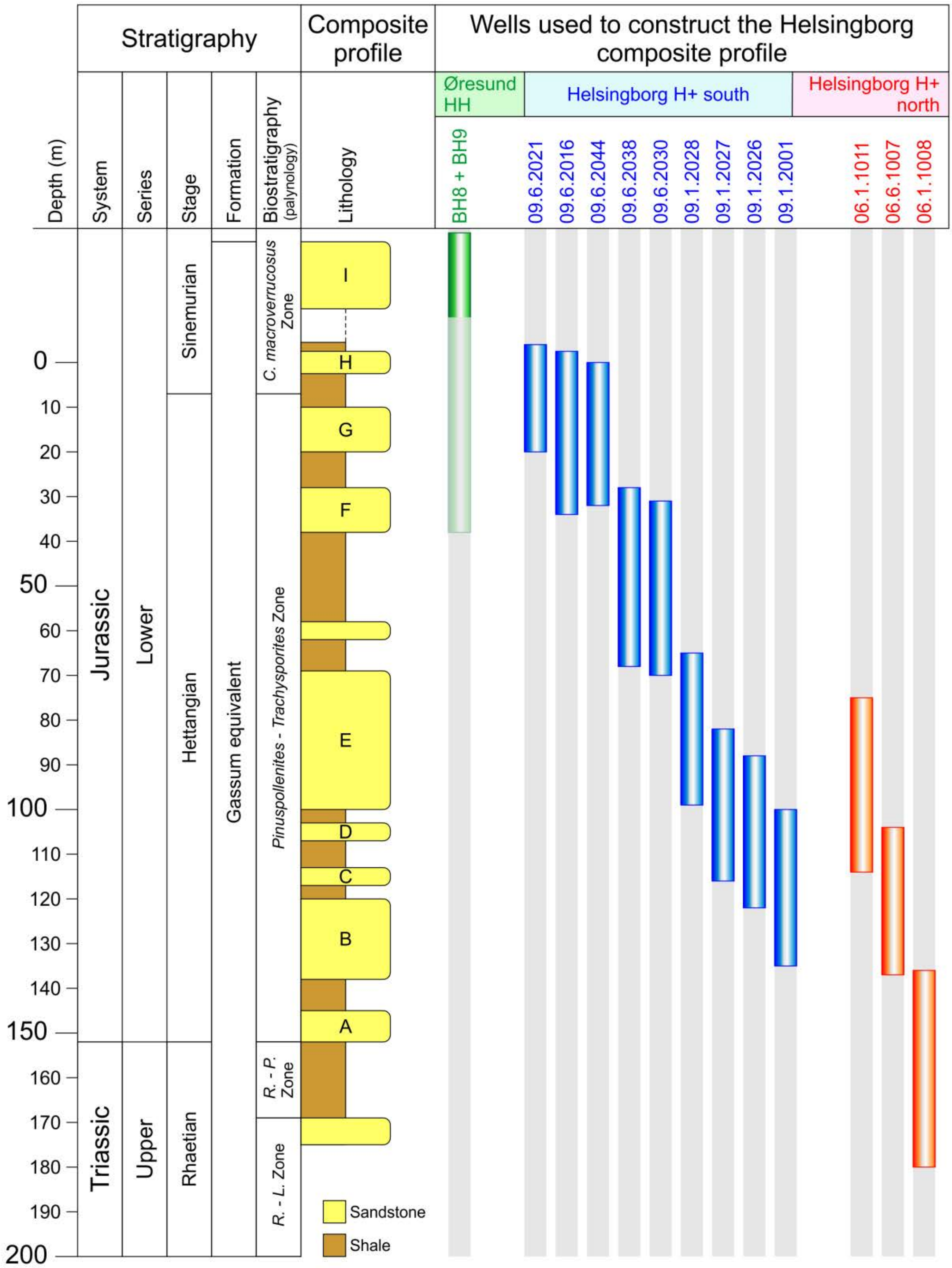



**Figure 16:** The Helsingborg composite profile constructed from well data obtained during the H+ tunnel project in Helsingborg and well data from the pre-investigation of a tunnel connection between Helsingør and Helsingborg (HH). To the right the construction principle behind the composite profile is shown with overlapping wells and color-coding according to well region; green: Øresund, blue: southern Helsingborg and red: northern Helsingborg. The lower dimmed part of the green Øresund well indicates that sandstone units found in the BH8 and BH9 wells are lithostratigraphic equivalents to sandstone units F, G and H, but a direct correlation between sandstone units is not possible. The sandstone unit "I" corresponds to the Döshult Member. Nearly the entire composite section is considered a lithostratigraphic equivalent of the Gassum Formation.

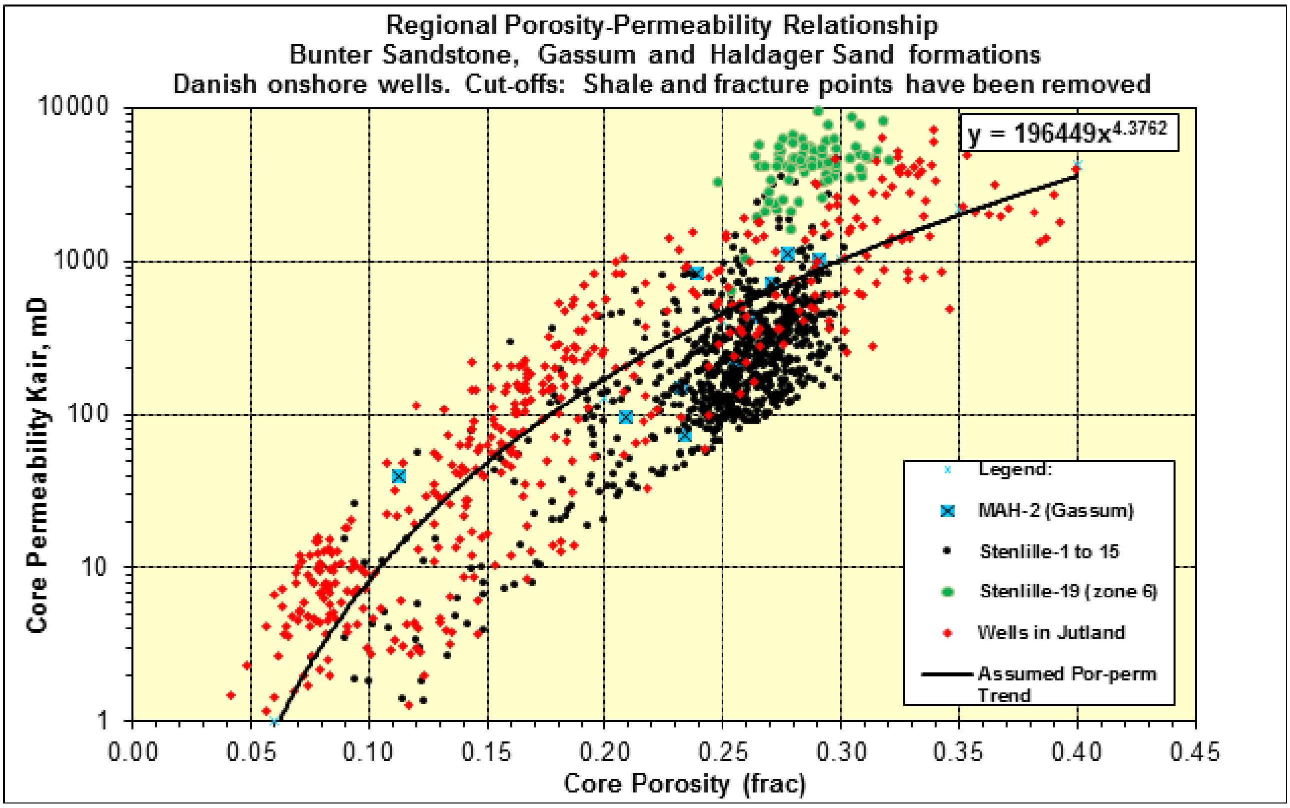



**Figure 17:** Regional porosity–permeability relationship based on core data from selected Danish onshore wells. Shale points and fracture points have been removed prior to plotting the data. All data points correspond to raw (uncorrected) core analysis data originating from Stenlille-1, -2, -4, -6, -10, -12, -13, -15 and -19 plus Margretheholm-2, Gassum-1, Vedsted-1, Børglum-1, Mors-1, Farsø-1, Tønder-3 and Tønder-4. The assumed Por-perm trend is based primarily on core analysis data originating from wells located in Jylland (data points in red colour).

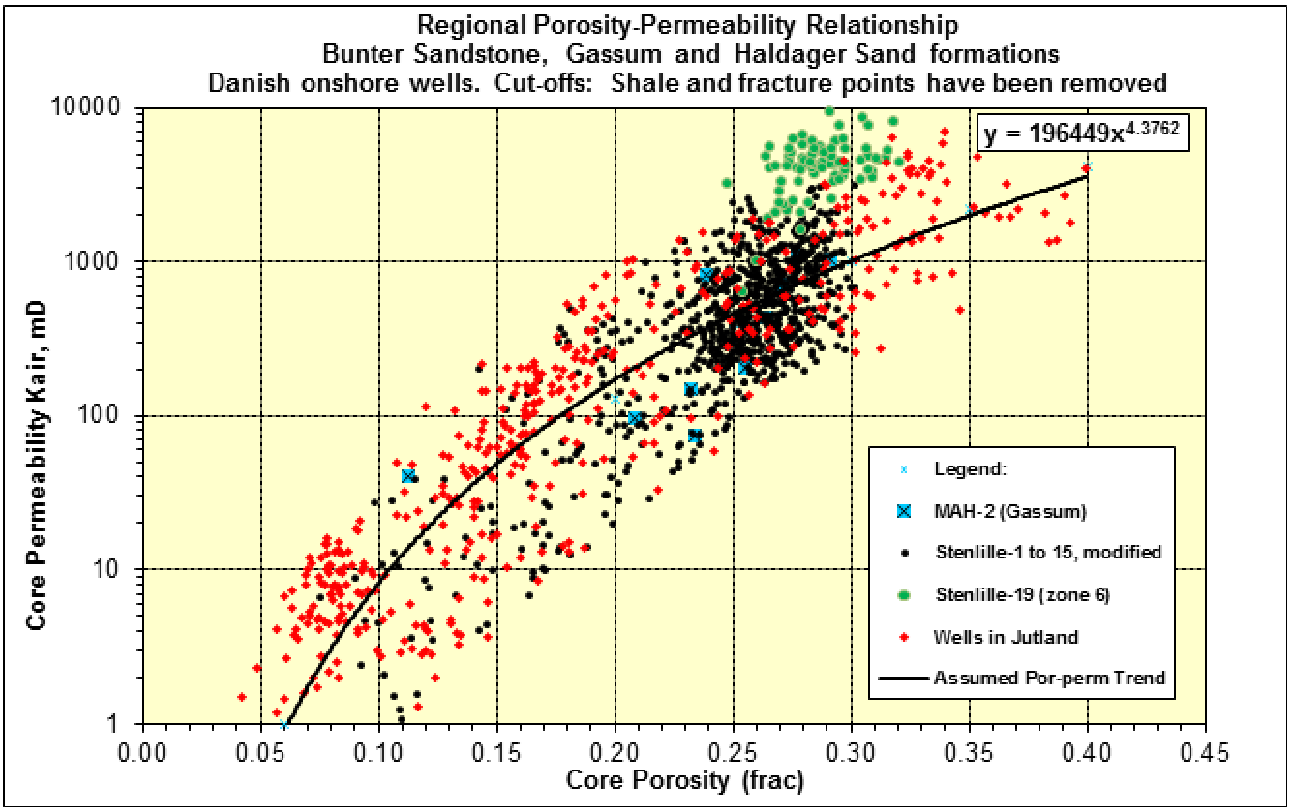



**Figure 18:** Regional porosity–permeability relationship based on core data from selected Danish onshore wells located on Sjælland (Stenlille wells and Margretheholm-2) and in Jylland (Gassum-1, Vedsted-1, Børglum-1, Mors-1, Farsø-1, Tønder-3 and Tønder-4). Shale points and fracture points have been removed prior to plotting the data. Furthermore, the permeability data from Stenlille-1 to -15 have been modified (multiplied by 2.5) in order to correct for the effect of differences in grain size. The basis for modifying the data is explained in the text. The plotted data are hereafter expected to represent fine to medium-grained sandstones; with one exception, however: Stenlillle-19. The Stenlille-19 data form an anomaly, because these data are related to predominantly medium-grained shoreface sandstones located in Zone 6 of the Gassum Formation., resulting in a permeability anomaly but not a porosity anomaly (similar porosities are interpreted from the log data throughout the Gassum Formation.). Zone 6 has not been cored in Stenlille-1 to -15, but this particular zone with excellent reservoir properties is expected to be present in most of the Stenlille area as mapped out by DONG (2001). The Stenlille-19 data have been excluded from the “regression” analysis, since this Zone 6 with very good reservoir properties is expected not to be present at Helsingør (see text). Note that the Stenlille-19 data have not been modified.

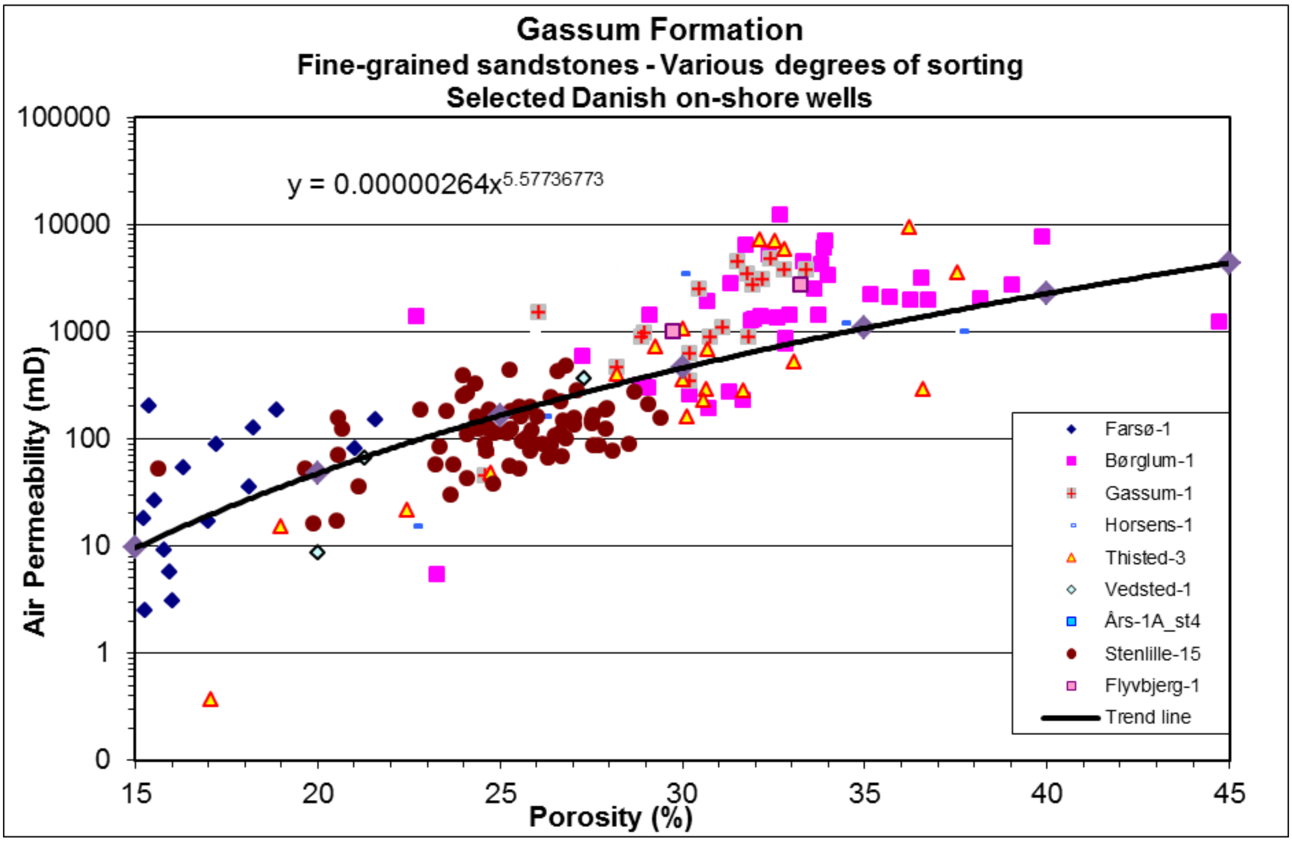



**Figure 19:** Poro-perm plot for fine-grained sandstones in selected wells. Gassum Formation

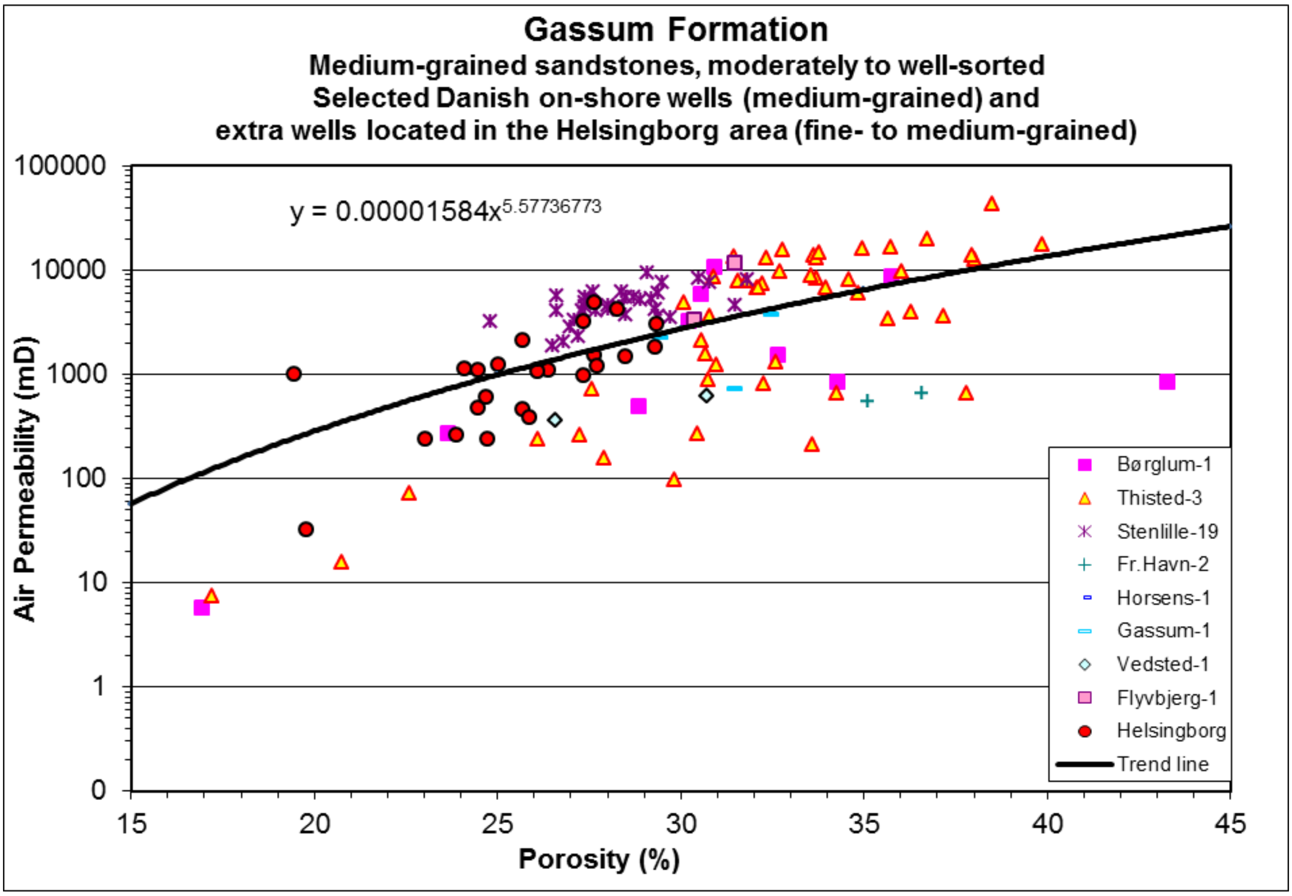



**Figure 20:** Poro-perm plot for medium-grained sandstones in selected wells. Gassum Formation

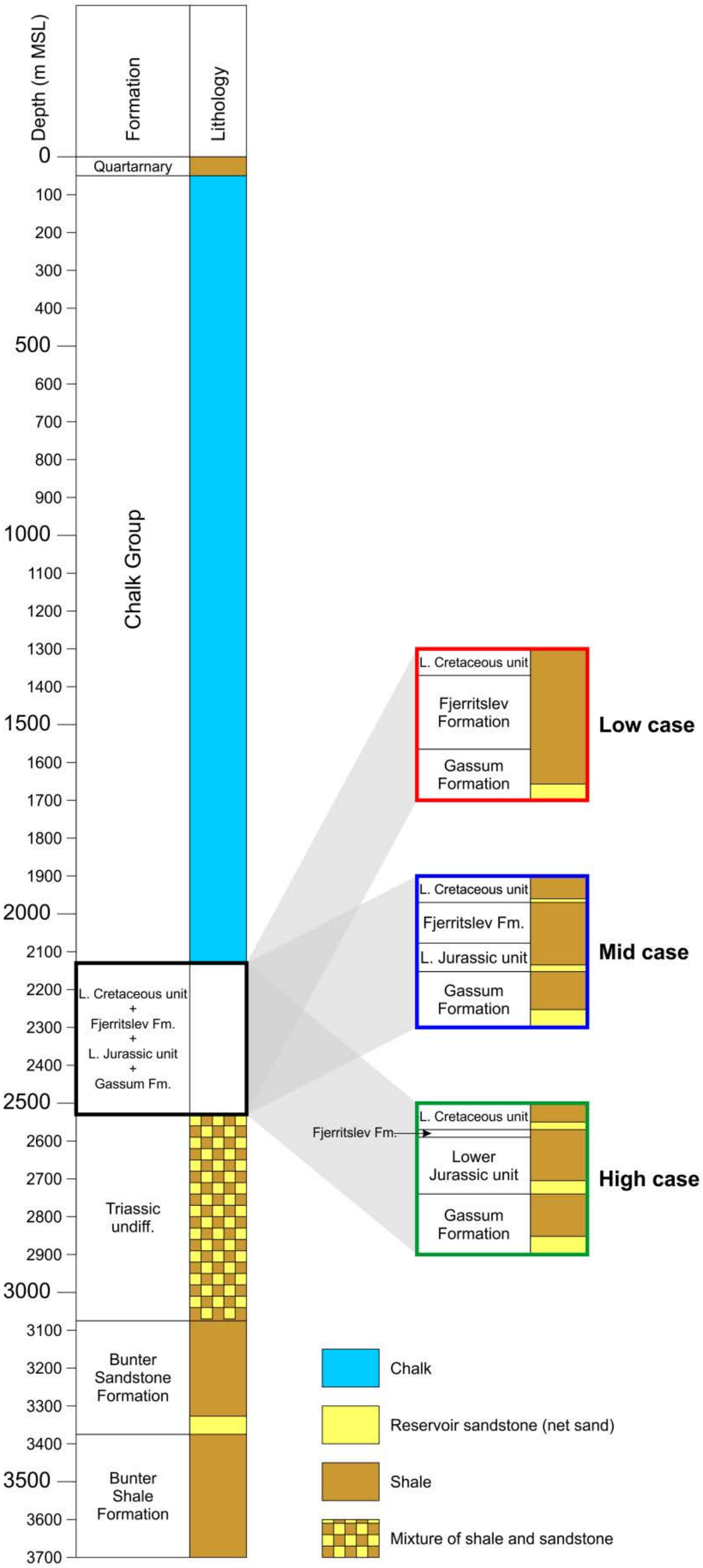



**Figure 21:** Assessed lithological log of the subsurface in the Helsingør area showing vertical distribution of Formations and lithologies in the low case and high case discussed in **Section 14.1**. Each depicted sandstone unit represents the accumulated net sand for one formation/unit and is placed at the bottom of the formation/unit; thus, the depicted sandstone beds do not necessarily correspond to actual sandstone beds. Note the presence of reservoir sandstone in the Gassum Formation in both the min and max case; further, note the lack of sandstones in the Lower Cretaceous and Lower Jurassic units in the min case. This lithological log is a preliminary estimate and should not be considered a well prognosis.

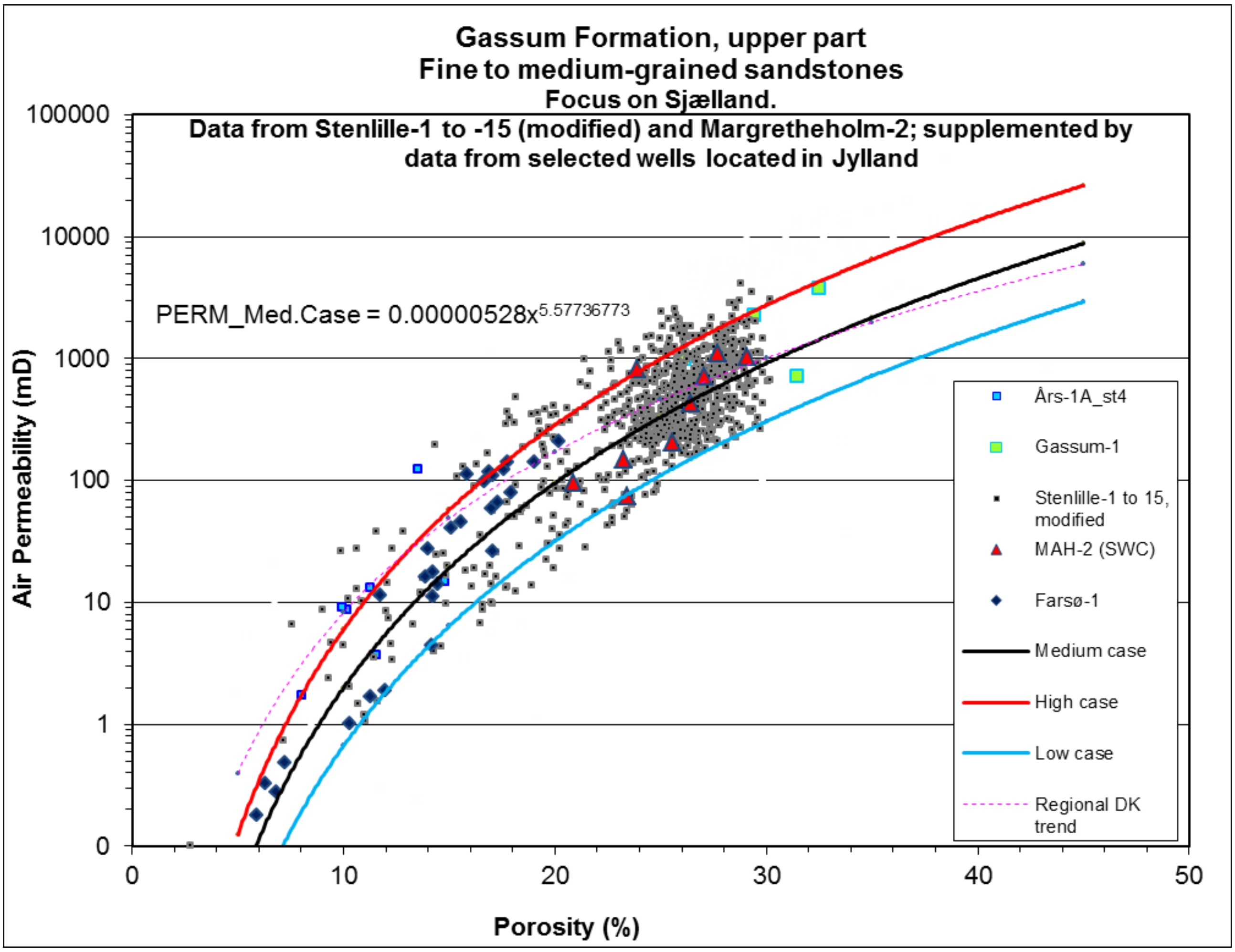



**Figure 22:** Porosity–permeability plot based on conventional core analysis data from Stenlille-1 to 15, Gassum-1, Års-1 and Farsø-1 combined with un-conventional core analysis data from Margretheholm-2 (side wall cores). Shale points and fracture points have been removed prior to plotting the data. Furthermore, the permeability data from Stenlille-1 to -15 have been modified (multiplied by 2.5) in order to correct for the effect of differences in grain size. The raw (i.e. original) Stenlille data represent fine-grained sandstones, but subsequent to modification, the plotted data presumes to represent fine- to medium-grained sandstones. The black line corresponds to a most likely poro-perm relationship (medium case), whereas the red and blue lines define an assumed permeability range, i.e. an uncertainty band delineated by 'High case' (multiplying by 3) and 'Low case' (dividing by 3). The DK Regional Porosity–Permeability relationship is plotted for comparison.

# 9 Enclosures

**Enclosure 1:** photomicrographs of 26 thin sections of sandstone samples from cores in the southern part of Helsingborg.

**Enclosure 2**: Compilation of composite logs with wire-line logs, core photos, logs and analytical data.

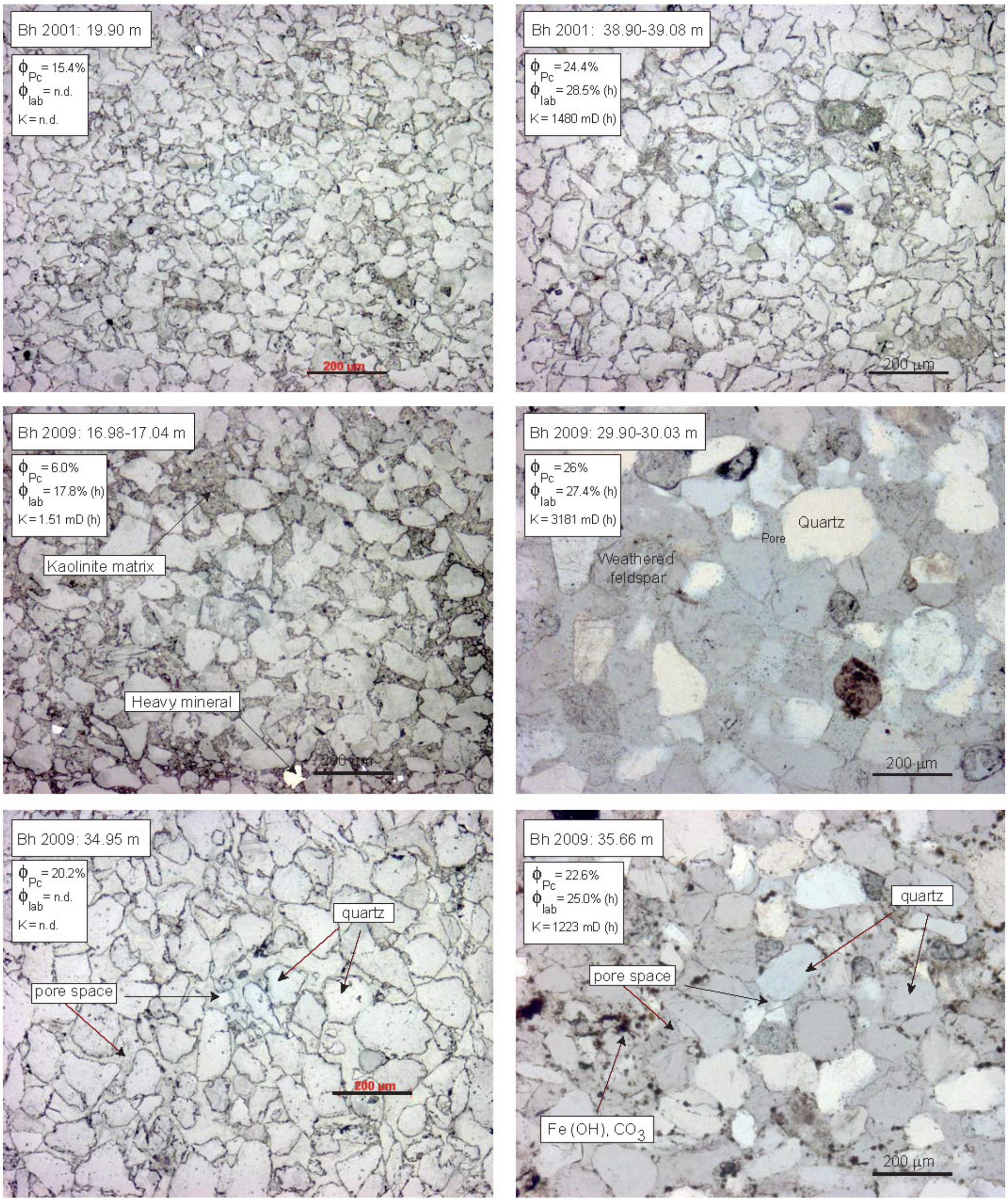
**Enclosure 3**: Range charts for genera and species identified in selected Helsingborg wells.

Thin sections - texture

Sandstone beds Höganäs Formation, Helsingborg Member

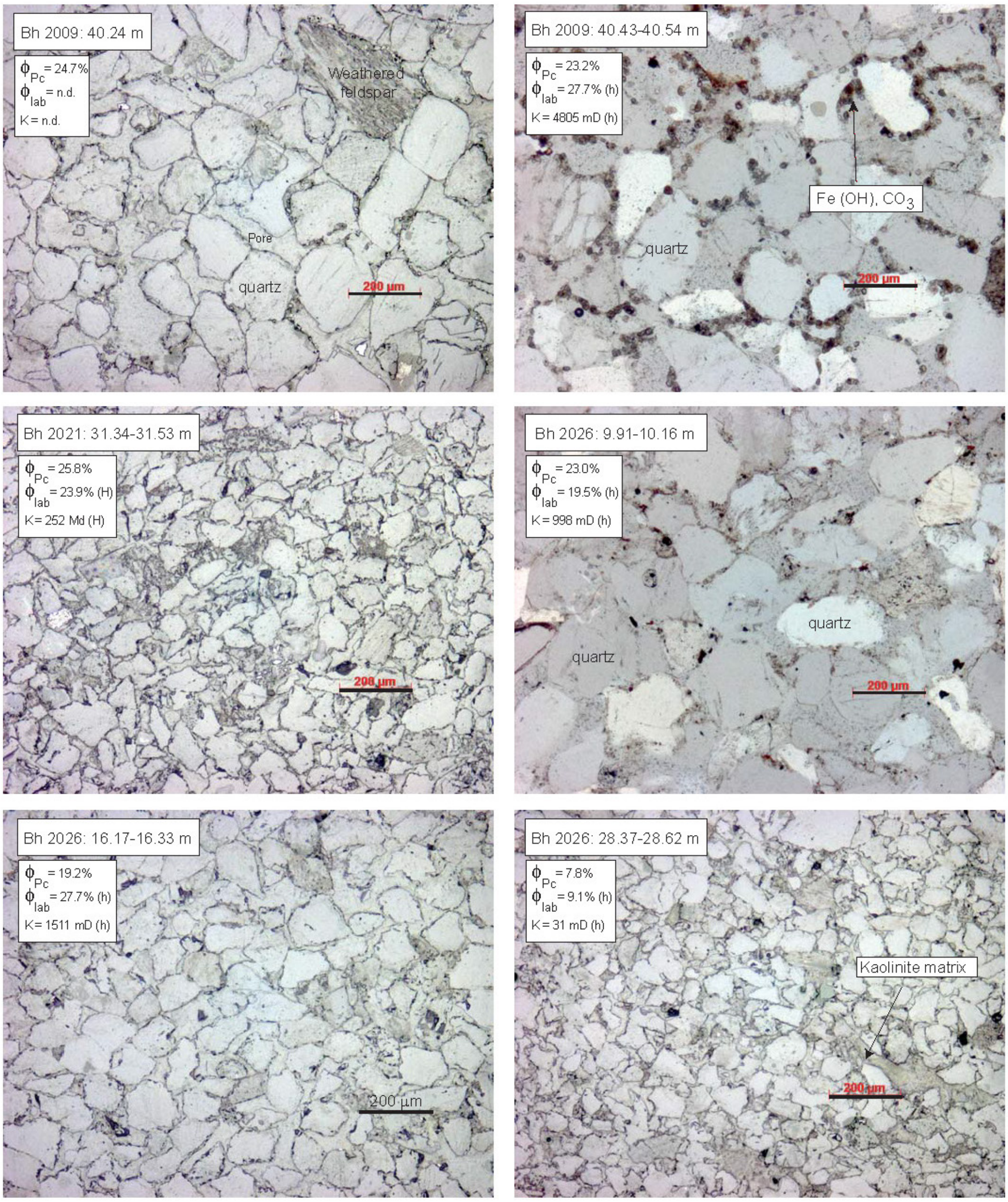
Lower Jurassic, Hettangian

Core material from S. Helsingborg



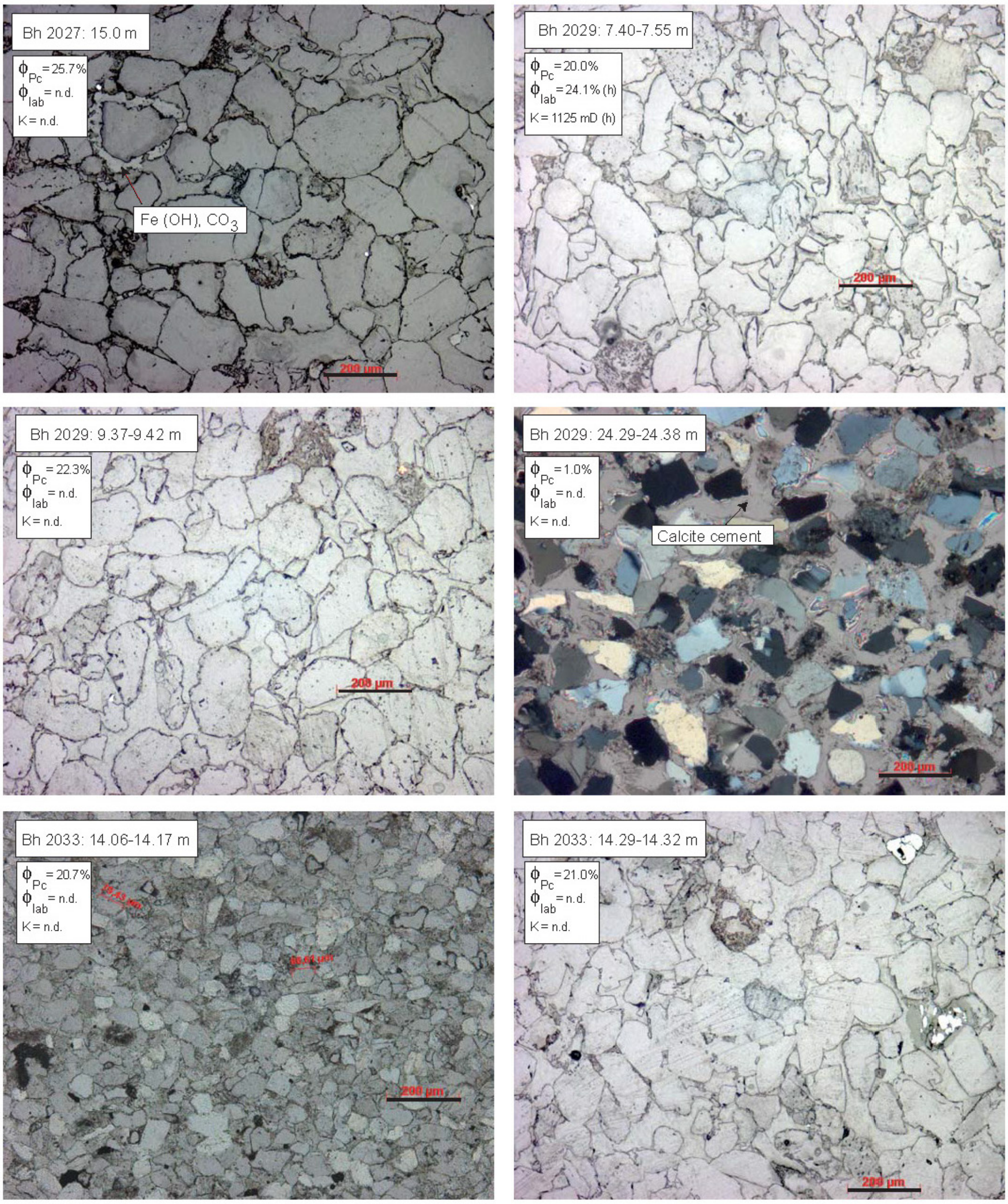

**Enclosure 1a:** Fine to very fine-grained sandstone (0.063–0.25 mm). The finer detrital material is dominated by angular and subangular grains. A secondary growth of silica cement enhances the irregular grain shapes in the very fine-grained samples. Siderite and Fe-oxyhydroxides occur commonly as attached micronodules on the grain surfaces in the coarser sandstones.

## Thin sections - texture
## Sandstone beds Höganäs Formation, Helsingborg Member
## Lower Jurassic, Hettangian
## Core material from S. Helsingborg



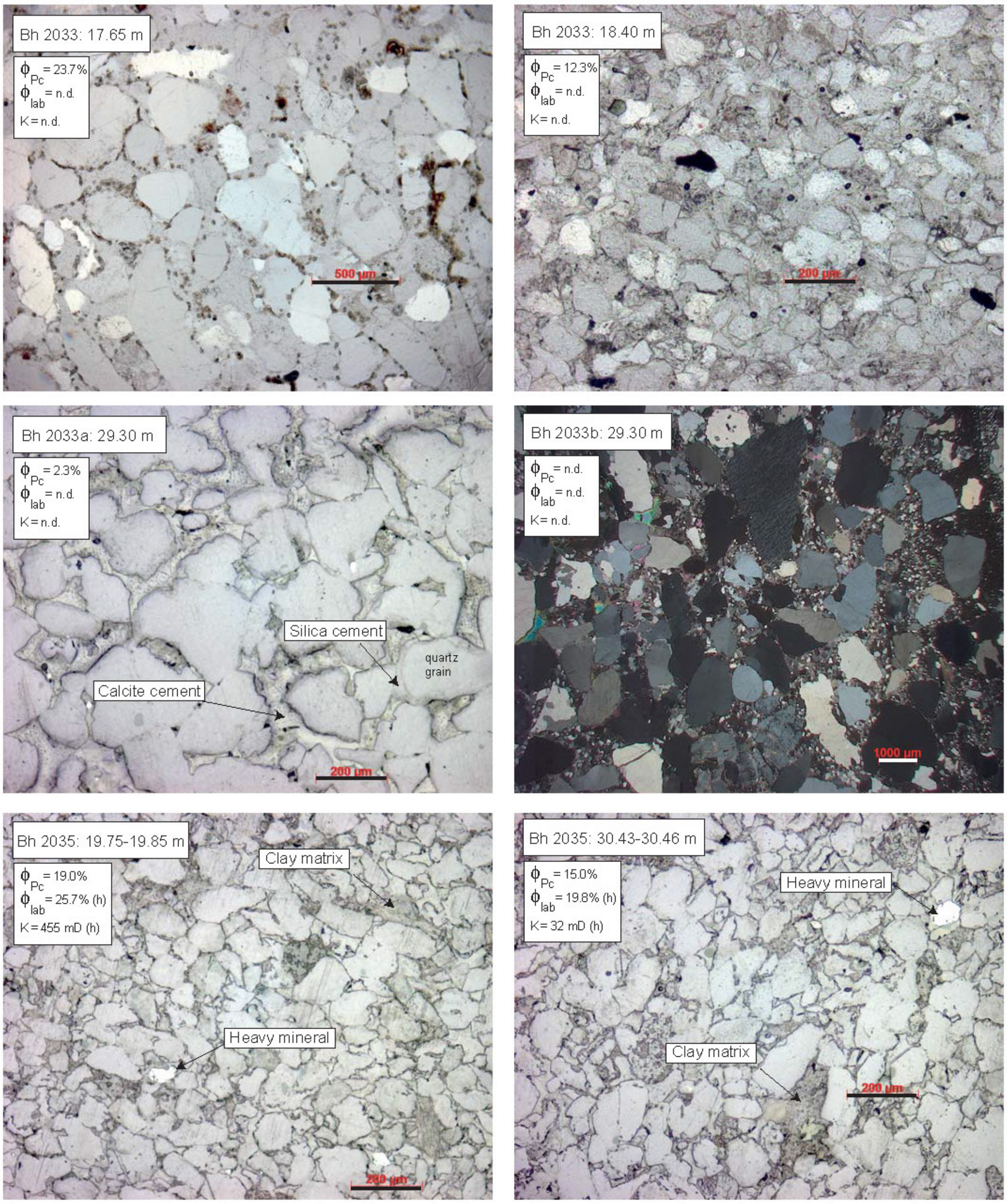

**Enclosure 1b:** Fine to very fine-grained sandstone (0.063–0.25 mm). The finer detrital material is dominated by angular and subangular grains. A secondary growth of silica cement enhances the irregular grain shapes in the very fine-grained samples. Siderite and Fe-oxyhydroxides occur commonly as attached micronodules on the grain surfaces in the coarser sandstones.

Thin sections - texture
Sandstone beds Höganäs Formation, Helsingborg Member
Lower Jurassic, Hettangian
Core material from S. Helsingborg



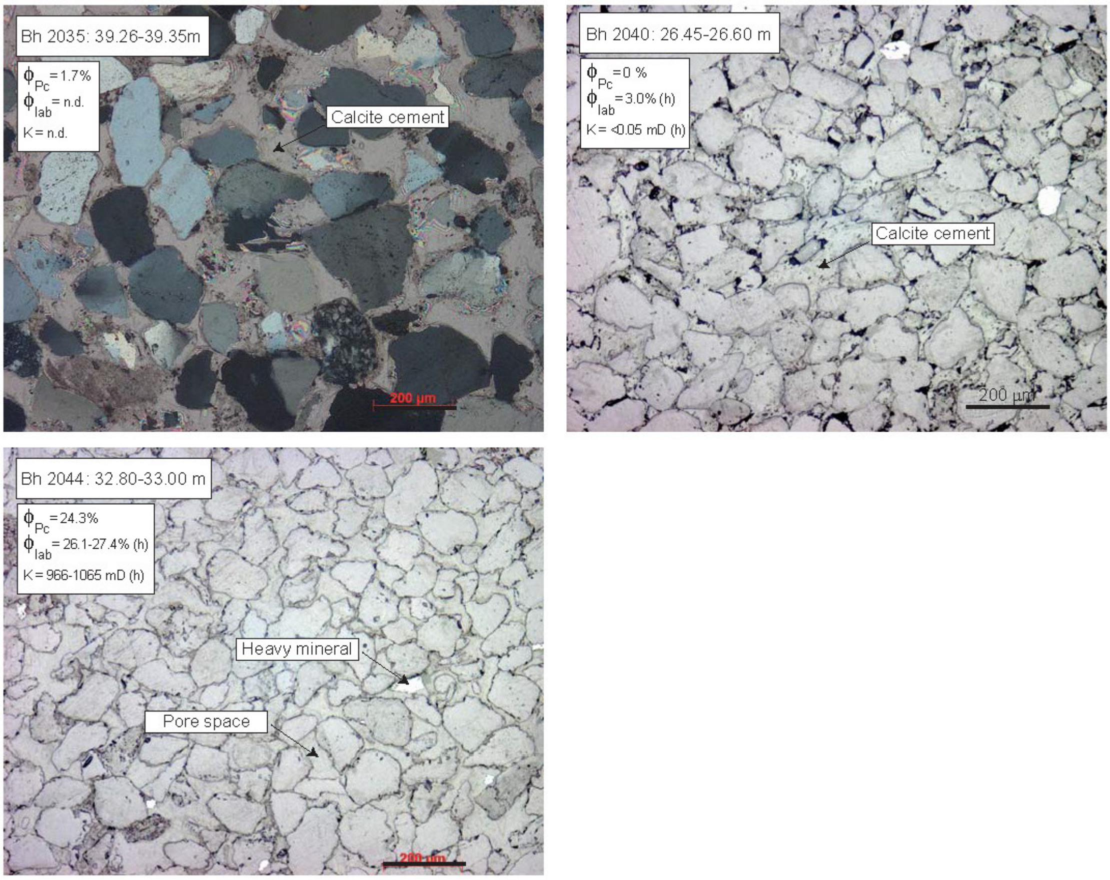

**Enclosure 1c:** Fine to very fine-grained sandstone (0.063–0.25 mm). Almost complete cementation of calcite occurs in scattered sandstone beds, exemplified by Bh 2029 (24.29-24.38 m).

Thin sections - texture
Sandstone beds Höganäs Formation, Helsingborg Member
Lower Jurassic, Hettangian
Core material from S. Helsingborg




**Enclosure 1d:** Examples of a porous and well sorted medium-grained sandstone with some micronodular siderite cementations, a matrix-rich and fine-grained sandstone with less porosity and a well cemented medium- and coarse-grained variety with very little porosity from the same borehole (2033). The two samples from bh 2035 display a fourth sandstone type characterized by fair porosity but with a high amount of clayey matrix, tangential silica cement and small grain-sizes.

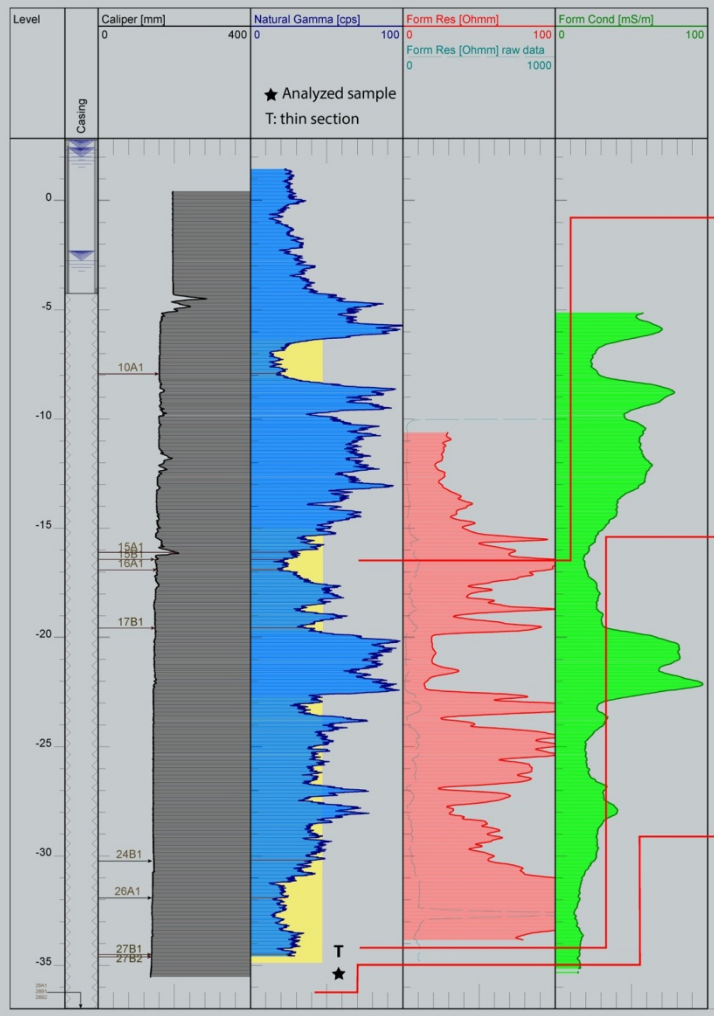
Thin sections - texture
Sandstone beds Höganäs Formation, Helsingborg Member
Lower Jurassic, Hettangian
Core material from S. Helsingborg




**Enclosure 1e:** 2040 and 2044. The detrital material in these samples is also less angular grading into dominantly subrounded grains giving a better sorted texture.

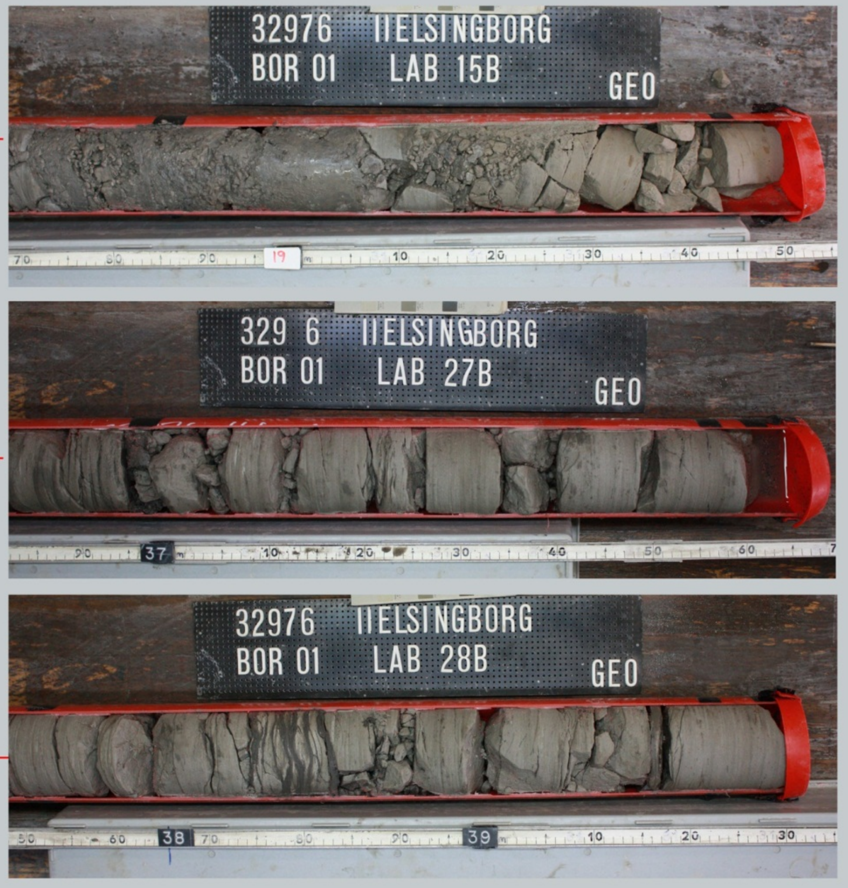
Geophysical logging – Cored Boring – Borehole 09.1.2001 – Helsingborg, Södertunneln

Logging performed by GEO (2009)




Results from Por/perm measurements on cores (GEUS 2014)

| BH | Sample Id | Depth, m GL | H/V | % | mD | g/cc |
|---|---|---|---|---|---|---|
| 2001 | 28B1 | 38,99 | Hori. | 28,51 | 1480 | 2,644 |
| 2001 | 28B1 | 38,99 | Vert. | 28,70 | 1128 | 2,639 |



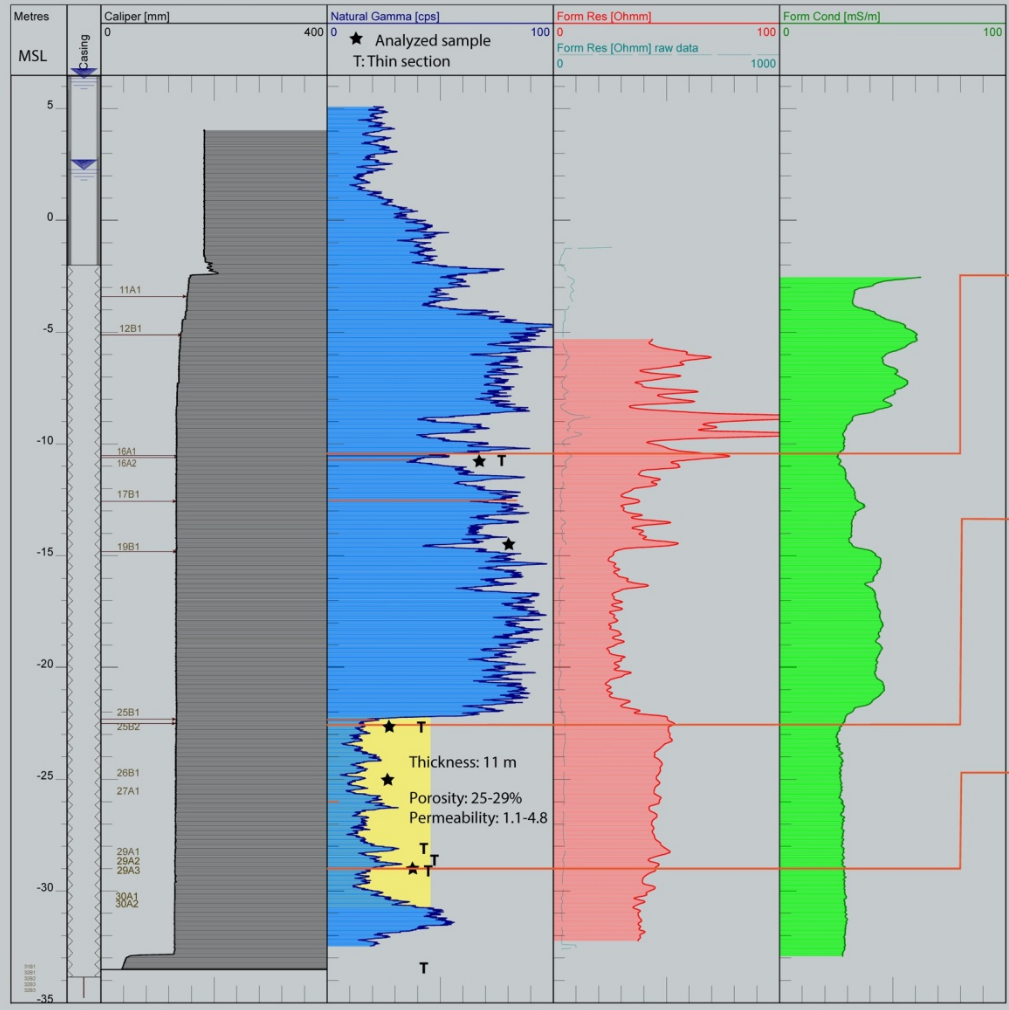

Modal data composition in thin sections (SGU 2014)

| BH | Sample Id | Depth, m GL | Quartz | Pores | Cement | RF | Matrix |
|---|---|---|---|---|---|---|---|
| 2001 | 27B2 | 38.90-39.08 | 60 | 24,4 | 0,4 | 5,8 | 9,4 |

**Enclosure 2a:** Compilation of composite logs with wire-line logs, core photos, logs and analytical data for borehole 09.1.2001.

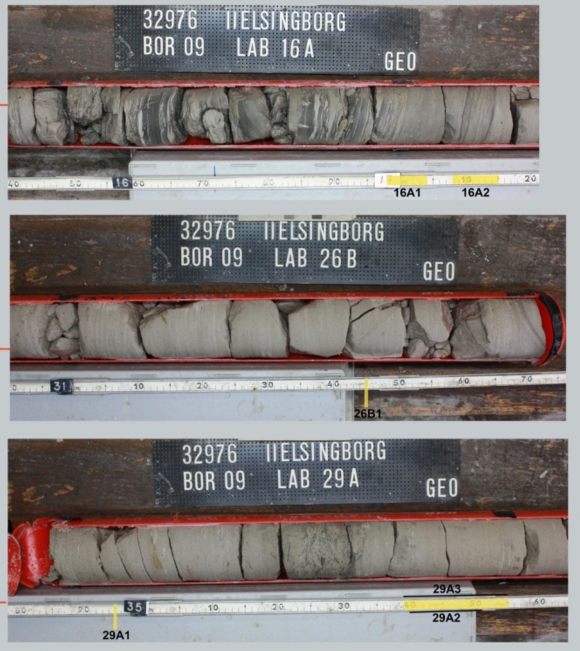
## Geophysical logging – Core Drilling – Borehole 09.1.2009 – Helsingborg, Södertunneln

Logging performed by GEO (2009)




Results from Por/perm measurements on cores (GEUS 2014)

| BH | Sample Id | Depth. m GL | H/V | [%] | [mD] | [g/cc] |
|---|---|---|---|---|---|---|
| 2009 | 32B2 | 40.49 | Hori. | 27.65 | 4804 | 2.657 |
| 2009 | 26B1 | 31.45 | Hori. | 28.28 | 4135 | 2.642 |
| 2009 | 29A3 | 35.45 | Hori. | 29.29 | 1828 | 2.656 |
| 2009 | 29 | 35.8 | Hori. | 25.03 | 1223 | 2.664 |
| 2009 | 29 | 35.8 | Vert. | 26.96 | 1900 | 2.648 |
| 2009 | 25B2 | 29.97 | Hori. | 27.36 | 3181 | 2.641 |
| 2009 | 19B1 | 21.3 | Hori. | 14.12 | 0.8 | 2.653 |
| 2009 | 16A1 | 17.01 | Hori. | 17.77 | 1.5 | 2.651 |



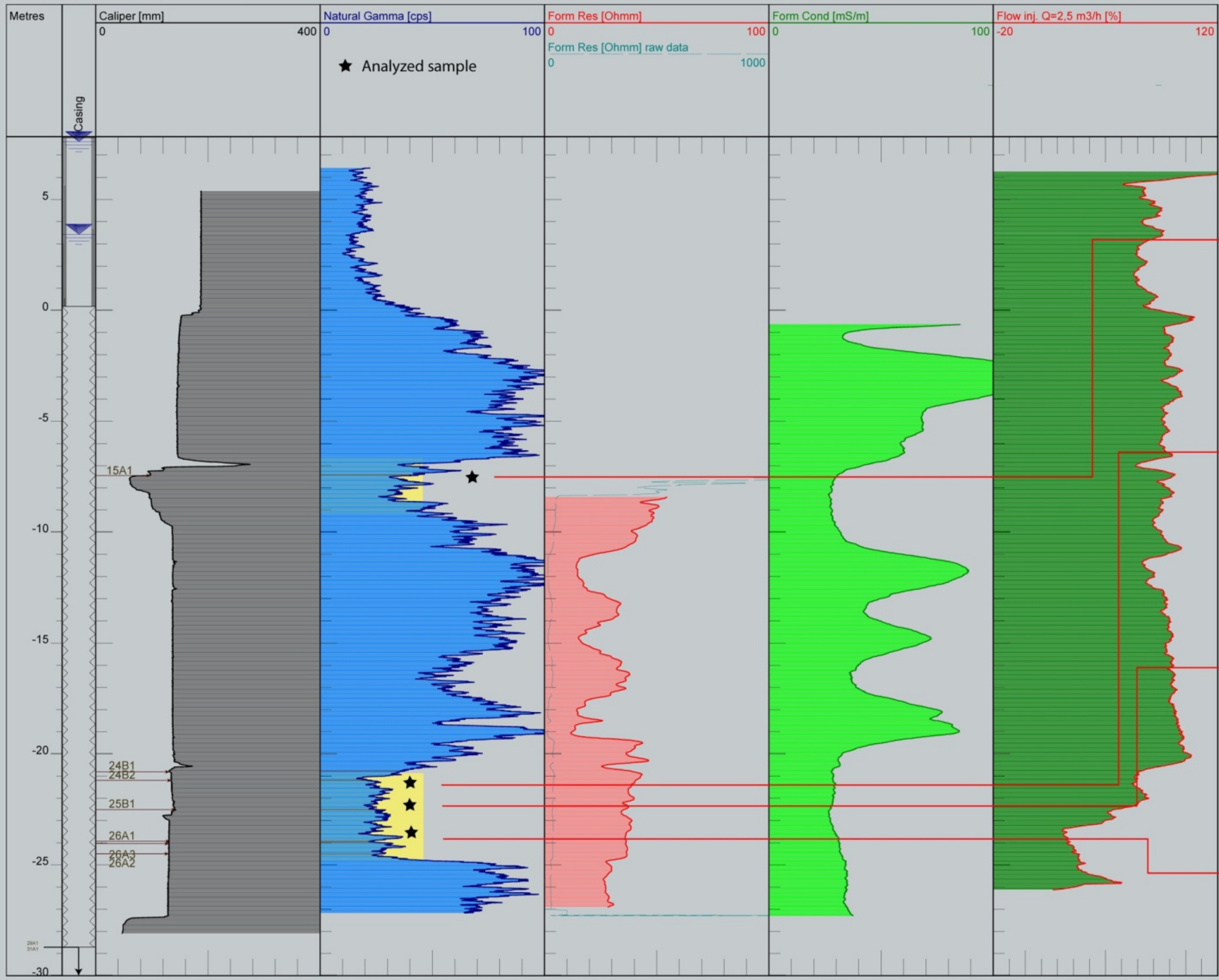

Modal data composition in thin sections (SGU 2014)

| BH | Sample Id | Depth, m GL | Quartz | Pores | Cement | RF | Matrix |
|---|---|---|---|---|---|---|---|
| 2009 | 16A1 | 16.98-17.04 | 52.6 | 6 | 3.2 | 3.8 | 34.4 |
| 2009 | 25B2 | 29.90-30.03 | 60.4 | 26 | 6.8 | 5.2 | 1.6 |
| 2009 | 29 | 34.95 | 63 | 20.2 | 7.4 | 5.4 | 4 |
| 2009 | 29 | 35.66 | 62 | 22.6 | 6.8 | 5.8 | 2.8 |
| 2009 | 29 | 40.24 | 58.6 | 24.2 | 5.8 | 7.2 | 4.2 |
| 2009 | 32 B2 | 40.43-40.54 | 61 | 23.2 | 11.2 | 3.2 | 1.4 |

**Enclosure 2b:** Compilation of composite logs with wire-line logs, core photos, logs and analytical data for borehole 09.1.2009.

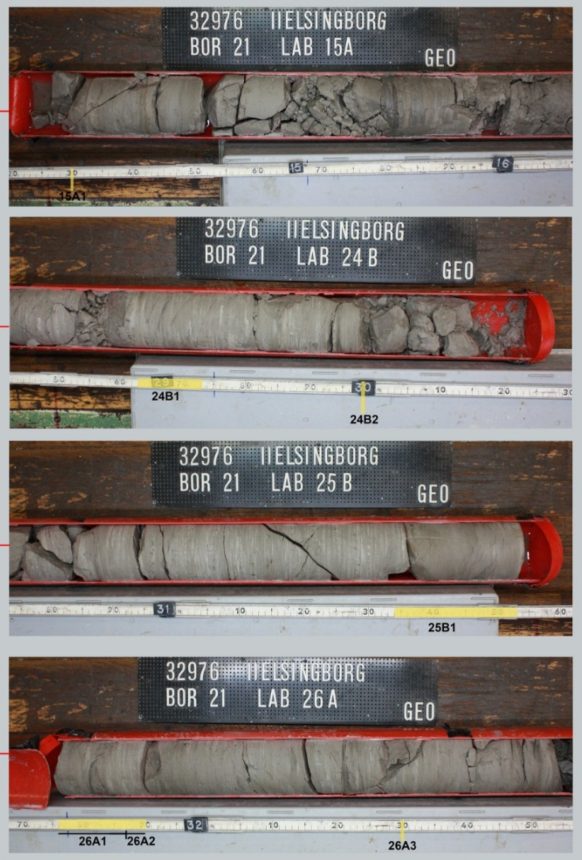
Geophysical logging – Core Drilling – Borehole 09.1.2021 – Helsingborg, Södertunneln

Logging performed by GEO (2009)

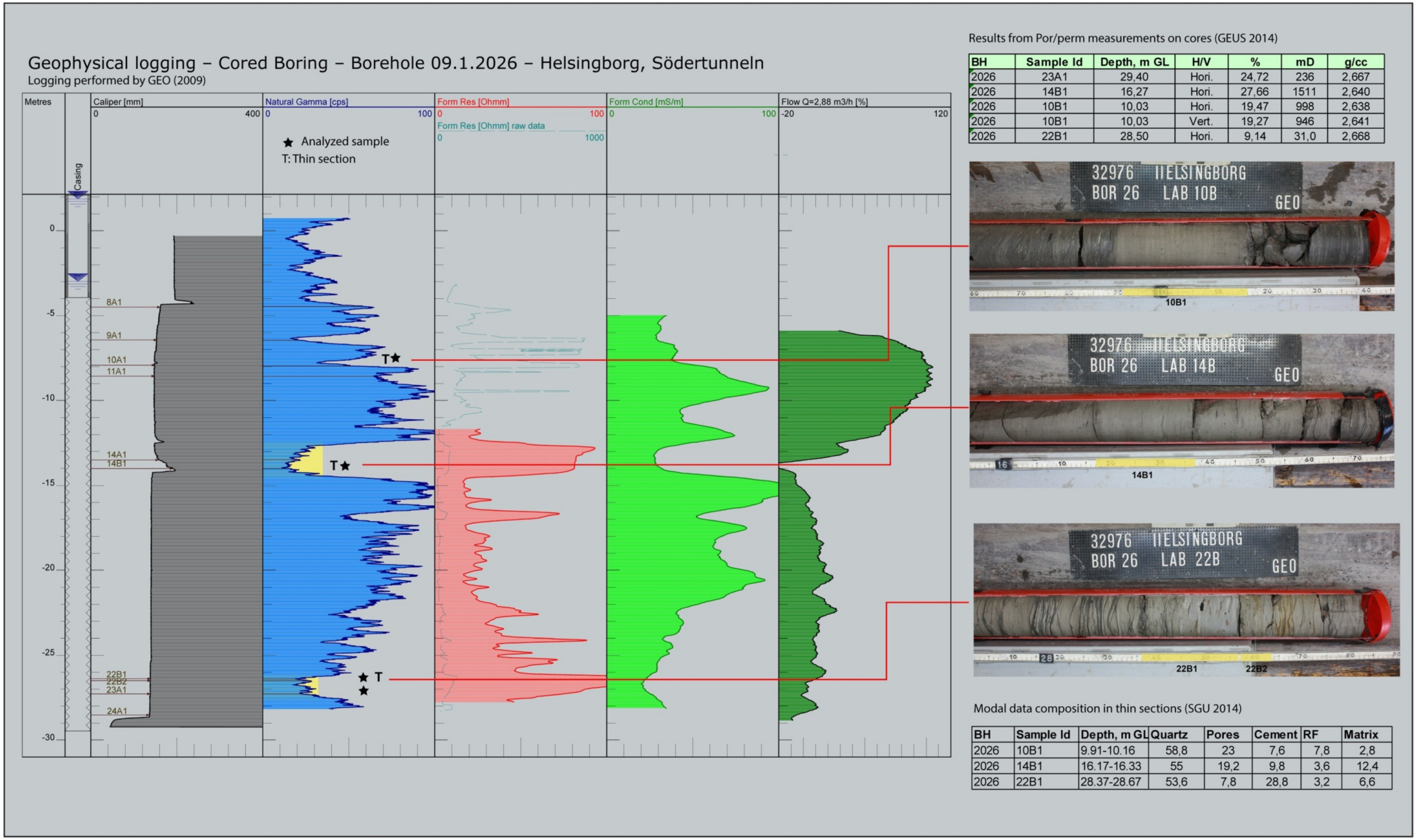



Results from Por/perm measurements on cores (GEUS 2014)

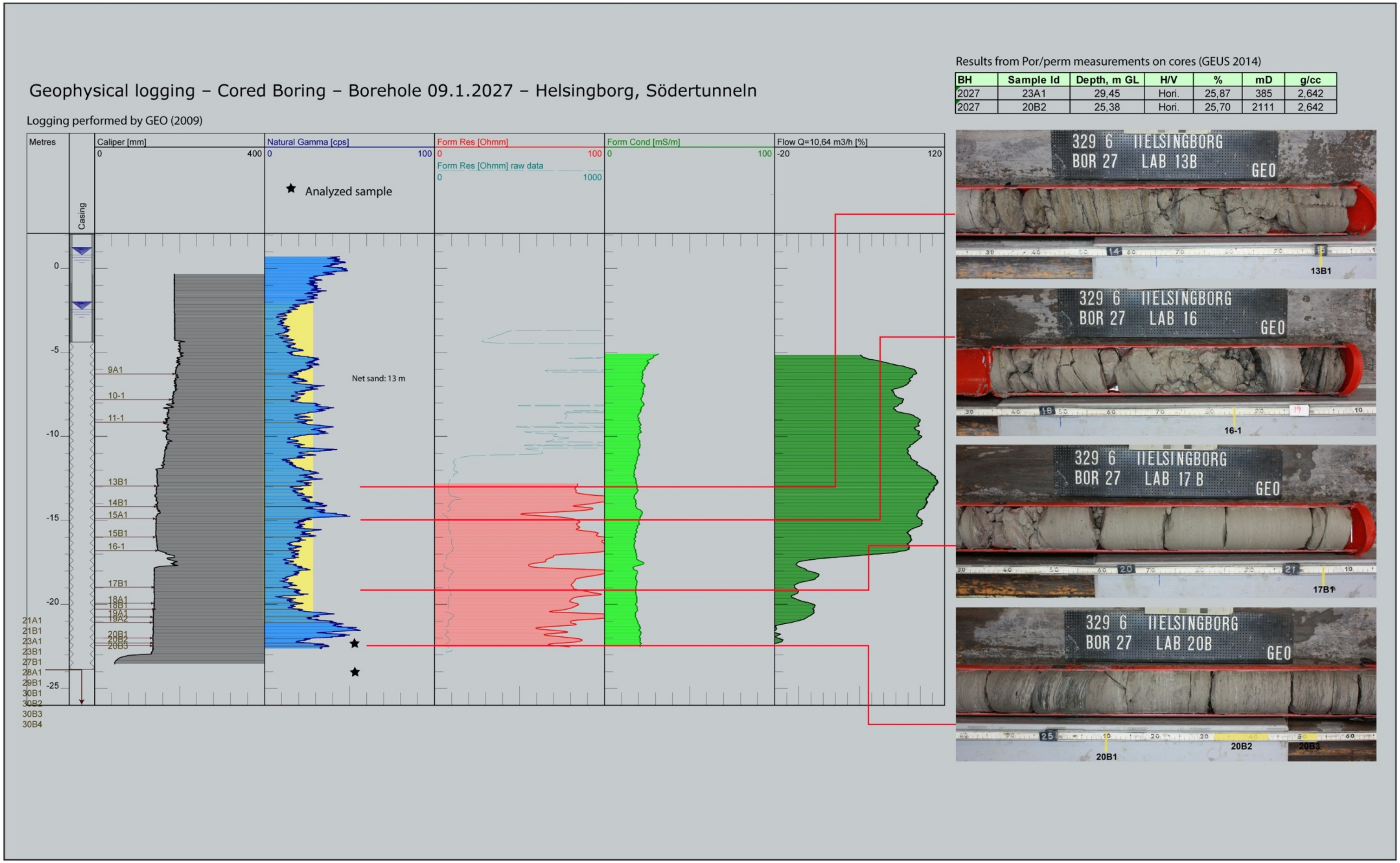
| BH | Sample Id | Depth, m GL | H/V | % | mD | g/cc |
|---|---|---|---|---|---|---|
| 2021 | 25B1 | 31,44 | Hori. | 23,90 | 262 | 2,641 |
| 2021 | 25B1 | 31,44 | Vert. | 24,24 | 94,3 | 2,641 |
| 2021 | 15A1 | 15,30 | Hori. | 24,48 | 471 | 2,652 |
| 2021 | 26A1 | 31,82 | Hori. | 24,69 | 596 | 2,644 |
| 2021 | 24B2 | 30,03 | Hori. | 26,40 | 1080 | 2,642 |



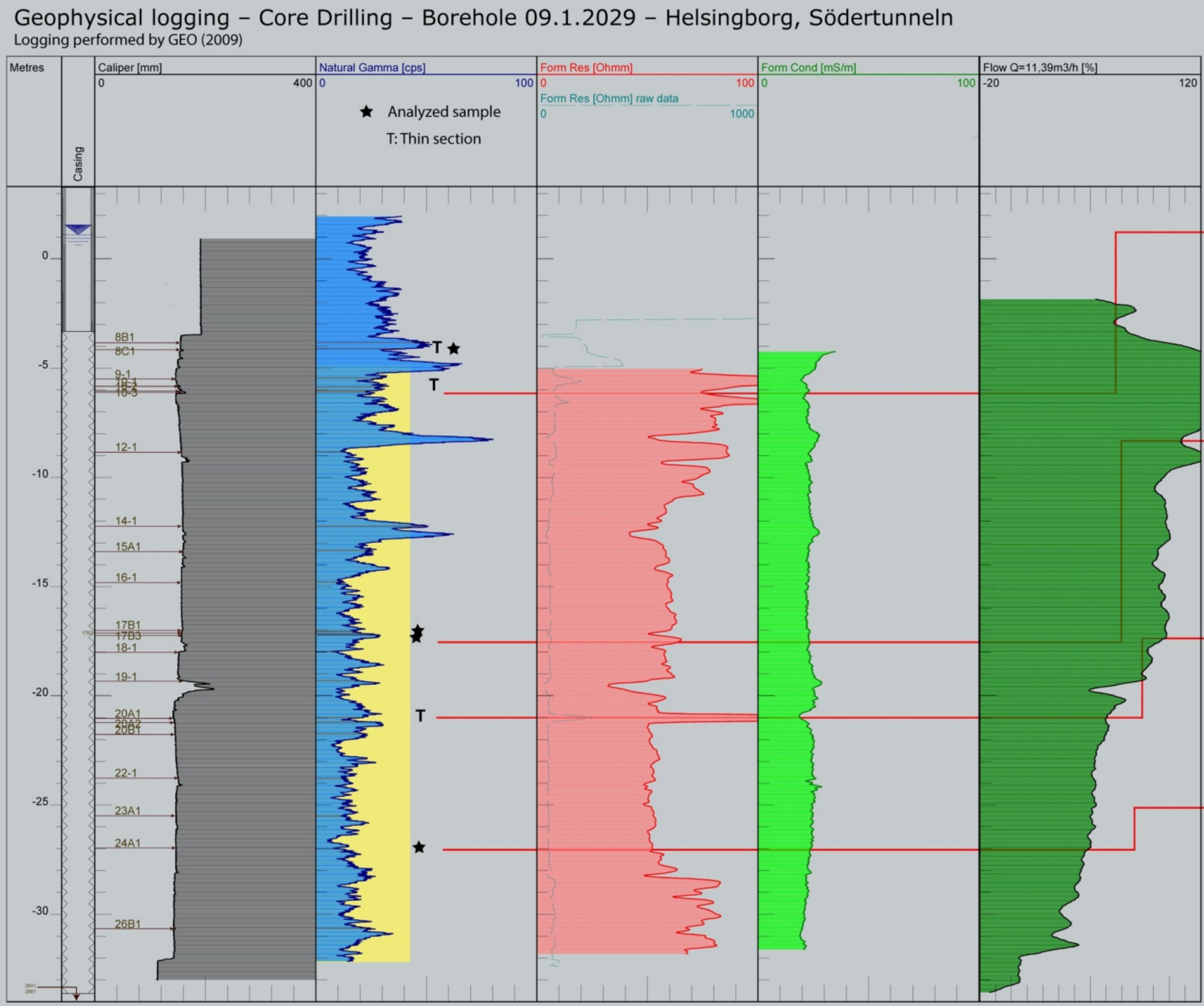

**Enclosure 2c:** Compilation of composite logs with wire-line logs, core photos, logs and analytical data for borehole 09.1.2021.




**Enclosure 2d:** Compilation of composite logs with wire-line logs, core photos, logs and analytical data for borehole 09.1.2026.




**Enclosure 2e:** Compilation of composite logs with wire-line logs, core photos, logs and analytical data for borehole 09.1.2027.




Results from Por/perm measurements on cores (GEUS 2014)

| BH | Sample Id | Depth, m GL | H/V | % | mD | g/cc |
|---|---|---|---|---|---|---|
| 2029 | 24A1 | 30,30 | Hori. | 29,24 | n.d | 2,639 |
| 2029 | 24A1 | 30,30 | Vert. | 29,33 | 3870 | 2,642 |
| 2029 | 17B3 | 20,54 | Hori. | 29,35 | 3047 | 2,641 |
| 2029 | 8C1 | 7,48 | Hori. | 24,12 | 1125 | 2,648 |
| 2029 | 17B1 | 20,35 | Hori. | 27,72 | 1193 | 2,657 |

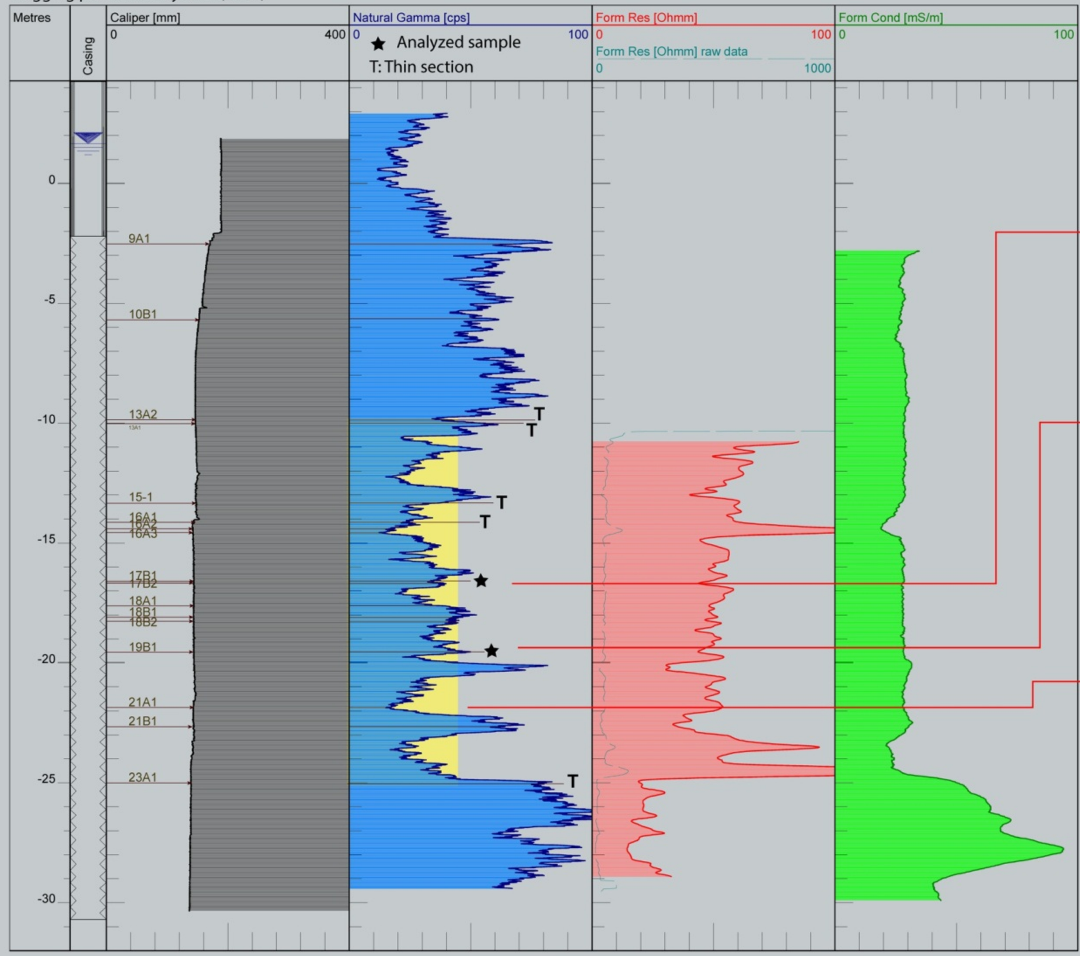

Modal data composition in thin sections (SGU 2014)

| BH | Sample Id | Depth, m GL | Quartz | Pores | Cement | RF | Matrix |
|---|---|---|---|---|---|---|---|
| 2029 | 8C1 | 7.40-7.55 | 60,0 | 20,0 | 14,3 | 4,0 | 1,7 |
| 2029 | 10-2 | 9.37-9.42 | 64,3 | 22,3 | 7,0 | 5,7 | 0,7 |
| 2029 | 20A1 | 24.29-24.38 | 53,0 | 1,0 | 38,3 | 5,7 | 2,0 |

**Enclosure 2f:** Compilation of composite logs with wire-line logs, core photos, logs and analytical data for borehole 09.1.2029.

## Geophysical logging – Cored Boring – Borehole 09.1.2033 – Helsingborg, Södertunneln

Logging performed by GEO (2009)



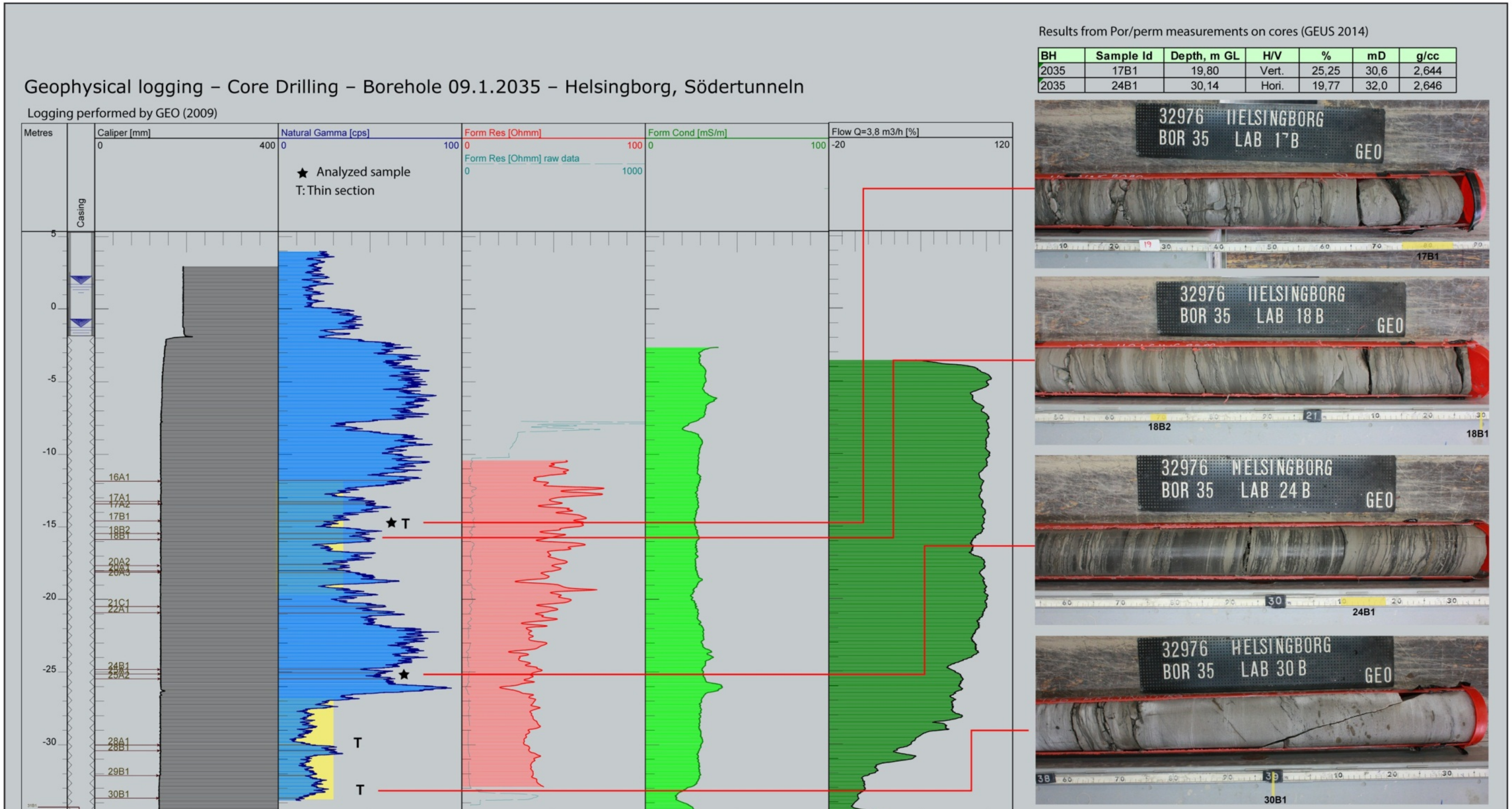

Results from Por/perm measurements on cores (GEUS 2014)

| BH | Sample Id | Depth, m GL | H/V | % | mD | g/cc |
|---|---|---|---|---|---|---|
| 2033 | 19B1 | 23,80 | Hori. | 24,49 | 1082 | 2,653 |
| 2033 | 17B2 | 20,94 | Hori. | 23,02 | 238 | 2,632 |


Modal data composition in thin sections (SGU 2014)

| BH | Sample Id | Depth, m GL | Quartz | Pores | Cement | RF | Matrix |
|---|---|---|---|---|---|---|---|
| 2033 | 23A1 | 29.30 | 61,3 | 2,3 | 27,7 | 5,7 | 3,0 |
| 2033 | 13A1 | 14.29-14.32 | 63,3 | 21,0 | 8,3 | 6,3 | 1,0 |
| 2033 | 16A1 | 18.40 | 56,7 | 12,3 | 26,0 | 2,7 | 2,3 |
| 2033 | 15A1 | 17.65 | 58,3 | 23,7 | 10,7 | 7,3 | 0,0 |
| 2033 | 13A2 | 14.06-14.17 | 54,7 | 20,7 | 14,0 | 3,7 | 7,0 |

**Enclosure 2g:** Compilation of composite logs with wire-line logs, core photos, logs and analytical data for borehole 09.1.2033.



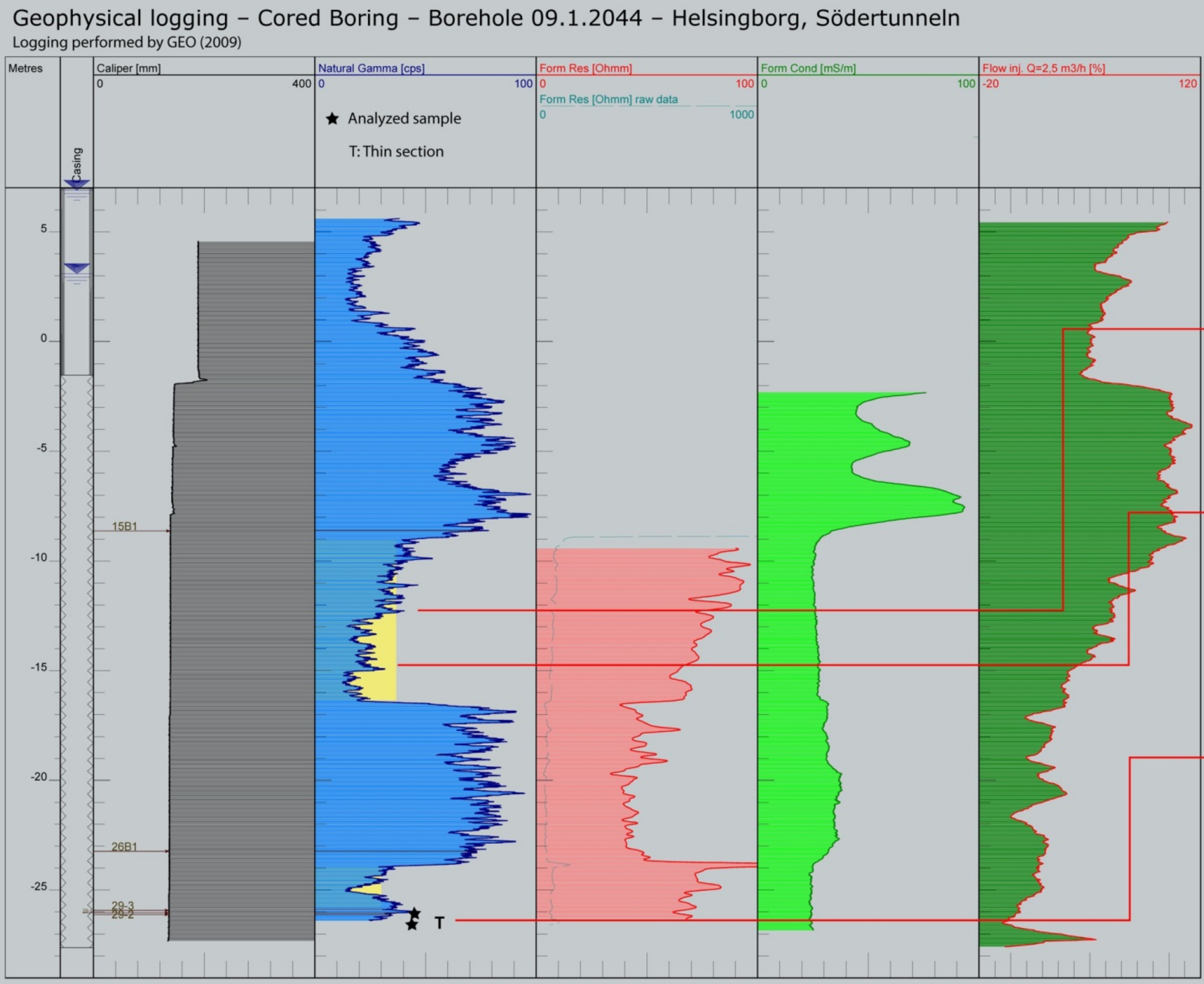

Results from Por/perm measurements on cores (GEUS 2014)

| BH | Sample Id | Depth, m GL | H/V | % | mD | g/cc |
|---|---|---|---|---|---|---|
| 2035 | 17B1 | 19,80 | Vert. | 25,25 | 30,6 | 2,644 |
| 2035 | 24B1 | 30,14 | Hori. | 19,77 | 32,0 | 2,646 |

Modal data composition in thin sections (SGU 2014)

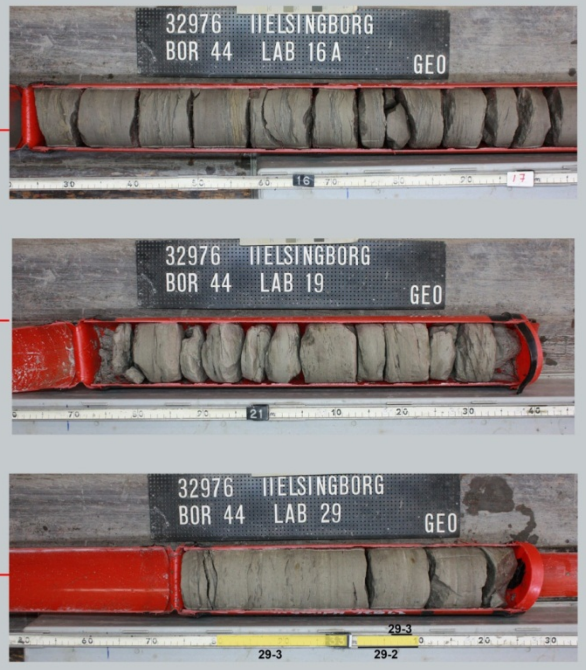
| BH | Sample Id | Depth, m GL | Quartz | Pores | Cement | RF | Matrix |
|---|---|---|---|---|---|---|---|
| 2035 | 17B1 | 19.75-19.85 | 55,7 | 19,0 | 12,3 | 4,3 | 8,7 |
| 2035 | 25A1 | 30.43-30.46 | 52,7 | 15,0 | 21,7 | 5,3 | 5,3 |
| 2035 | 30B1 | 39.26-39.35 | 54,0 | 1,7 | 31,0 | 7,7 | 5,7 |

**Enclosure 2h:** Compilation of composite logs with wire-line logs, core photos, logs and analytical data for borehole 09.1.2035.




Results from Por/perm measurements on cores (GEUS 2014)

| BH | Sample Id | Depth, m GL | H/V | % | mD | g/cc |
|---|---|---|---|---|---|---|
| 2044 | 29-3 | 32,90 | Hori. | 27,36 | 966 | 2,644 |
| 2044 | 29-2 | 33,06 | Hori. | 26,10 | 1065 | 2,649 |




Modal data composition in thin sections (SGU 2014)

| BH | Sample Id | Depth, m GL | Quartz | Pores | Cement | RF | Matrix |
|---|---|---|---|---|---|---|---|
| 2044 | 29-3,29-2 | 32.88-33.00 | 58.0 | 24.3 | 7.3 | 5.7 | 4.7 |

**Enclosure 2i:** Compilation of composite logs with wire-line logs, core photos, logs and analytical data for borehole 09.1.2044.

Scale : 1:100

Enclosure 3a

# HBG 1.1008

Scale : 1:100

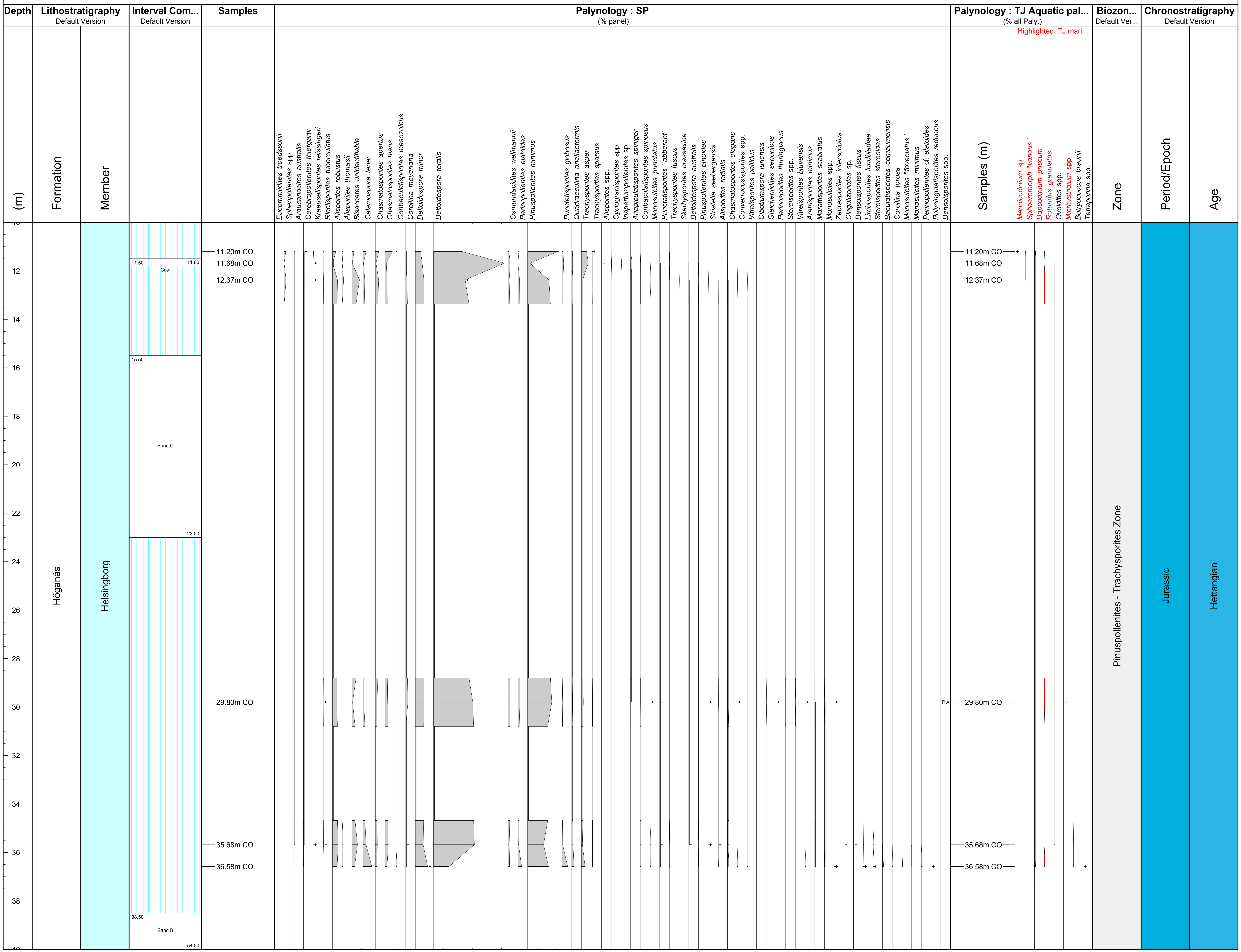
Enclosure 3b

# HBG 1.1008

Scale : 1:100

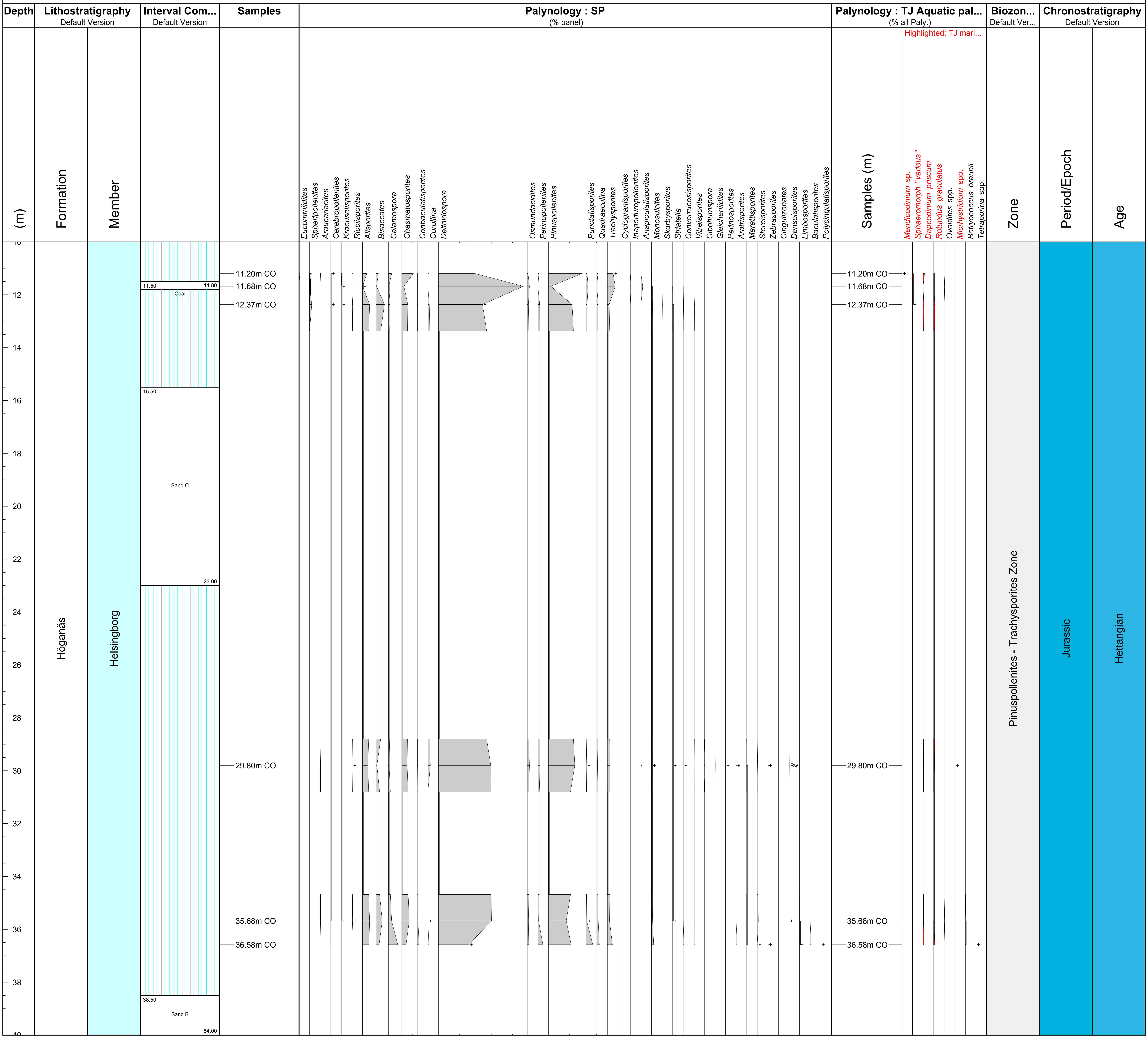
Enclosure 3c

# HBG 1.1007



Enclosure 3d

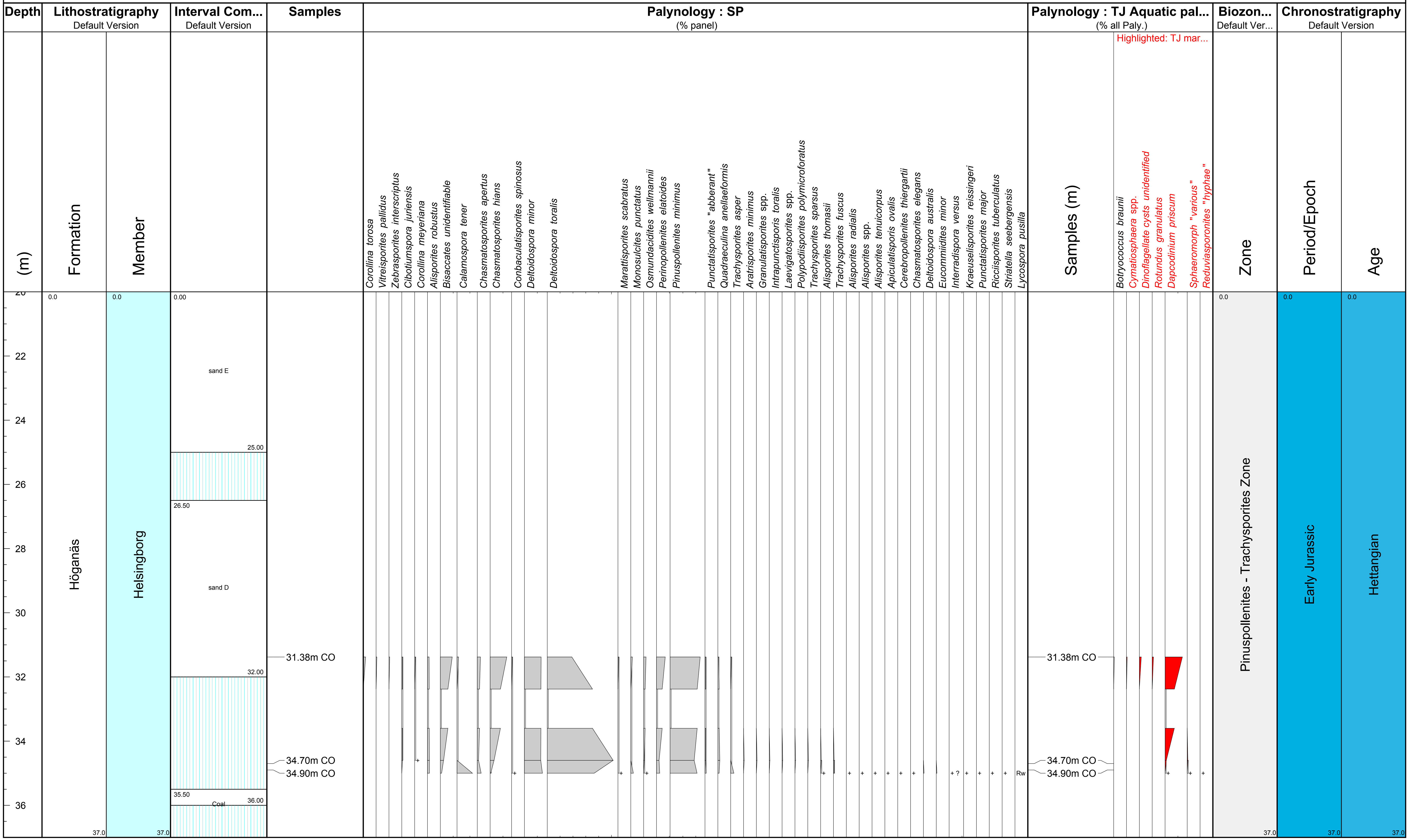
# HBG 1.1007



Scale : 1:100

Enclosure 3e

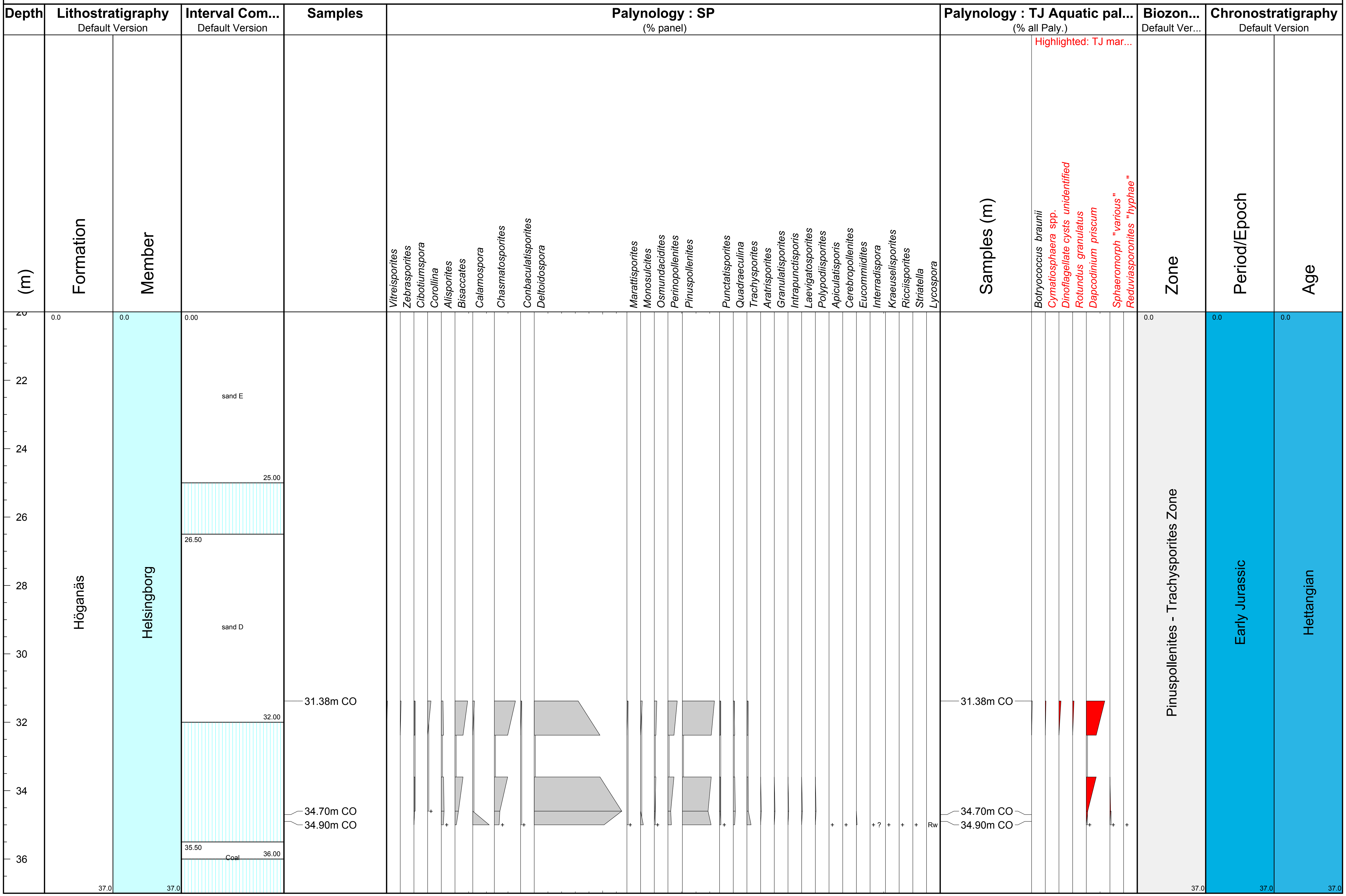
# HBG 1.1011



Enclosure 3f

# HBG 1.1011

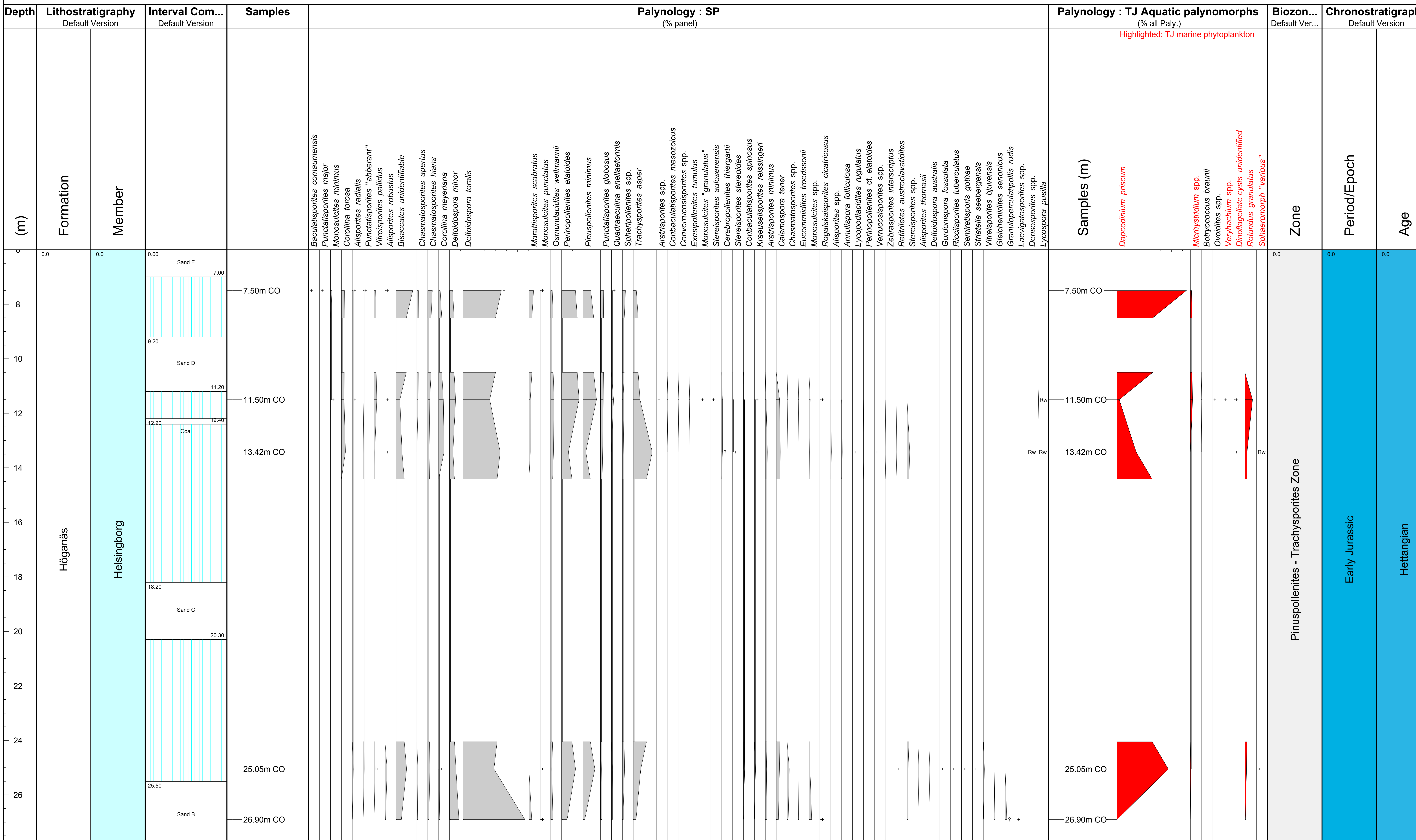
Scale : 1:100



Enclosure 3g

Scale : 1:100

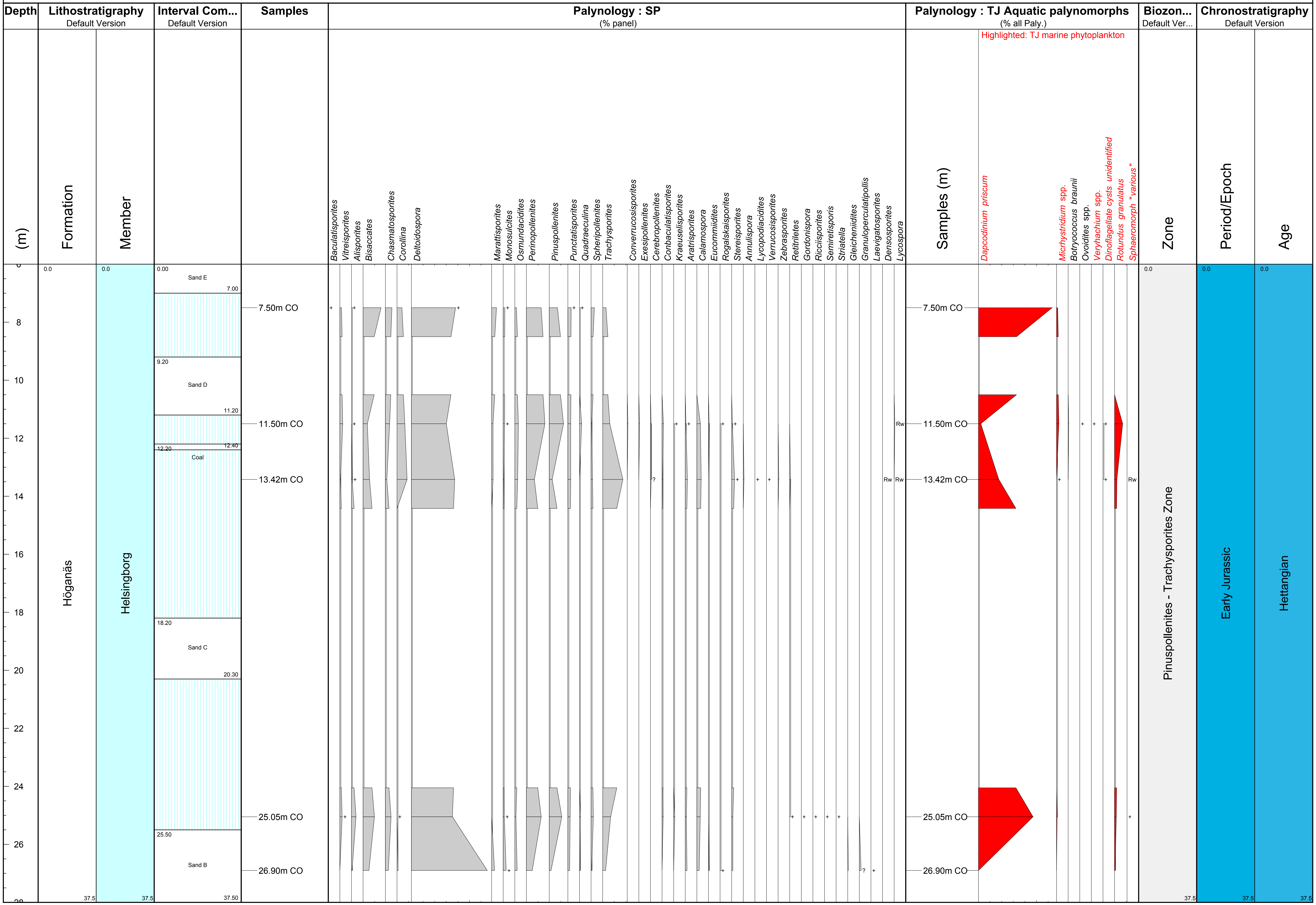
# HBG 09.1.2001



Enclosure 3h

Scale : 1:100

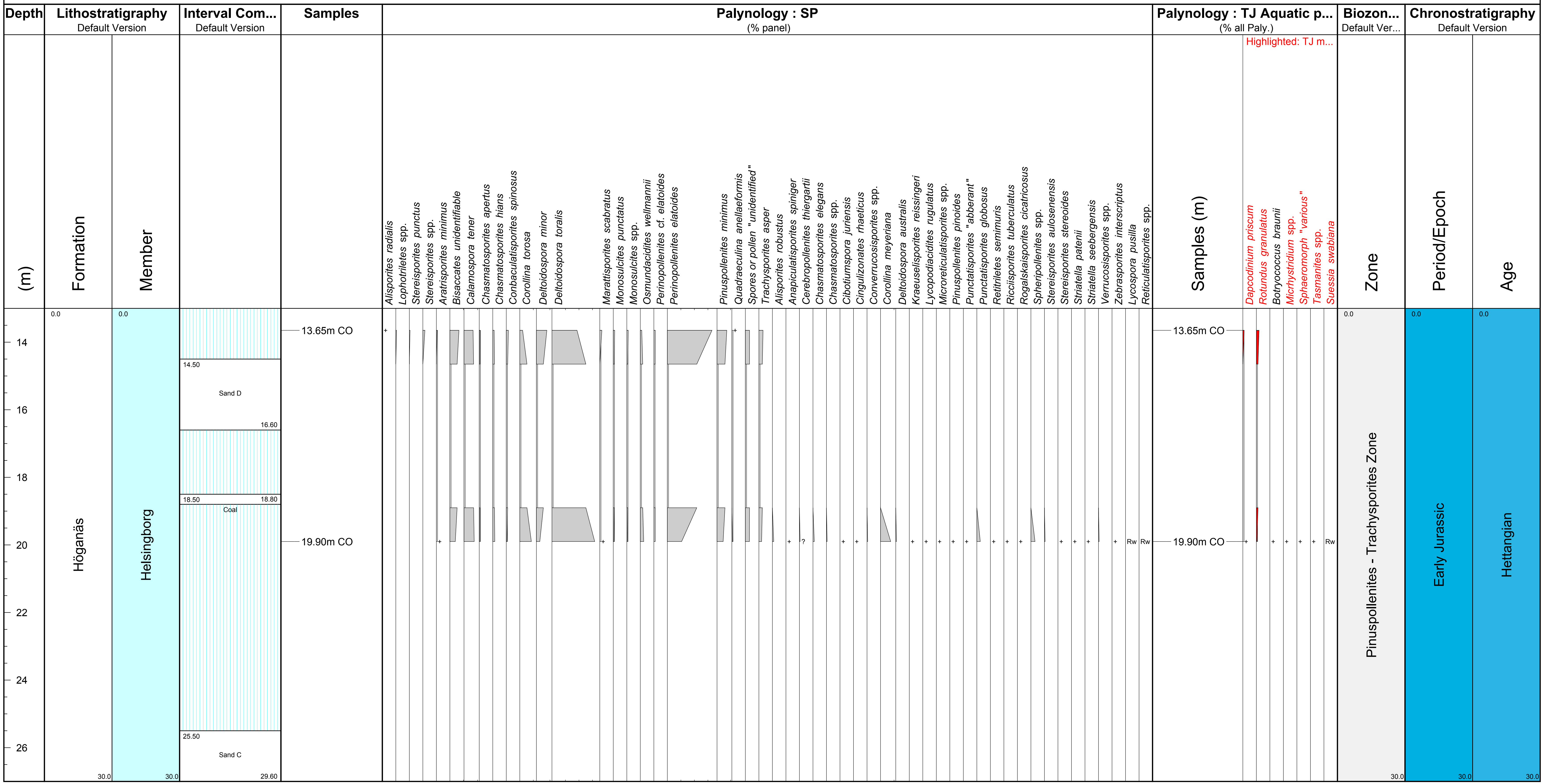
# HBG 09.1.2001



Enclosure 3i

Scale : 1:100

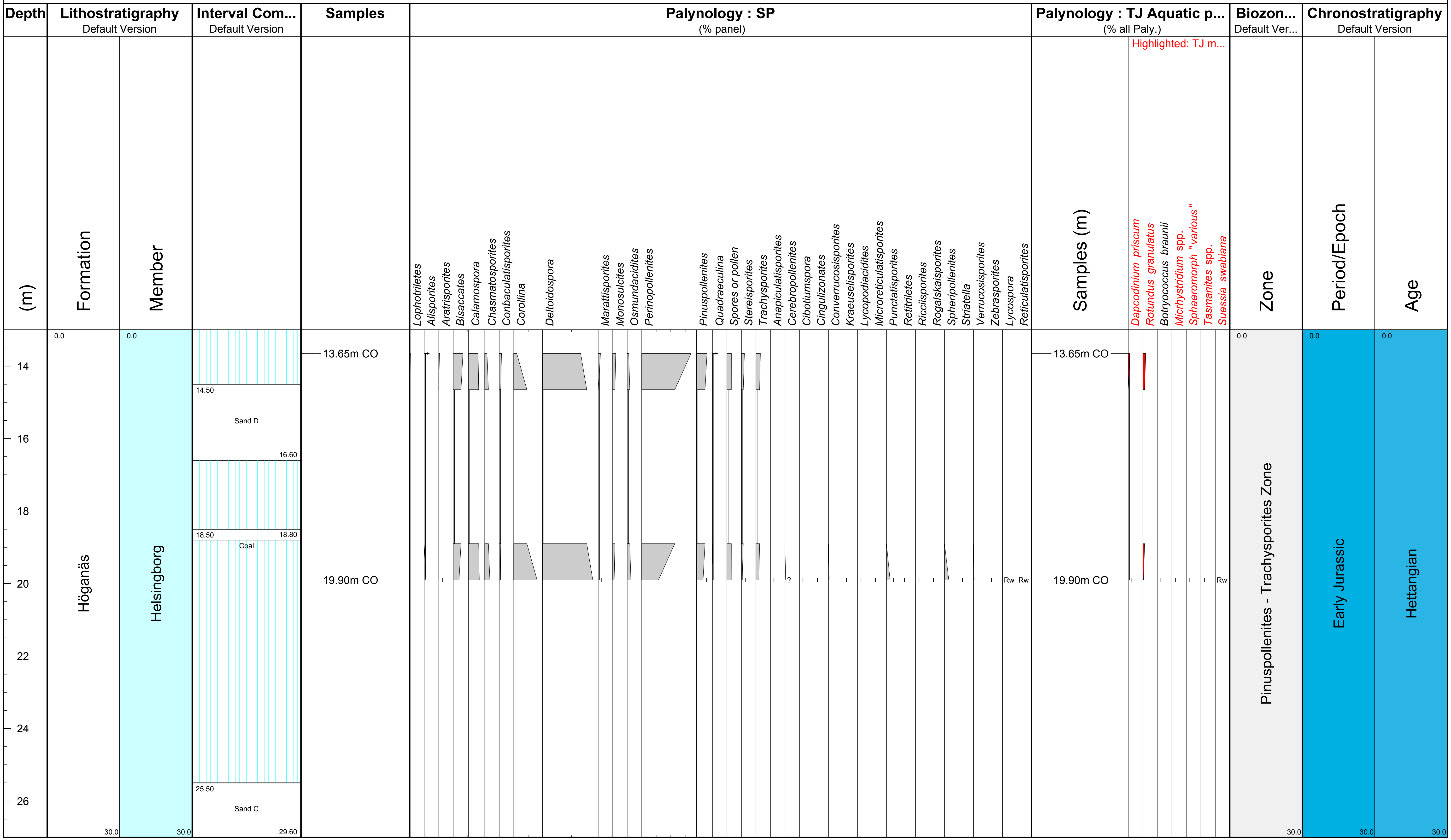
# HBG 09.1.2026



Scale : 1:100

Enclosure 3j

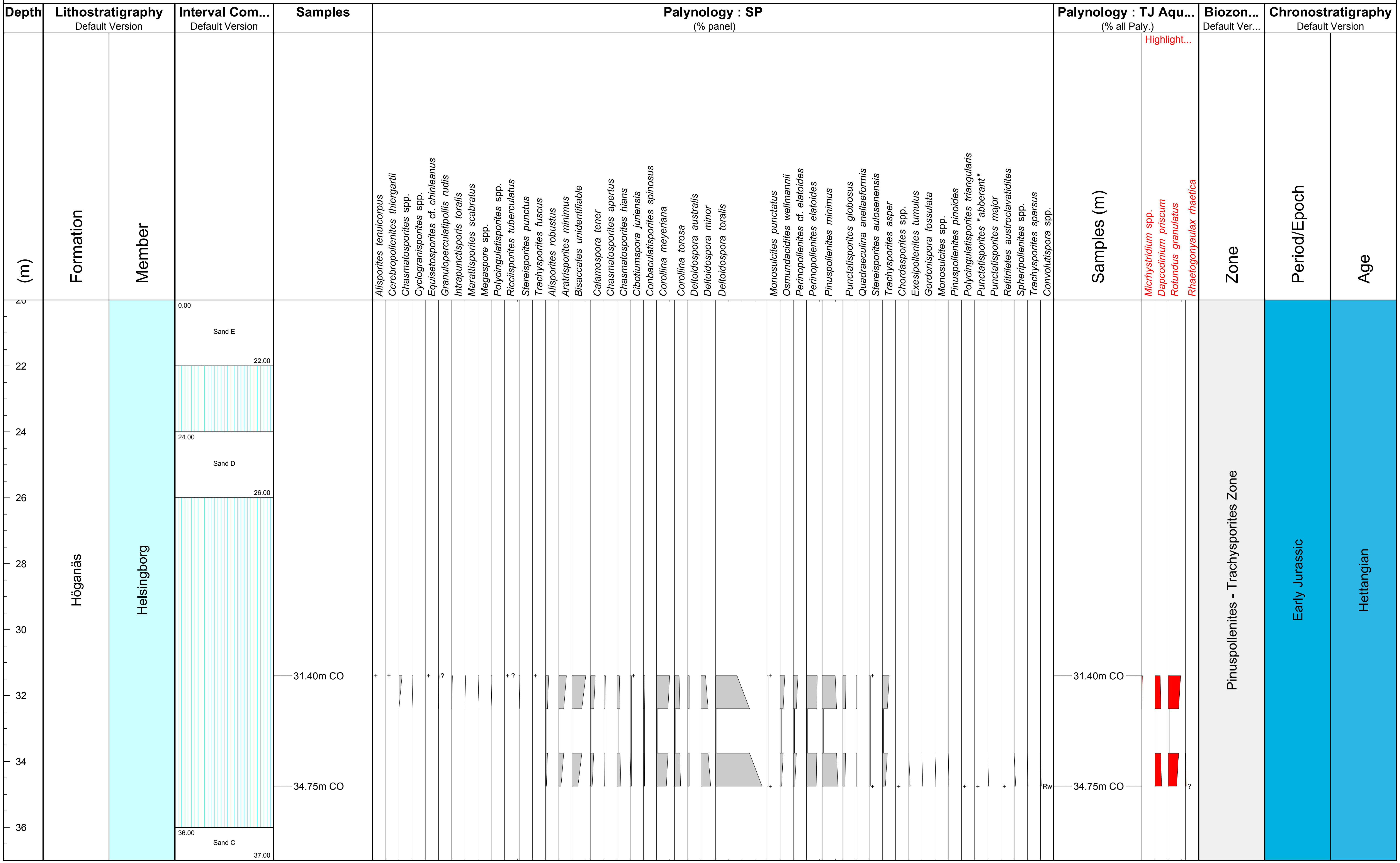
# HBG 09.1.2026



Scale : 1:100

Enclosure 3k

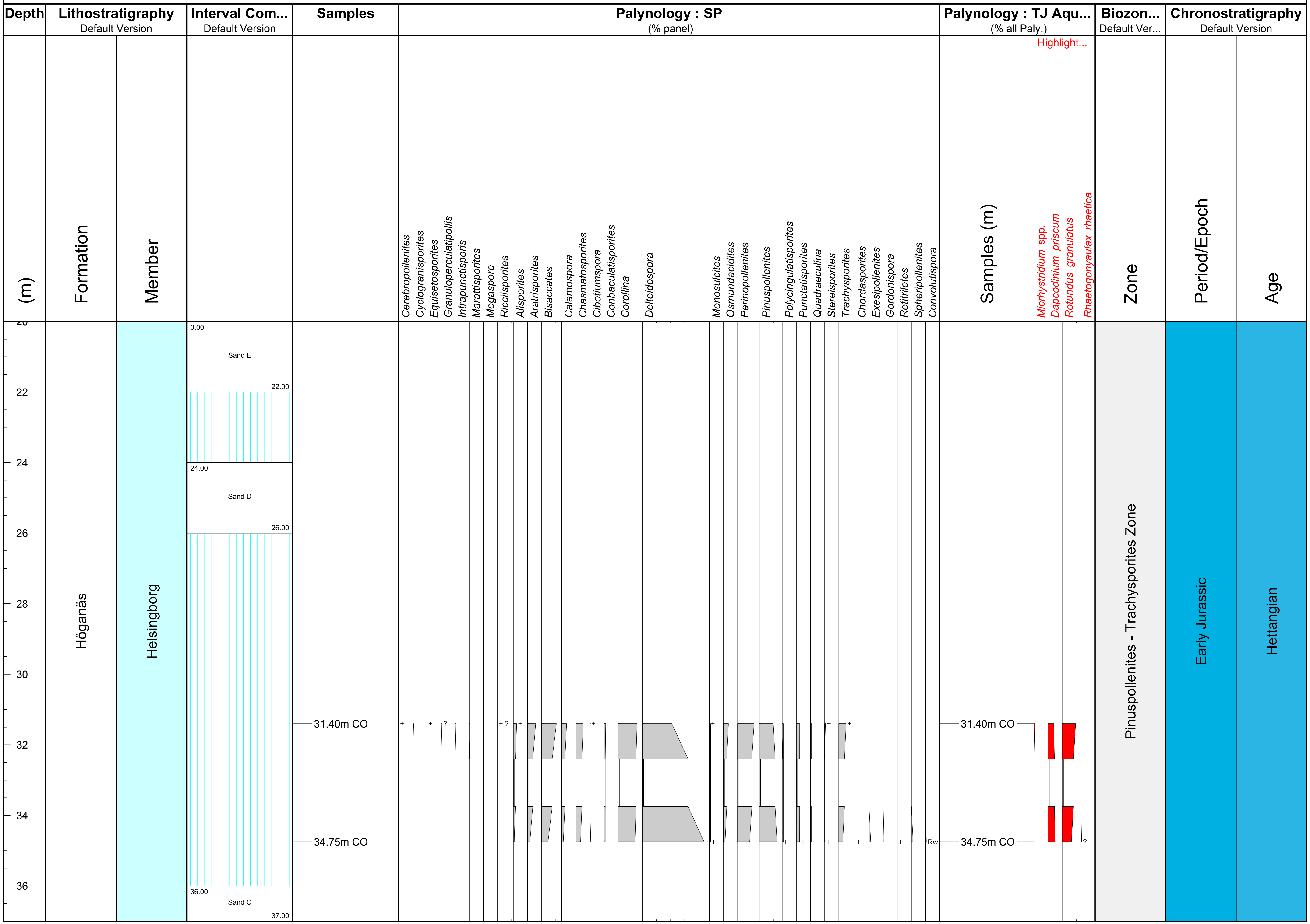
# HBG 09.1.2027



Scale : 1:100

Enclosure 3l

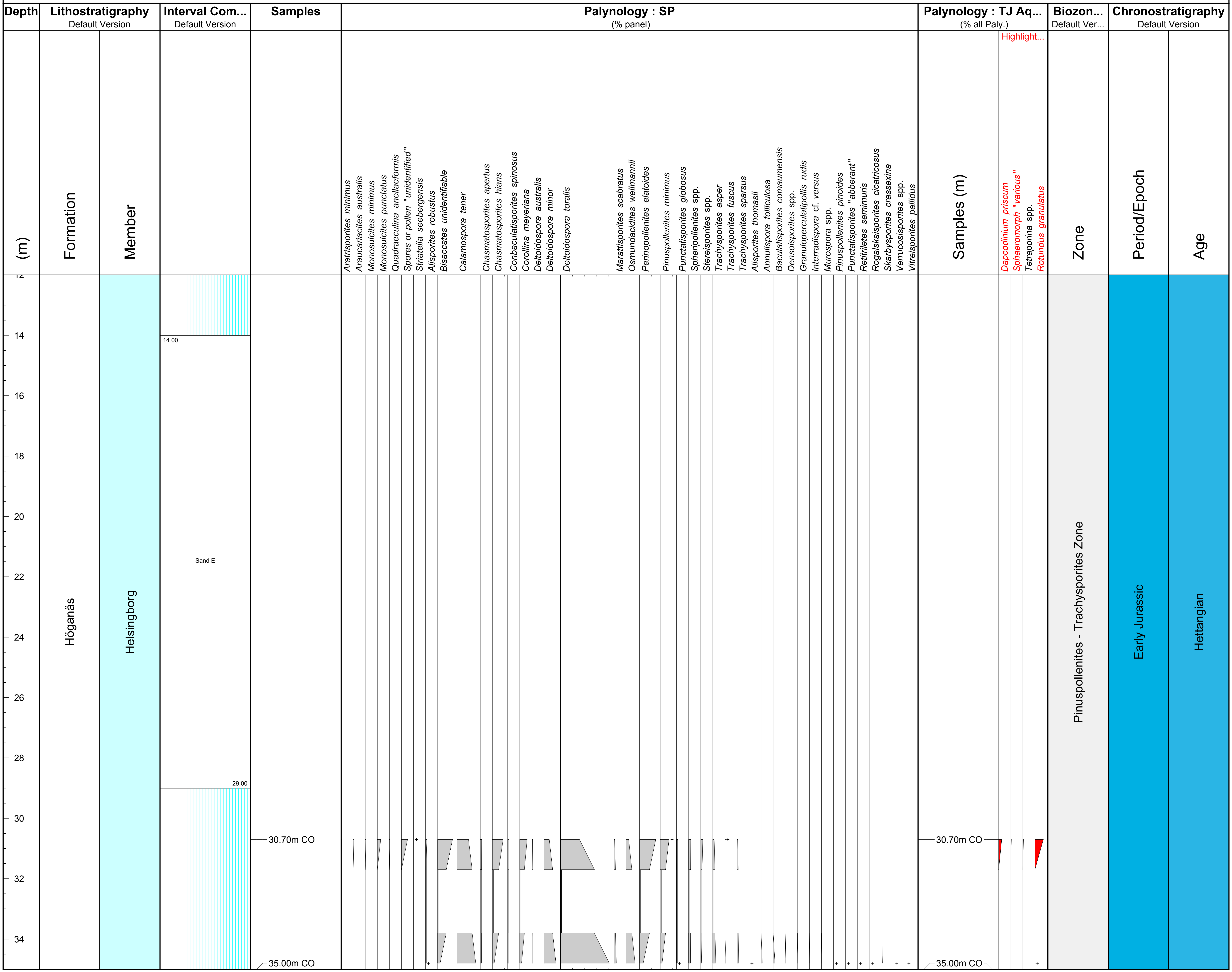
# HBG 09.1.2027



Scale : 1:100

Enclosure 3m

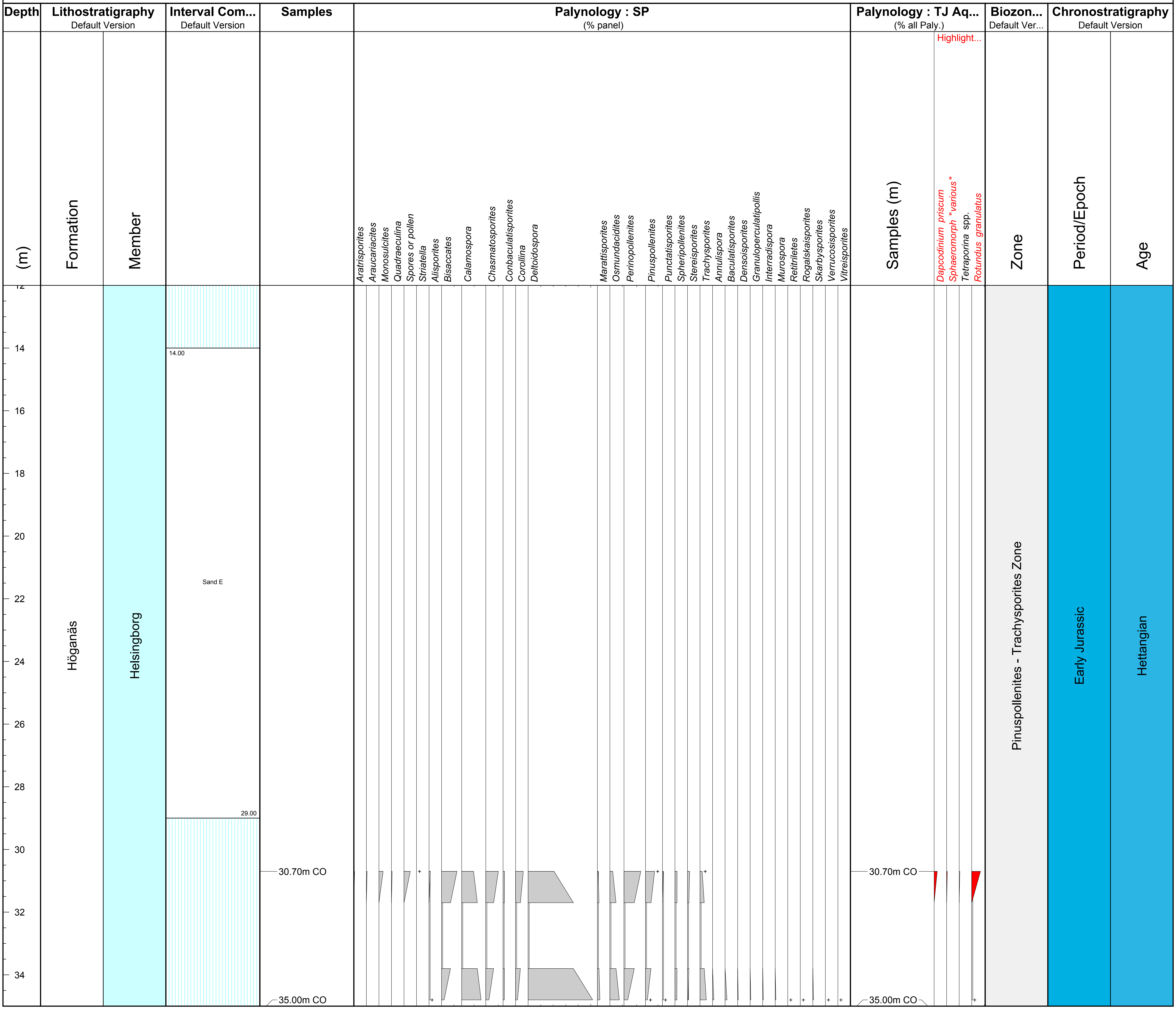
# HBG 09.1.2033



Scale : 1:100

Enclosure 3n

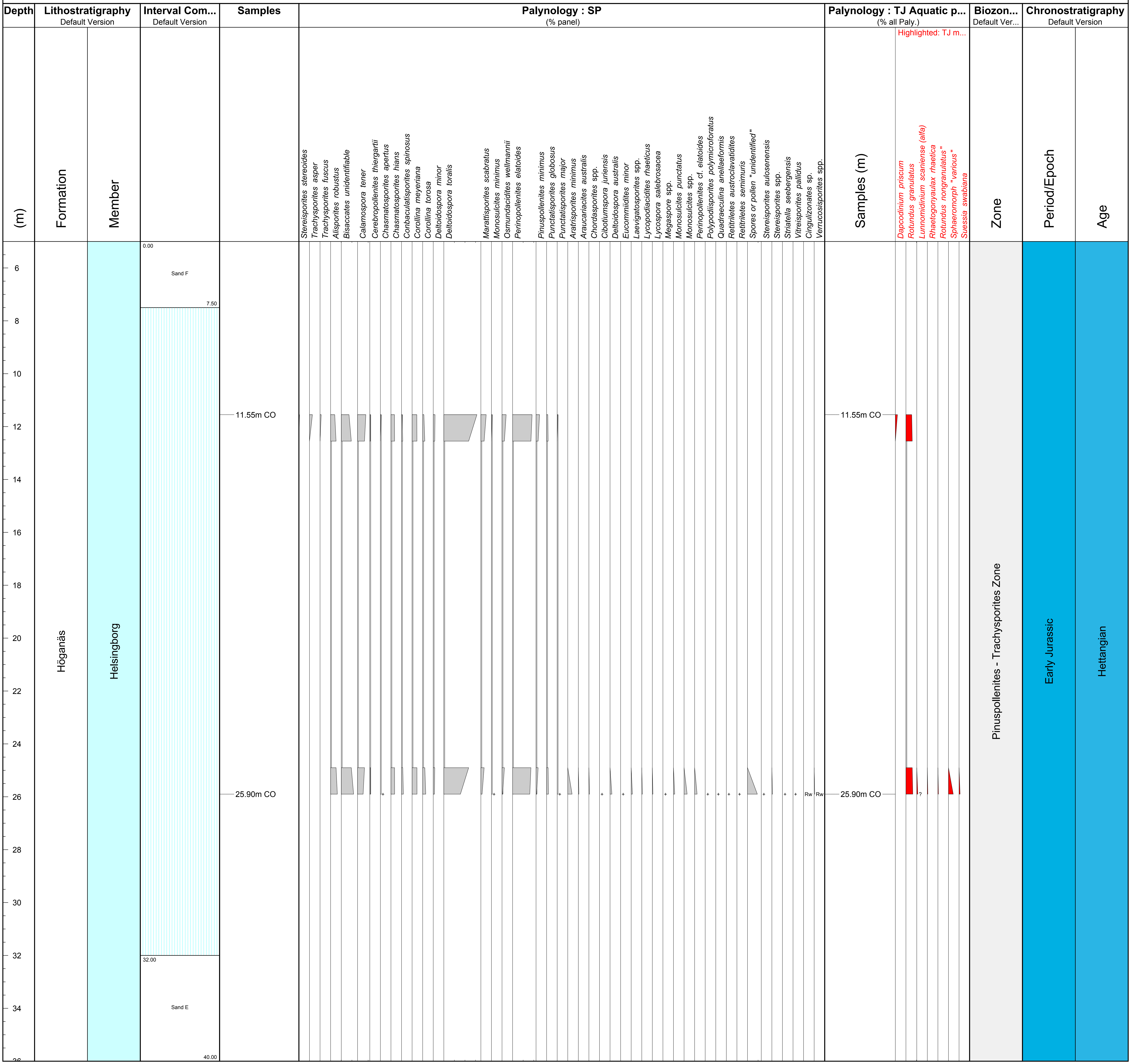
# HBG 09.1.2033



Scale : 1:100

Enclosure 3o

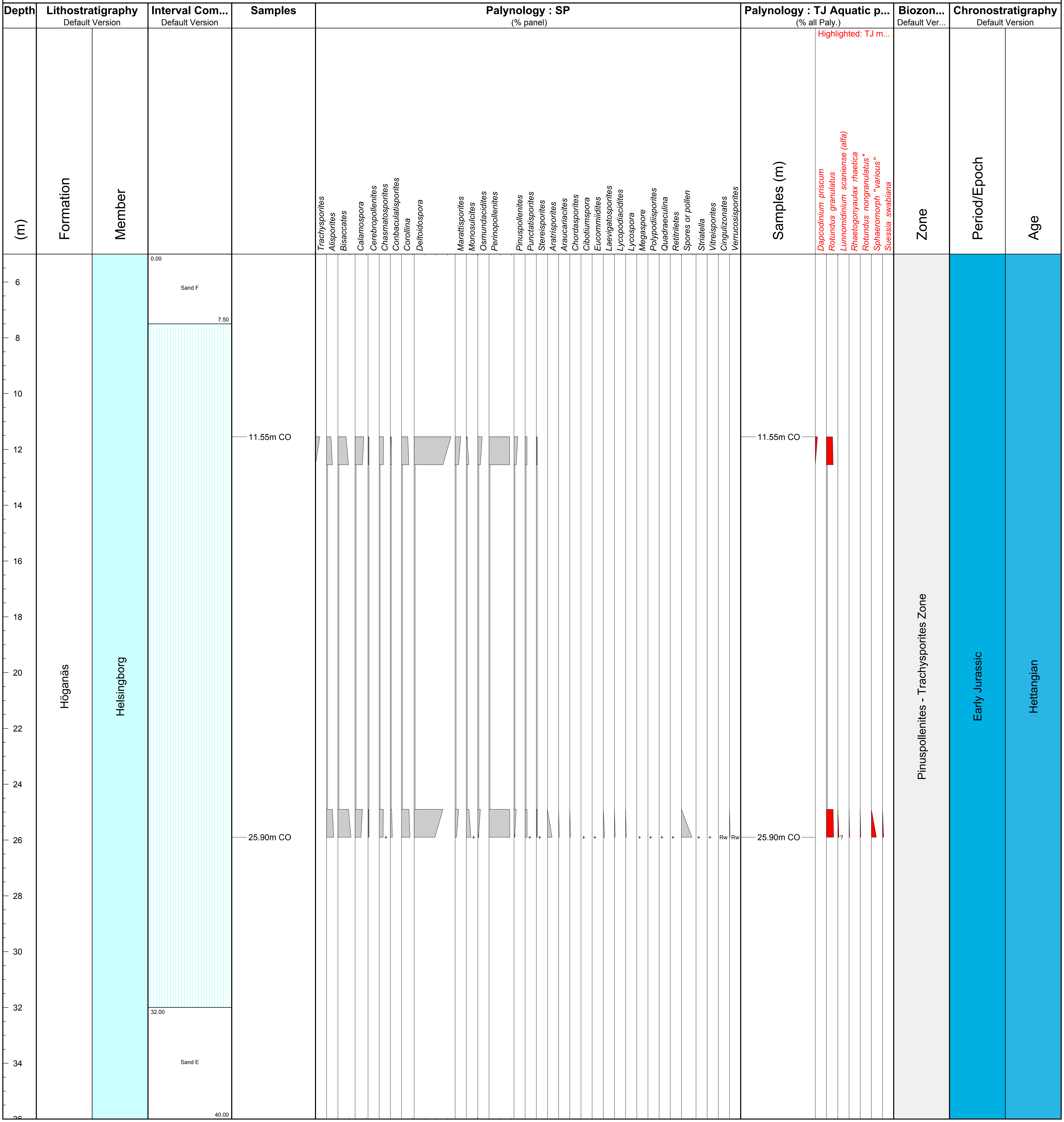
# HBG 09.1.2035



Scale : 1:100

Enclosure 3p

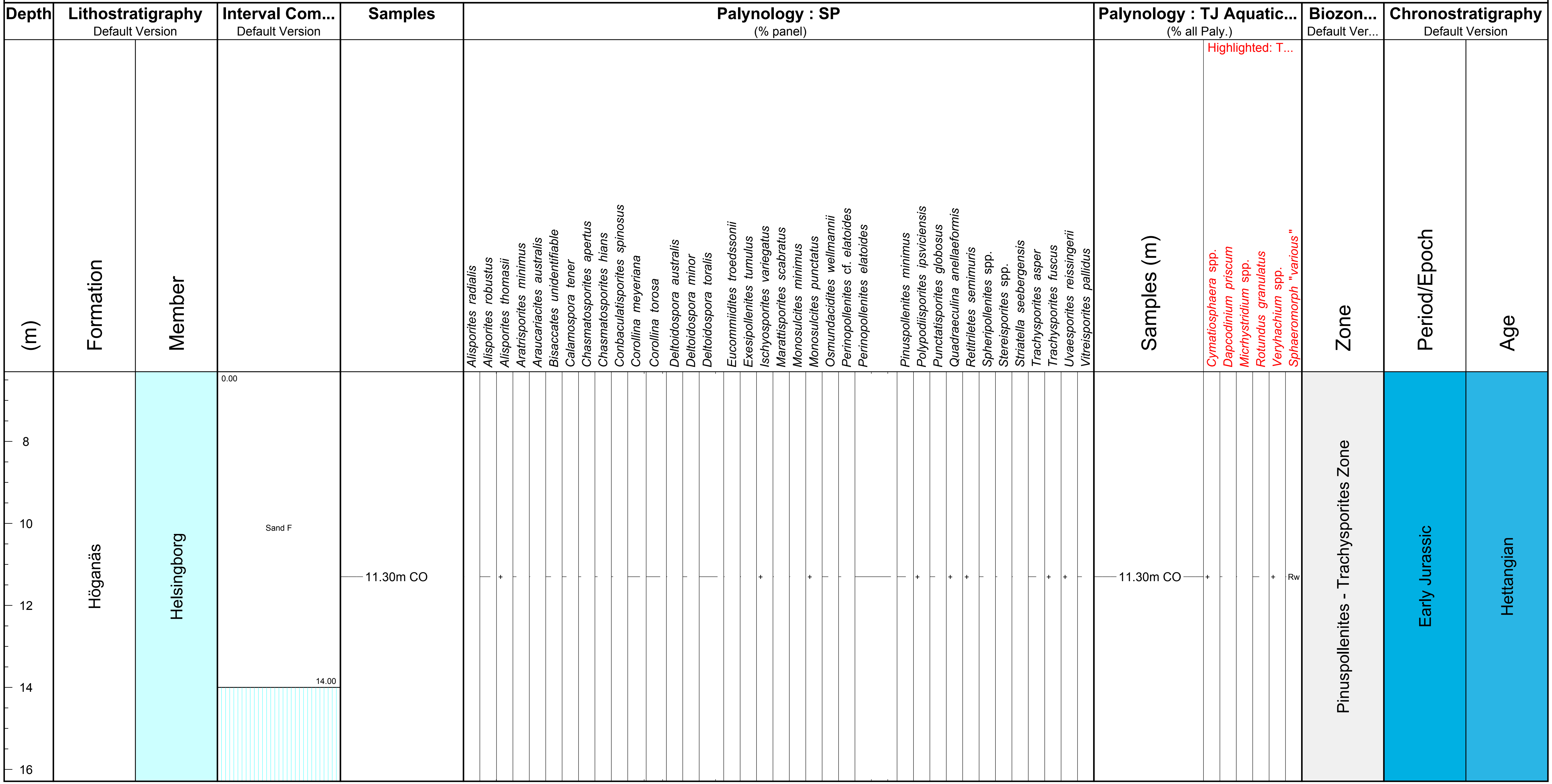
# HBG 09.1.2035



Scale : 1:100

Enclosure 3q

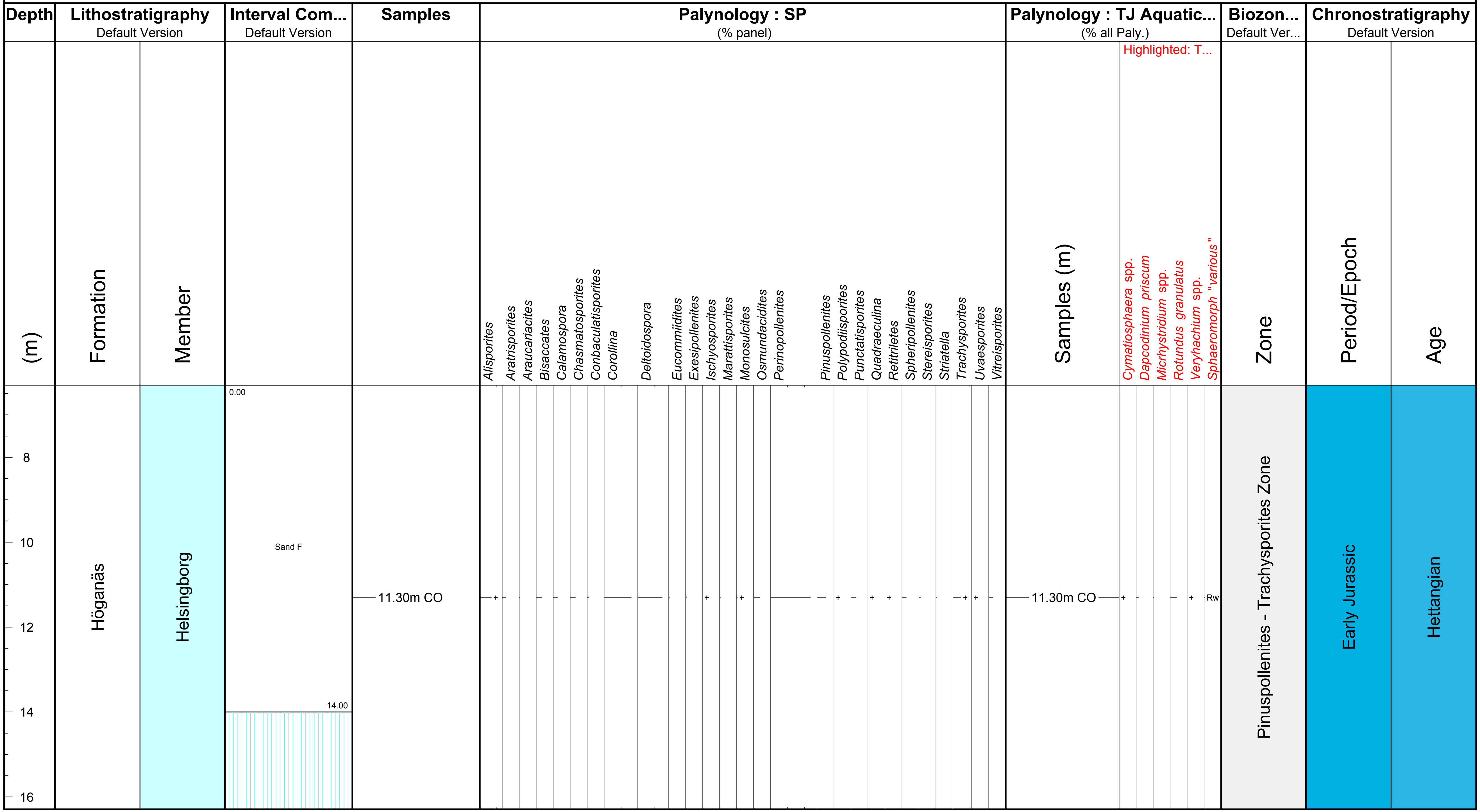
# HBG 09.1.2040



Scale : 1:100

Enclosure 3r

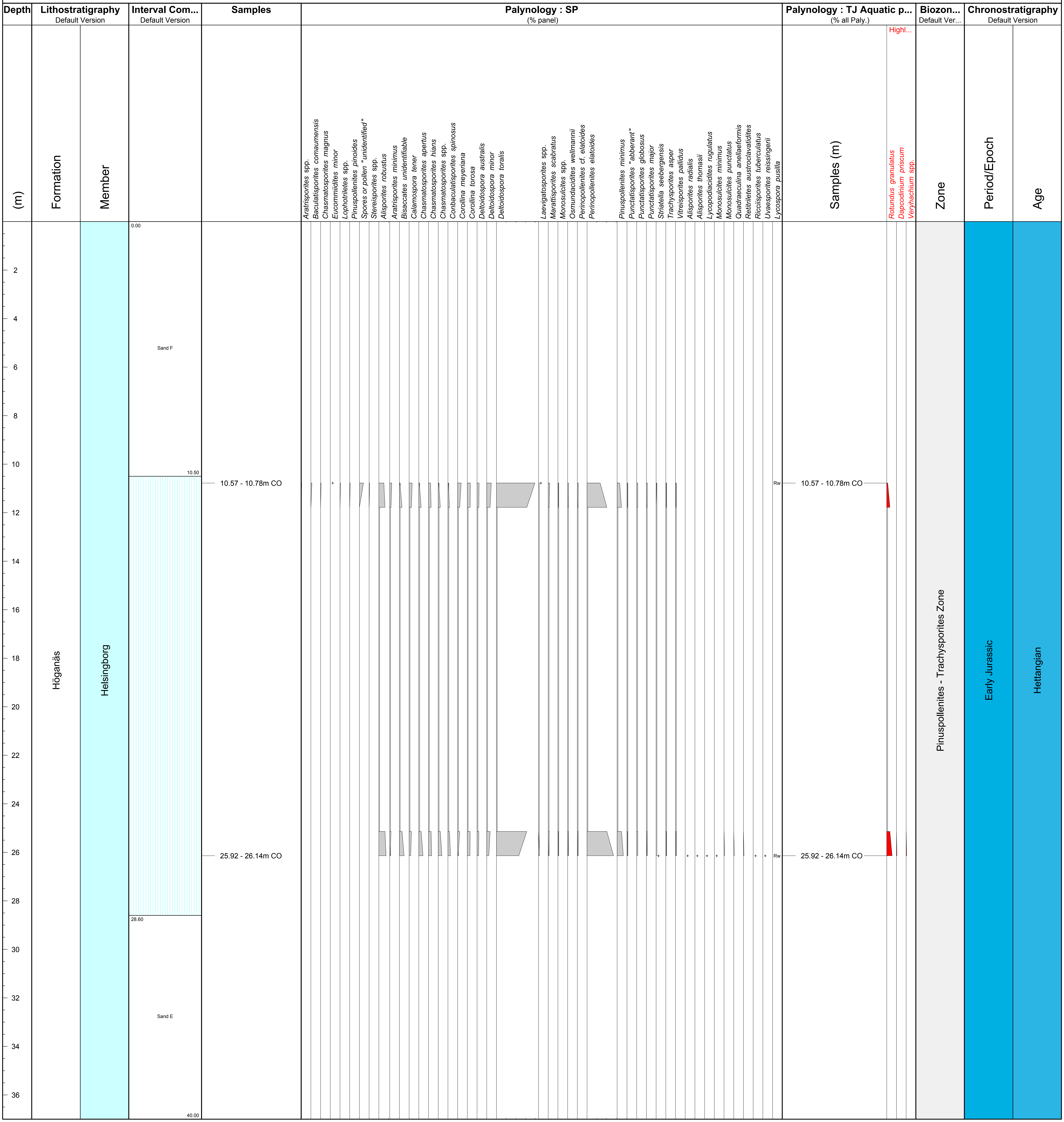
# HBG 09.1.2040



Scale : 1:100

Enclosure 3s

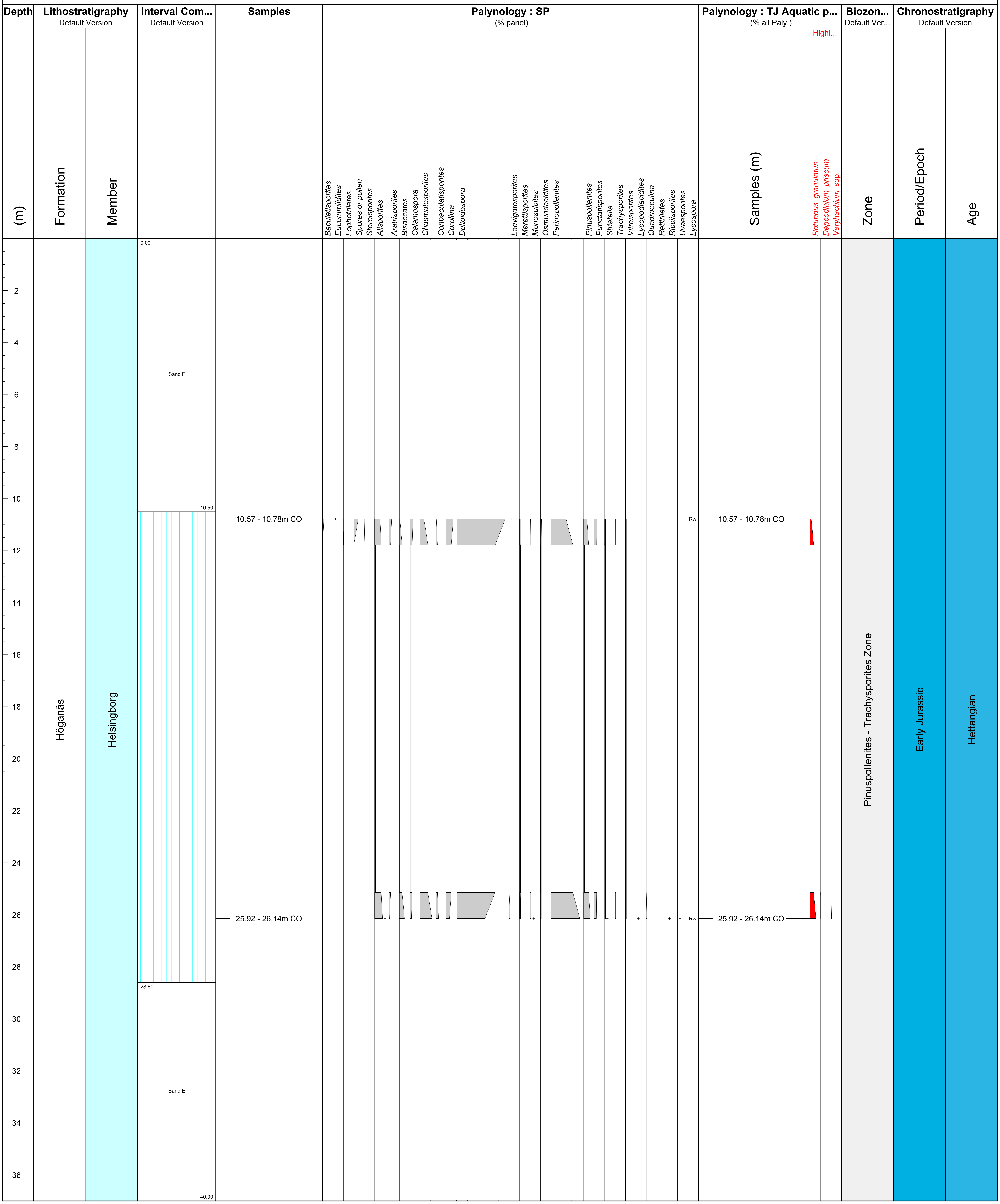
# HBG 09.1.2009



Scale : 1:100

Enclosure 3t

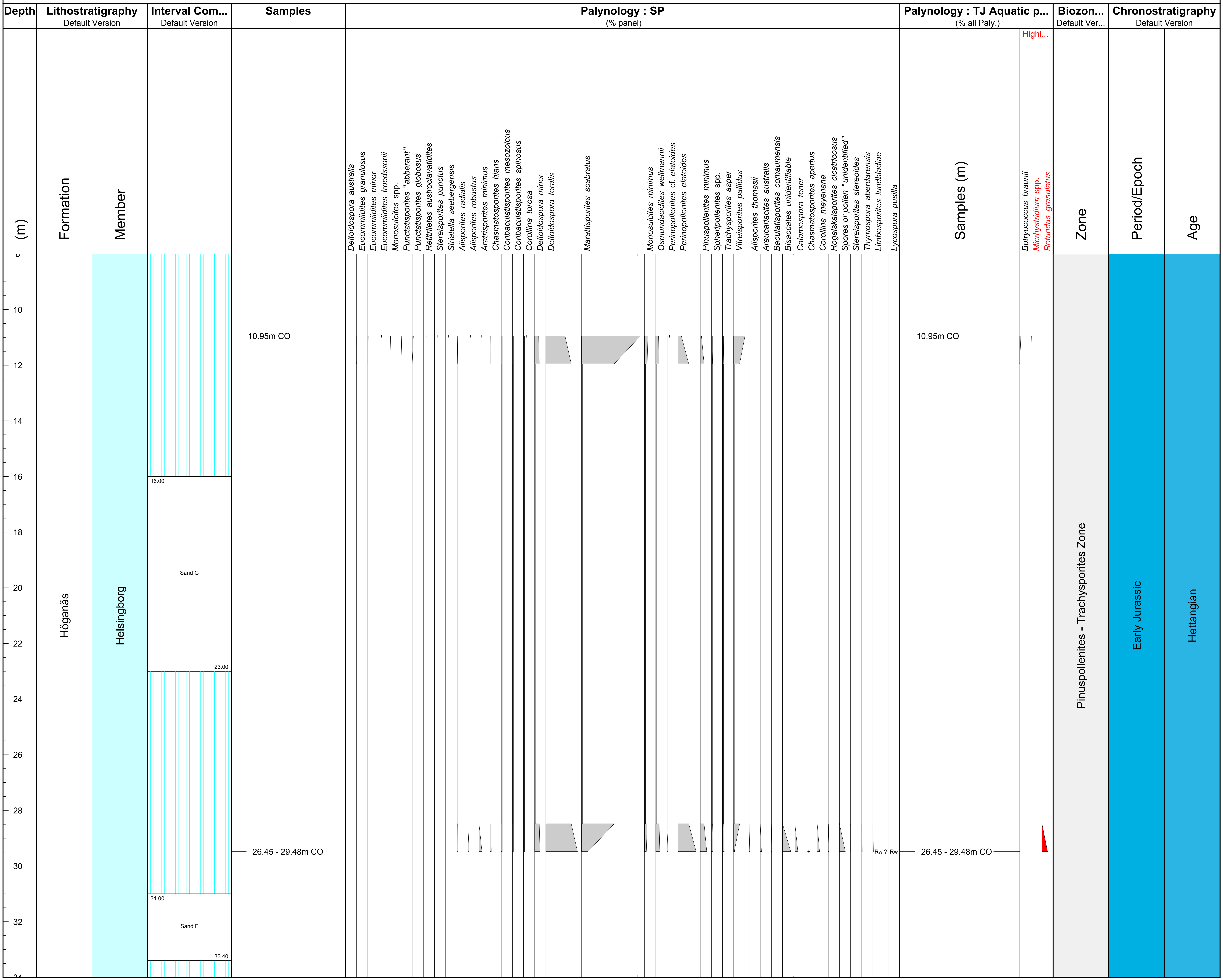
# HBG 09.1.2009



Scale : 1:100

Enclosure 3u

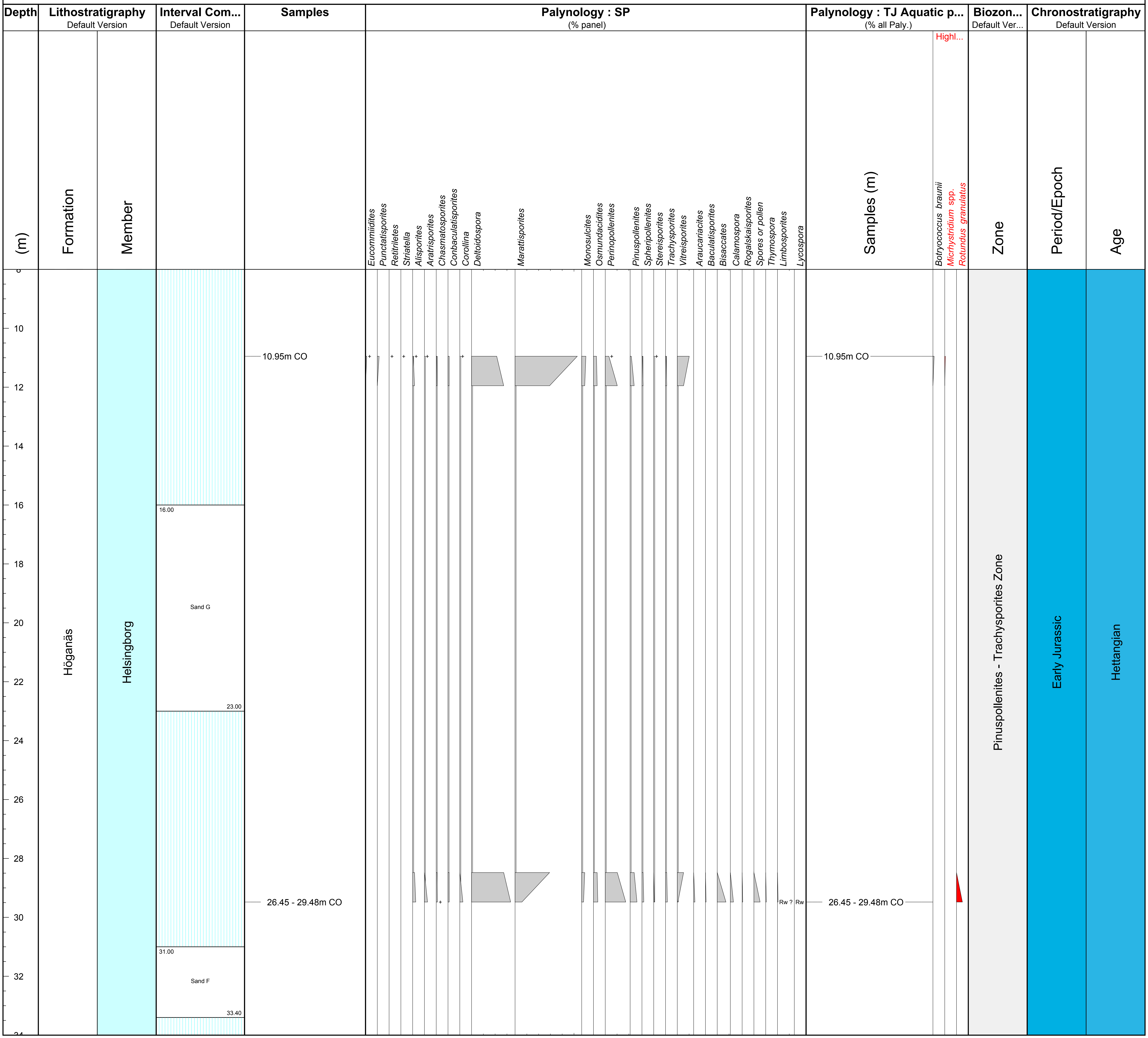
# HBG 09.1.2044



Scale : 1:100

Enclosure 3v

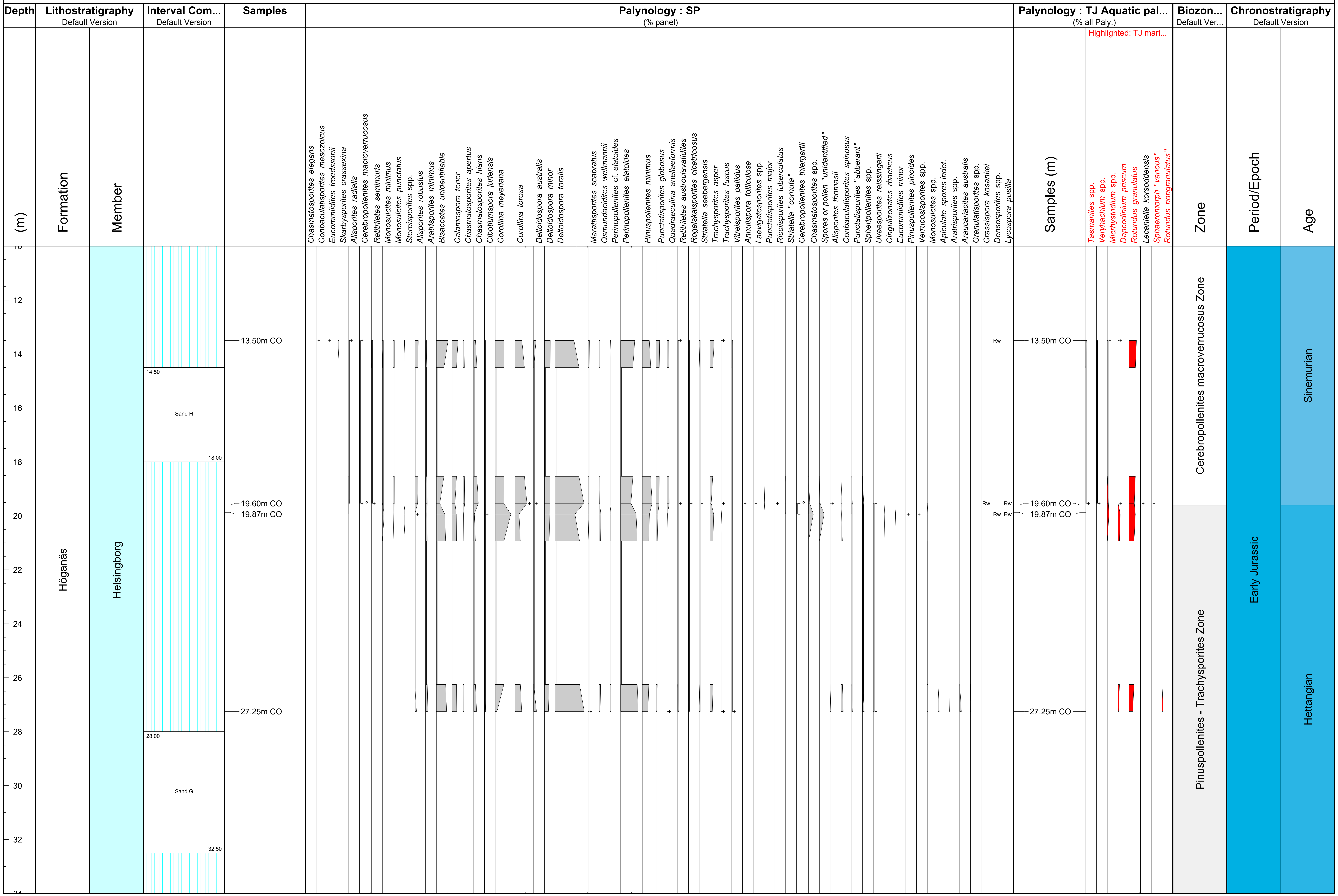
# HBG 09.1.2044



Scale : 1:100

Enclosure 3w

# HBG 09.1.2021



Enclosure 3x

Scale : 1:100

# HBG 09.1.2021