DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2013/20

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Contribution to an evaluation of the geothermal potential

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Preface

This report is prepared by GEUS for Forsyning Helsingør with the objective to assess the geothermal potential of sandstone formations in the Helsingør area. These formations include Lower Cretaceous Unit, Lower Jurassic Unit, the Gassum Formation and the Bunter Sandstone Formation.

GEUS has recently assessed the regional geothermal potential in Denmark at several local areas. This includes a pre-investigation of the need for improving seismic coverage in the Helsingør area in order to assess the geothermal potential (Mathiesen et al., 2005). In addition GEUS has conducted studies of the regional development of the investigated formations (Mathiesen et al., 2009).

This report builds on all available and released data that are relevant for an assessment of the geothermal potential at the three locations of interest as specified by Forsyning Helsingør. The present database includes 2D seismic data, well data, wireline log data, cores, core analysis data and cuttings descriptions. The report contains both a quantitative petrophysical interpretation of the investigated sandstone formations based on well-logs and the existing cores in order to estimate the net-to-gross ratio along with porosity, permeability and transmissivity, and furthermore an interpretation of the existing seismic data in order to map the depth to the formations and to investigate the presence of faults. As no wells are situated in immediate vicinity of the areas of interest the assessment is based on well data from the Karlebo-1/1A, Lavø-1, Margretheholm-1/1A and the Stenlille wells supported by GEUS´ general geological interpretations of the Norwegian-Danish Basin and Fennoscandian Borderzone.

The report includes:

1. An assessment of the potential reservoirs in the Helsingør area based on well data (from Karlebo-1/1A, Lavø-1, Margretheholm-1/1A and the Stenlille wells) and GEUS' regional geological model, focussing primarily on the Gassum and Bunter Sandstone formations as well as the Lower Cretaceous Unit and Lower Jurassic Unit; the latter two units do not have formal lithostratigraphic names yet.
2. A petrophysical evaluation of the Karlebo-1/1A, Lavø-1, Margretheholm-1/1A and the Stenlille-1 well in order to assess the net sand thickness, net-to-gross ratio, reservoir porosity, permeability and transmissivity of the Lower Cretaceous Unit and Lower Jurassic Unit and the Gassum and Bunter Sandstone formations.
3. An interpretation of the existing released seismic data in the greater Helsingør area in order to map the distribution, depth and lateral continuity of the Lower Cretaceous Unit, the Lower Jurassic Unit and the Gassum and Bunter Sandstone formations.

CONTENT

1 Dansk resumé

Det geotermiske potentiale i Helsingør-området er blevet evalueret på baggrund af tilgængelige seismiske data i interesseområdet samt datamateriale fra de nærmeste dybe boringer. Den afsluttende rapport præsenterer en analyse af det geotermiske potentiale i henholdsvis Gassum Formationen og Bunter Sandsten Formationen samt i sandstensforekomsterne i Nedre Kridt og Nedre Jura.

Som udgangspunkt er kendskabet til undergrunden i Helsingør-området begrænset, hvilket skyldes den ringe seismiske dækning og manglen på dybe boringer i området. De nærmeste dybe boringer i det østlige Sjælland, Karlebo-1/1A, Lavø-1, Margretheholm-1/1A, bliver således relevante for vurderingen af det geotermiske potentiale i Helsingør, selvom de står langt fra interesseområdet. De eksisterende seismiske linjer er af meget ringe til moderat kvalitet, men mulighederne for forbindelse (tie) til boringerne er begrænset. Tilstedeværelsen af Trias-lag i Helsingør-området kan således ikke bekræftes direkte via direkte seismiske ties til boringer.

Udover de danske data fra seismik og boringer findes data fra Helsingborg-området, hvor Øvre Trias–Nedre Jura-lag er blottet i kystklinterne og kendes fra en række korte boringer i byen udført i forbindelse med større konstruktionsarbejder. Derudover udførtes i forbindelse med en mulig tunnelforbindelse mellem Helsingør og Helsingborg i 1964 19 boringer, som giver information om Jura–Kridt-lagene i Sundet.

Baseret på den overordnede geologiske viden om det sydlige Sverige og østlige Danmark og ovennævnte spredte data vurderer GEUS, at der findes en Trias-lagpakke på op til en kilometers tykkelse i dybdevinduet ca. 2–3 km i Helsingør-området. Over Trias-lagpakken findes en Jura-lagpakke, som også har et potentiale.

I Trias-lagpakkens nedre del forventes sandsten svarende til Bunter Sandsten Formationen i Margretheholm-boringerne, mens der i den øvre del af lagpakken formentlig findes sandsten svarende til Gassum Formationen i Karlebo-1/1A- og Lavø-1-boringerne, men muligvis tyndere udviklet end i Karlebo-1/1A. Derudover findes formentlig sandsten i Nedre Jura- og Nedre Kridt-lagpakken på et niveau over Gassum Formationen svarende til Lavø-1- og Karlebo-1/1A-boringerne. Det er endvidere sandsynligt, at der findes sandsten over Nedre Kridt-lagpakken i Arnager Grønsand Formationen og den overliggende Lunda Sand, som kendes fra tunnelboringerne og Skåne. Endvidere er der muligvis Mellem–Øvre Jura-sandsten (Haldager Sand Formation) på et niveau mellem Nedre Jura og Nedre Kridt-lagene; Mellem–Øvre Jura kendes fra Skåne og tunnel-boringerne, men findes dog ikke i områderne ved Lavø-1, Karlebo-1/1A eller Margretheholm-1/1A.

Med udgangspunkt i det sparsomme datagrundlag konkluderer GEUS, at undergrunden i Helsingør-området må forventes at indeholde flere niveauer med sandsten af rimelig tykkelse inden for Trias–Jura–Kridt-lagserien. I den dybeste del af lagserien – Bunter Sandsten Formationen – er der en ikke ubetydelig risiko for, at diagenetiske ændringer kan have reduceret porøsitet, permeabilitet og transmissivitet mærkbart.

Endvidere kan det konkluderes, at behovet for indsamling af nye seismiske data er betydeligt; nye data er uomgængelige, hvis kortlægningen af undergrunden og vurderingen af det geotermiske potentiale skal forbedres. Det skønnes, at seismiske data skal indsamles over en strækning på minimum 40 km i fugleflugt, hvilket erfaringsmæssigt øges med ca. 50 %, når linjerne skal udlægges langs veje o.l. Pga. vanskelighederne med at opnå gode ties vil der – selv efter indsamling af nye seismiske data – være en ret stor usikkerhed på dybderne til formationerne, formentlig mere end +/- 10–15 %. Denne usikkerhed elimineres først, når den første boring er foretaget. Formålet med indsamling af nye seismiske data er i høj grad at sikre, at lokale forkastninger ikke bryder reservoirernes kontinuitet; især i den østlige del af byen er der en øget risiko for forkastninger pga. nærheden til den markante Sorgenfrei-Tornquist Zone. Vi forventer endvidere, at nye seismiske data vil kunne forbedre kendskabet til undergrunden ved Helsingør i betydelig grad, hvorved man vil kunne opnå en væsentlig bedre kortlægning af lagene i undergrunden, end tilfældet er i dag. Det bør med indsamling af ny seismik tilstræbes at opnå et godt tie fra interesseområderne til Karlebo-1/1A-boringen, hvorved usikkerheden på dybdeestimaterne vil kunne reduceres.

Grundet det ringe seismiske datagrundlag forekommer muligheden for en differentiering mellem de tre mulige borelokaliteters geotermiske potentiale vanskelig på nuværende tidspunkt. At de tre interesseområder kan have forskelligt geotermisk potentiale er dog absolut muligt. Regionale og lokale trends mht. mulige sandstensintervallers dybde, tykkelse, sortering, kornstørrelse, renhed etc. kan ikke observeres direkte, men udledes ved at sammenholde den overordnede, geologiske udvikling i Østsjælland-Skåne-området med den sparsomme information fra de seismiske data og boringerne. På den baggrund vurderes det, at flere trends, der er vigtige for reservoirernes kvalitet, går i hver sin retning, men det kræver et væsentligt forbedret datagrundlag at vurdere, om der er afgørende geologiske forskelle mellem de tre lokaliteter.

2 Introduction

The general guidelines for suitable geothermal reservoirs in the subsurface fulfilling the requirements for safe, sustainable and economic exploitation of geothermal water are based on the experiences that GEUS in collaboration with DONG Energy previously have established. As a rule of thumb the reservoir interval needs to be reasonably thick, situated at a depth of 800–3000 m and preferably dominated by medium-grained or coarser-grained sandstones. The lower depth limit is selected due to the increasing risk of insufficient porosity and permeability in reservoirs at depths exceeding 3000 m. The upper limit is selected to ensure that formation water has a sufficient temperature. Usually, the temperature of reservoirs shallower than *c.* 800 meters (i.e. 20–30ºC) is too cold for geothermal production.

This report presents the results of an evaluation of the reservoir quality of the potential geothermal reservoirs for three areas of interest in the Helsingør area, i.e. Lower Cretaceous Unit, Lower Jurassic Unit, the Upper Triassic–Lower Jurassic Gassum Formation and the Lower Triassic Bunter Sandstone Formation. The study is building on GEUS' regional geological models and based on a local dataset comprising seismic data, wireline logs, cores etc. supplemented with descriptions of cuttings. Apart from Danish seismic and well data, the Helsingborg area provide some information via Upper Triassic–Lower Jurassic strata exposed in coastal cliffs and a number of shallow wells drilled for construction works. Further, Jurassic and Cretaceous strata are known from several shallow wells performed in 1964 in relation to the planned tunnel for connecting Helsingør and Helsingborg (see Larsen et al., 1968).

Data from four wells are discussed in detail in the study: Karlebo-1/1A (2006), Lavø-1 (1959), Margretheholm-1/1A (2002) and Stenlille-1 (1980) (Fig. 1). The Karlebo-1/1A and Lavø-1 wells were drilled to investigate whether sandstone layers from the Triassic–Lower Jurassic section were hydrocarbon-bearing, but encountered no hydrocarbons with economic potential. The Margretheholm-1/1A was drilled to test the geothermal potential of the Bunter Sandstone Formation. The Stenlille-1 was drilled with the objective to test the Gassum Formation for potential gas-storage in the Stenlille structure.

Information on the geology of the drilled sections and the lithostratigraphic subdivision is available from well completion reports (Christensen, 1981; DAPCO 1959; DAPCO/DGU, 1993; DONG E&P, 2003; Tethys Oil Denmark AB, 2007) and tables presented in Nielsen & Japsen (1991). The seismic interpretation is based on available 2D seismic lines that have been tied as good as possible to well-known lithostratigraphic tops (or picks) at well locations. The available 2D seismic data used in this study are of poor to relatively poor quality, and only offer limited coverage of the areas of interest (Fig. 2).

All wells confirmed the presence of sandstones in the Lower Cretaceous and Lower Jurassic units (Karlebo-1/1A, Lavø-1, Margretheholm-1/1A), the Gassum Formation (Karlebo-1/1A, Lavø-1, Margretheholm-1/1A, Stenlille-1) and in the Bunter Sandstone Formation (Margretheholm-1/1A), proving the existence of potential geothermal reservoirs in the study area (Fig. 2).

Distribution and petrophysical properties of the Lower Jurassic and Lower Cretaceous units is less known compared to the Gassum and Bunter Sandstone Formations, since they probably only exist in the east and north-eastern Sjælland; the assessment of their geothermal potential is therefore more uncertain. The Gassum Formation is located at the deepest level in the Lavø-1 well (2293–2368 m), while the Bunter Sandstone Formation was found at 2385–2684 m in the Margretheholm-1/1A well. The Bunter Sandstone Formation, or formations of similar age, is also known from the Slagelse-1 well and wells in Southern Sweden, but due to the long distance between the wells and the area of interest, these wells were not directly included in this study. The Stenlille-19 well drilled the uppermost part of the Bunter Sandstone Formation and this information is used together with other regional data to constrain the conclusions. In the Helsingør area the burial depth of the Bunter Sandstone Formation may have caused diagenetic effects reducing porosity, permeability and thus transmissivity.

3 Geological background

The Helsingør area is located in the northern part of Höllviken Graben, a downfaulted basin constituting the transition zone between the southeastern part of the Danish Basin and the Sorgenfrei-Tornquist Zone (Fig. 3). To the southwest a series of faults separates the Höllviken Graben and Danish Basin, to the north and northeast the Höllviken Graben is separated from the Sorgenfrei-Tornquist Zone by the Romeleåsen Fault. The intense tectonic evolution of the Sorgenfrei-Tornquist Zone taking place from Paleozoic to recent times may have induced the development of faults in the Höllviken Graben affecting the continuity of potential geothermal reservoirs in the Helsingør area.

At present, the structural history of the Höllviken Graben is poorly known, however an increasing interest in exploiting the geothermal potential in the Øresund area has led to ongoing investigations aiming at improving our understanding of the rather complicated structural framework the graben is part of. Based on well data and seismic data Erlström & Sivhed (2012)) in close cooperation with GEUS discovered that a structural high, the Barsebäck Platform, divides the Höllviken Graben into three units: the Höllviken Halfgraben to the south, the Barsebäck Platform and a northern, unnamed graben. It is worth noting, that the Helsingør area and the Karlebo-1/1A well is situated in the northern graben while the Margretheholm-1/1A well, according to Erlström & Sivhed (2012), is situated on the Barsebäck Platform.

Based on GEUS' general knowledge of the Helsingør area the subsurface is expected to contain a number of sandstone units with geothermal potential. From the top downward the principal units are: Lower Cretaceous Unit, Lower Jurassic Unit, the Gassum Formation and the Bunter Sandstone Formation. A less understood potential may be present in the Lunda Sand, Arnager Greensand Formation and the Middle Jurassic Haldager Sand Formation.

3.1 Lower Cretaceous Unit

In most of the Danish Basin the Lower Cretaceous comprises marine claystones or fine-grained, clayey sandstones with no or very limited geothermal potential. However, in the easternmost Sjælland Lower Cretaceous sandstones of considerable thickness are present, which is likely to provide considerable potential (Mathiesen et al., 2007).

3.2 Middle-Upper Jurassic sandstone (Haldager Sand Formation)

Sandstones of Middle–Upper Jurassic age have not been penetrated in the Sjælland wells, however, they are known from several Scanian wells in the eastern part of the Höllviken Graben and from the tunnel driving between Helsingør and Helsingborg (Larsen et al., 1968). It is thus possible that the Middle–Upper Jurassic sandstone may constitute a potential geothermal reservoir in the Helsingør area (Mathiesen et al. 2007). As this unit is situated above the Gassum and Bunter Sandstone Formations it will be penetrated and evaluated by wells with target in the deeper formations. Further attention is not given to these sandstones in this report.

3.3 Lower Jurassic Unit

In most parts of the Danish Basin the Lower Jurassic Fjerritslev Formation consists almost entirely of claystones. However, in the eastern part of the Danish Basin it is known from the Karlebo-1/1A, Lavø-1 and Margretheholm-1/1A wells that several sandstone layers with geothermal reservoir potential occur interbedded in the Fjerritslev Formation.

3.4 Gassum Formation

The Upper Triassic–Lower Jurassic Gassum Formation has been penetrated by many wells proving that the formation is present in most of the Norwegian-Danish Basin except for significant salt structures and on the high-lying basement blocks of the Ringkøbing-Fyn High (Michelsen et al., 2003; Nielsen, 2003). The formation consists mainly of marine and fluvial sandstones interbedded with marine and lagoonal mudstones, minor siltstones and thin coal beds formed during a period with recurrent sea-level changes. Generally the sandstones are considered to be widespread with relatively good lateral continuity in areas unaffected by faults or salt structures. The formation forms an excellent reservoir in the Stenlille area where it is used for storage of natural gas.

3.5 Bunter Sandstone Formation

The Lower Triassic Bunter Sandstone Formation occurs widespread in the Norwegian-Danish Basin and the North German Basin as shown by several deep wells. The formation accumulated during a period dominated by an arid climate. The sandstones were mainly deposited by ephemeral braided rivers and windblown dunes. Interbedded mudstones and siltstones, occasionally with evaporates, were mainly formed in shallow, ephemeral lakes and sabkhas. Generally, the sandstones are considered to be widespread with relatively good lateral continuity in areas unaffected by faults or salt structures.

4 Assessment of the reservoir quality in the Helsingør area

Forsyning Helsingør has defined three areas of interest (called AOI-1, AOI-2 and AOI-3 in this report) west of Helsingør within the Höllviken Graben (Figs. 1–2). None of these areas are situated in the immediate vicinity of deep wells. The closest well, Karlebo-1/1A, is situated within the Höllviken Graben c. 10 km south of AOI-3. The Lavø-1 well is situated c. 20 km west of AOI-1 and AOI-3 and outside the Höllviken Graben. The Margretheholm-1/1A well is situated c. 30 km south of AOI-3 within the Höllviken Graben.

The evaluation of reservoir quality of the Lower Cretaceous Unit, Lower Jurassic Unit and the Gassum Sandstone Formation is based primarily on wireline logs from the Karlebo-1/1A, Lavø-1 and Margretheholm-1/1A wells, and core analysis data from the Lavø-1 well. There is no direct seismic and well based evidence confirming the presence of the Bunter Sandstone Formation in the Helsingør area. Only the Margretheholm-1/1A well penetrates the Bunter Sandstone Formation, but no seismic tie connects the Margretheholm-1/1A well to the Karlebo-1/1A well or the areas of interest. However, though available seismic data west of Helsingør do not confirm the presence of the Bunter Sandstone Formation, it hints at the presence of a thick sediment package below the Gassum Formation, which could include the Bunter Sandstone Formation. Likewise, a thick sandstone dominated succession is present in the Terne-1 well in the Southern Kattegat area (Nielsen & Japsen, 1991; Michelsen & Nielsen, 1993). Consequently, the evaluation of the reservoir quality of the Bunter Sandstone Formation at Helsingør must be based on well log data etc. that have been acquired in wells located outside the northern part of the Höllviken Graben, i.e. the Margretheholm-1/1A well on the Barsebäck Platform (Erlström & Sivhed, 2012) and the Slagelse-1 well located far to the southeast. In this context GEUS´s general knowledge of the regional geology combined with information on the depositional environment is utilised.

4.1 Database, log quality and petrophysical evaluation

The petrophysical evaluation is based on the wireline logs acquired in the four wells (listed in Table 1) along with relevant information extracted from well completion reports etc. A petrophysical evaluation has been carried out in Karlebo-1/1A, Margretheholm-1/1A and Stenlille-1, using the stratigraphic sub-division of the reservoir units listed in Table 2. A full log suite was not acquired in Lavø-1 and a full-scale modern petrophysical evaluation is, therefore, not possible. In Karlebo-1/1A, the lowermost part of the Gassum Formation was not logged due to technical problems during logging, leading to some uncertainty in determining reservoir parameters.

Table 1: List of raw logs and interpreted log curves for the Karlebo-1/1A, Lavø-1, Margretheholm-1/1A and Stenlille-1 wells

Log name	**Description, application and comments**
GR	Gamma ray log (API). Measuring natural radioactivity
GRpseudo	Re-scaled SP (Spontaneous Potential) log (millivolt, mV)
SP	Spontaneous potential (millivolt, mV). Measuring electric potential
GR_SON	Gamma ray log (run together with the sonic log)
DT/DTCO	Sonic log (microsec/ft). Acoustic log measuring travel time (/velocity)
CALI	Caliper log (inches). Measuring borehole size (diameter)
18F8	Old resistivity log (ohmm); laterolog, spacing 18ft 8 inch.
64IN	Old normal resistivity log (ohmm); spacing 64 inch.
RT_HLRT	'True' resistivity (ohmm). Measuring resistivity
ILD	Deep-reading resistivity log (Induction log) (ohmm)
NPHI	Neutron porosity (fraction). Measuring apparent porosity
RHOB/RHOZ	Density log (g/cc). Measuring bulk density
PERM_log	Log-derived permeability (mD). Interpreted/calculated log curve
PHIE	Log-derived *effective* porosity (fraction). Interpreted/calculated log curve

Table 2: Stratigraphic reservoir units, depth intervals and cored sections

Well	Stratigraphic reservoir unit (GEUS, 2007)	Depth interval [m MD]	Comments on formations and available cores
Karlebo-1/1A	Lower Cretaceous undiff.	1794-1865	No cores were cut. Sandstone reservoir 1840–1864 m MD
	Lower Jurassic Unit	1946-2132	Informal unit defined by GEUS (2007). No cores cut. Sandstone reservoir 1984–2016 m MD
	Gassum Fm	2132-2279	No cores were cut. Top and base Gassum Fm defined by GEUS (2007)
	Bunter Sst. Fm	N/A	The Formation was not drilled.
Lavø-1	Lower Cretaceous undiff	1999-2073	
	Lower Jurassic Unit	2134-2293	Informal unit; defined by GEUS (2007)
	Gassum Fm	2293-2368	Cores are available. Top Gassum Fm revised by GEUS (2007)
	Bunter Sst. Fm	N/A	The Formation was not drilled
Margretheholm-1/1A	Lower Cretaceous undiff	1623-1648	No cores were cut.
	Lower Jurassic Unit	1713-1842	Informal unit defined by GEUS (2007) No cores were cut.
	Gassum Fm	1842-1977	No cores were cut. Top and base Gassum Fm defined by GEUS (2007)
	Bunter Sst. Fm	2385-2684	No cores were cut. Top and base Bunter Sandstone Fm. defined by GEUS (2007)
Stenlille-1	Lower Cretaceous undiff	1200-1247	No cores were cut.
	Lower Jurassic Unit	1368-1507	Informal unit defined by GEUS (2007) Cores are available
	Gassum Fm	1507-1651	Cores are available. Top and base Gassum Fm from Nielsen & Japsen (1991)
	Bunter Sst. Fm	N/A	The Formation was not drilled.

Comments: N/A: No Data; parameters cannot be calculated

4.2 Interpretation of lithology

The lithologies of the drilled well sections are interpreted using raw log data, core samples, description of cuttings and information from well completion reports and mud logs available in the archives of GEUS. A lithology column, bounded by the gamma-ray and sonic logs, is generated for each well (Figs. 5–11). In Enclosures 1–4 a more precise lithologic description is given for potential sandstone sections in each well based on descriptions of core and cuttings samples.

4.3 Evaluation of shale volume and porosity

The shale volume is calculated from the gamma-ray (GR) log using well-specific shale parameters, i.e. background radiation (GR_clean) and the GR response for pure clay (GR_clay); see Table 3. The shale volume (V_{shale}) is then calculated as follows:

$$\mathbf{V_{shale} = (GR - GR\_clean)/(GR\_clay - GR\_clean)}$$

The background radiation related to the sandstone beds may vary due to the presence of radioactive minerals other than clay/shale, e.g. heavy minerals or mica. A gamma-ray log was not acquired in the Lavø-1 well and therefore, the shale volume was estimated from the SP log.

Table 3: Response parameters for the gamma-ray (GR) log (SP log in Lavø-1)

Well	Reservoir Interval	GR_clean / SP_clean	GR_clay /SP_clay
Karlebo-1/1A	Lower Cretaceous	75	163
	Lower Jurassic	75	163
	Gassum	75	225
Lavø-1	All reservoir units	37	180
Margretheholm-1/1A	Lower Cretaceous	58	140
	Lower Jurassic	58	140
	Gassum	58	140
	Bunter Sst. Fm.	87 – 100	150 – 250
Stenlille-1	Lower Cretaceous	22	122
	Lower Jurassic	22	122
	Gassum	12 – 25	122

In the Margretheholm-1/1A and Stenlille-1, the porosity variation is determined from a shale-corrected density log. A density log was not acquired in the Karlebo-1/1A well and instead, the porosity was estimated from the sonic (DT) log. The input parameters used for the porosity evaluation are listed in Table 4; note that a log-porosity cannot be derived for the Gassum Formation in Lavø-1 owing to the absence of adequate logs.

Table 4: Response parameters for the density log (RHOB/RHOZ) and the sonic log (DT)

Well	Interval/Formation	Matrix	Shale
Karlebo-1/1A	All reservoir units	DT_matrix: 55.5 µs/ft	DT_shale: 100 µs/ft
Lavø-1	All reservoir units	N/A	N/A
Margretheholm-1/1A	All reservoir units	RHO_matrix: 2.65 g/cc	RHO_shale: 2.4 g/cc
Stenlille-1	All reservoir units	RHO_matrix: 2.65 g/cc	RHO_shale: 2.4 g/cc

4.4 Permeability

Technically, it is not possible to log the permeability in a well; however, a permeability estimate can be derived from a porosity-permeability relationship set up on the basis of core data. It is important to realize that this porosity-permeability relationship is based on gas permeability and not liquid permeability as only a limited amount of permeability data is available for the latter. These two types of permeabilities differ in size; the gas permeability is approx. twice the size of the liquid permeability.

GEUS has established such a porosity-permeability relation using a regional dataset, which encompasses data from several Danish onshore wells including core analysis data from the Stenlille-1 well plus a few measurements on sidewall cores from the Margretheholm-2 well (Fig. 4, table 5). This non-linear relationship, which is shown by a solid curve in the figure, has been used for assessing the average gas permeability, acknowledging that a deviation from this trend line obviously exists on a local scale. The log-derived gas permeability (PERM_log) is calculated from the log porosity (PHIE) using a mathematical expression: PERM_log = $a \cdot (PHIE)^b$, where a and b are constants. Consequently the log-derived gas permeability is not a direct measurement, but a calculated estimate. The permeability curve is derived from the log porosity curve using the following mathematical expression:

$$\mathbf{PERM\_log = 196449 \cdot (PHIE)^{4.3762}}$$

where PHIE is a fraction and the log-derived gas permeability (PERM_log) is in mD.

Table 5 Core analysis data of Lower Jurassic, Gassum Formation and Triassic undifferentiated sidewall cores from the Margretheholm-2 well. Data extracted from Springer (2003)

Sandstone Unit / Fm	**SWC no.**	**Depth** (m)	**Lithology**	**Porosity** (%)	**Gas permeability** (mD)
Lower Jurassic	13	1835.0	Sandstone	25.55	206.8
Gassum	12	1847.7	Sandstone	23.87	824.0
	11	1893.5	Sandstone	27.71	1111.4
	10	1962.1	Sandstone	23.26	148.6
Triassic undiff.	9	2004.0	Sandstone	26.43	431.9
	8	2041.0	Sandstone	27.04	716.9
	6	2061.0	Sandstone	20.86	96.8
	5	2090.0	Sandstone	23.41	74.1
	4	2134.0	Sandstone	29.09	1027.0

4.5 Results of petrophysical evaluation and reservoir parameters

The log data and the cutting descriptions from all four study wells have been used in the lithological interpretation and the petrophysical evaluation. The results of the petrophysical evaluations are given in the tables 6–9 below. The tabulation encompasses: formation thickness, accumulated net sand thickness, net-to-gross ratio and average net porosity, estimated transmissivity and – based on the latter – a calculated average permeability. Prior to calculating reservoir parameters, cut-offs were applied to examine the sensitivity to variations in porosity (PHIE) and shale content (V_{shale}).

A 30% V_{shale} cut-off was applied to exclude claystones and shaly sandstones with a poor reservoir potential. Furthermore, various porosity cut-offs were also applied to qualify and characterise the potential reservoir sandstones. This analysis results in an assessment of the accumulated net sand thickness based on a certain minimum porosity. Four sets of minimum porosities have been considered: 0%, 10%, 15 and 20% as listed in Tables 6–9 (the 0% scenario corresponds to no porosity cut-off). The net-to-gross ratio, which is abbreviated as N/G in the tables, is calculated for each formation separately, and N/G equals ‘net sand thickness’ divided by ‘total formation thickness’.

The transmissivity for each formation/stratigraphical unit is calculated from log-based permeability estimates (Tables 6–9). During logging, petrophysical measurements are performed for every ½ ft., and each of these intervals is evaluated as a reservoir or non-reservoir interval by applying shale cut-off and porosity cut-off. For each reservoir interval a permeability and corresponding transmissivity is estimated. Adding up all reservoir intervals provides the accumulated net sand thickness; and adding up the transmissivity values for the reservoir intervals provides the formation/stratigraphical unit transmissivity.

The average gas permeability for each formation/stratigraphical unit (Tables 6–9) is calculated by dividing the transmissivity by the net sand thickness (a similar approach to estimate average permeability, i.e. the weighted-average method, is described in Ahmed, 2001).

The Lower Cretaceous Unit (Tables 6–9) contains sandstones with good reservoir properties in Karlebo-1/1A, especially in the lower part of the unit (Fig. 5). The unit can be correlated to Lavø-1, Stenlille-1 and Margretheholm-1/1A (Fig. 12). The reservoir parameters for Lavø-1 cannot be derived, however, due to an incomplete old log suite.

The Lower Jurassic Unit contains - in all the studied wells - a number of porous sandstone layers imbedded in mudstones, and the accumulated net sand thicknesses for the Lower Jurassic sandstone layers are listed in Tables 6–9. In Karlebo-1/1A the most pronounced layer (1984–2016 m MD) is about 30 m thick with a porosity in the range of 15–25% (Fig. 5).

The petrophysical evaluation of the Gassum Formation sandstones indicates relatively high average porosities. When considering the Gassum Formation in Margretheholm-1/1A and Stenlille-1, average porosities exceed 20%, whereas the porosity level for the Gassum Formation is slightly lower in the Karlebo-1/1A well. However, the lowermost part of the Gassum Formation was not logged due to technical problems in the well (Table 6). The log porosity and gas permeability estimates for the Margretheholm-1/1A well corresponds well with the core analysis data performed on Lower Jurassic, Gassum Formation and Triassic undifferentiated sidewall cores from the Margretheholm-2 well (compare Table 5 with Tables 6–9 and Fig. 9).

Compared to the Gassum Formation the Bunter Sandstone Formation shows lower average porosities in the Margretheholm-1/1A well. However, it should be noted that the Bunter Sandstone Formation has only been encountered in this well. Prior to water production a communication test was conducted between the Margretheholm-1/1A and -2 wells in the Bunter Sandstone reservoir. A *fluid* transmissivity of 11.7 Dm was calculated by DONG E&P (2004); and for comparison, GEUS has calculated a *gas* transmissivity of 19.9 Dm. Based on this transmissivity and the assumption that the net sand thickness is 28 m DONG calculated a liquid permeability of approximately 420 mD for the reservoir sandstone. This fluid permeability is somewhat higher than the log-derived gas permeability calculated by GEUS (333 mD at 15% porosity cut-off).

The accumulated net sand thickness for each stratigraphic reservoir unit varies considerably within the study area. With respect to the Gassum Formation, for example, the accumulated net sand thickness varies from more than 26 m (as observed in the logged section – more sand is probably present in the un-logged section; see Fig. 6 and Tables 6–9) in Karlebo-1/1A to more than 100 m in Stenlille-1, when applying a 15% porosity cut-off (Table 8). For all instances, it is recommended to consider a certain minimum porosity (e.g. 10, 15 or 20%) prior to assessing the net sand thickness. Furthermore, it should be kept in mind that the well data are point data and that the distance between the area of interest and the nearest wells is large (Fig. 1). Thus, the reservoir parameters in coming Helsingør wells may deviate from those listed in the Tables 6–9.

Table 6 (Scenario #1: Reservoir parameters for net sand: Shale cut-off applied, no porosity cut-off applied) Net sand defined as sandstone with **< 30% shale, and porosity > 0%**.

Well	**Sandstone Unit / Fm**	**Formation thickness** (m)	**Net sand thickness** (m)	**N/G**	**Avg. porosity** (%)	**Gas trans-missivity** (Dm)	**Estimated gas perm.** (mD)
Karlebo-1/1A	L. Cretaceous	71	28.8	0.41	18.8	5.6	194
	L. Jurassic	186	80.6	0.43	16.3	10.9	135
	Gassum	147 (97*)	>40	(0.42)*	(16.7)*	5.6*	(139)*
Lavø-1	L. Cretaceous	74	No porosity log		N/A	N/A	N/A
	L. Jurassic	159	No porosity log		N/A	N/A	N/A
	Gassum	75	No porosity log		N/A	N/A	N/A
Margretheholm-1/1A	L. Cretaceous	25	Poor logs		N/A	N/A	N/A
	L. Jurassic	129	30.0	0.23	24.7	10.2	340
	Gassum	135	63.1	0.47	20.4	16.6	263
	Bunter Sst.	299 (255”)	>149	(0.58)”	(12.2)”	20.7”	(139)”
Stenlille-1	L. Cretaceous	47	7.5	0.16	20.3	3.2	427
	L. Jurassic	139	20.3	0.15	23.8	9.4	463
	Gassum	144	106.1	0.74	27.0	95.2	661

Comments: N/A: Parameter cannot be calculated, *and”: Parameters related to logged section only

Table 7 (Scenario #2: Reservoir parameters for net sand: Shale cut-off applied, porosity cut-off applied) Net sand defined as sandstone with **< 30% shale, and porosity >10%**.

Well	**Sandstone Unit / Fm**	**Formation thickness** (m)	**Net sand thickness** (m)	**N/G**	**Avg. porosity** (%)	**Gas trans-missivity** (Dm)	**Estimated gas perm.** (mD)
Karlebo-1/1A	L. Cretaceous	71	28.4	0.40	18.9	5.6	197
	L. Jurassic	186	66.3	0.36	18.1	10.8	163
	Gassum	147 (97*)	>37	(0.38)*	(17.6)*	5.6*	(151)*
Lavø-1	All units	---	N/A	N/A	N/A	N/A	N/A
Margretheholm-1/1A	L. Cretaceous	25	Poor logs		N/A	N/A	N/A
	L. Jurassic	129	28.3	0.22	24.7	10.2	360
	Gassum	135	61.1	0.45	20.8	16.6	272
	Bunter Sst.	299 (255”)	>91	(0.36)”	(17.6)”	20.7”	(227)”
Stenlille-1	L. Cretaceous	47	7.2	0.15	20.8	3.2	444
	L. Jurassic	139	20.1	0.14	23.9	9.4	467
	Gassum	144	105.9	0.66	27.0	95.0	897

Comments: N/A: Parameter cannot be calculated, *and”: Parameters related to logged section only

Table 8 (Scenario #3: Reservoir parameters for net sand: Shale cut-off applied, porosity cut-off applied) Net sand defined as sandstone with **< 30% shale, and porosity > 15%**.

Well	**Sandstone Unit / Fm**	**Formation thickness** (m)	**Net sand thickness** (m)	**N/G**	**Avg. porosity** (%)	**Gas trans-missivity** (Dm)	**Estimated gas perm.** (mD)
Karlebo-1/1A	L. Cretaceous	71	22.2	0.31	20.7	5.4	243
	L. Jurassic	186	47.5	0.26	20.3	10.4	219
	Gassum	147 (97*)	>26	(0.27)*	(19.5)*	5.3*	(202)*
Lavø-1	All units	---	N/A	N/A	N/A	N/A	N/A
Margretheholm-1/1A	L. Cretaceous	25	Poor logs		N/A	N/A	N/A
	L. Jurassic	129	26.7	0.21	24.8	10.1	378
	Gassum	135	55.2	0.41	21.8	16.7	303
	Bunter Sst.	299 (255”)	>60	(0.23)”	(20.2)”	19.9”	(333)”
Stenlille-1	L. Cretaceous	47	5.2	0.11	23.4	3.2	615
	L. Jurassic	139	19.5	0.14	24.2	9.3	477
	Gassum	144	105.9	0.74	27.1	95.1	898

Comments: N/A: Parameter cannot be calculated, *and”: Parameters related to logged section only

Table 9 (Scenario #4: Reservoir parameters for net sand: Shale cut-off applied, porosity cut-off applied)
Net sand defined as sandstone with **< 30% shale, and porosity > 20%**.

Well	**Sandstone Unit / Fm**	**Formation thickness** (m)	**Net sand thickness** (m)	**N/G**	**Avg. porosity** (%)	**Gas trans-missivity** (Dm)	**Estimated gas perm.** (mD)
Karlebo-1/1A	L. Cretaceous	71	13.0	0.18	23.1	4.5	346
	L. Jurassic	186	25.5	0.14	22.8	8.2	322
	Gassum	147 (97*)	>16	(0.16)*	(20.7)*	4.2*	(271)*
Lavø-1	All units	---	N/A	N/A	N/A	N/A	N/A
Margretheholm-1/1A	L. Cretaceous	25	Poor logs		N/A	N/A	N/A
	L. Jurassic	129	19.4	0.15	25.2	9.4	485
	Gassum	135	36.1	0.27	24.0	14.8	410
	Bunter Sst.	299 (255")	>28	(0.11)"	(23.3)"	16.8"	(596)"
Stenlille-1	L. Cretaceous	47	3.2	0.07	26.6	3.0	938
	L. Jurassic	139	16.2	0.12	25.6	9.0	556
	Gassum	144	102.6	0.71	27.4	94.1	917

Comments: N/A: Parameter cannot be calculated, *and": Parameters related to logged section only

The results of the petrophysical evaluations are presented as log plot displays in Figures 5–11. Each plot includes a lithology column bounded by the gamma-ray (GR) and sonic (DT) logs, if available. The interpreted porosity (PHIE) is shown to the right (blue colour fill, scale 0–40%), and the log-derived gas permeability (PERM_log) is plotted by a red curve to the left of the porosity curve (a logarithmic scale is used for the permeability, 10000–0 mD). If available, resistivity (e.g. 18F8 and 64IN), neutron (NPHI) and density (RHOB or RHOZ) logs are also plotted.

5 The distribution and lateral continuity of the potential reservoirs

The seismic data available around and near the Helsingør area is very limited (see Figs. 1 and 2). Seismic data located west of the area have been acquired as parts of the previous hydrocarbon exploration activities, and the newest seismic data, located to the south was acquired in the initial phase of the Margretheholm Geothermal Plant project in 2006.

The interpreted seismic data have been used in order to evaluate the presence and variations of the reservoirs, reservoir depth, changes in reservoir thickness and the occurrence of significant faults which may inflict on lateral continuity of the potential reservoirs. The seismic interpretation is accompanied by relevant seismic sections illustrating the geological conditions close to the wells (Figs. 13–20) and a very generalized model of the study area (Fig. 21). The seismic sections are mainly located west of the study area while a few old, poor to moderate quality sections pass in the vicinity of the three areas of interest.

Except for the high quality seismic data acquired in the Margretheholm-area most of the seismic data close to the study area were produced before 1970 and in the mid-seventies to the mid-eighties. The quality of these older seismic data is mostly poor to moderate (Table 10).

Table 10 An assessment of the quality of selected seismic lines used in this study is given below:

Line No. (see also Fig. 1+2)	**Quality assessment**
hgs001	Very Good
AO85I-100 [1)]	Moderate-good
AO85I-110 [1)]	Moderate-good
AO85I-120 [1)]	Moderate-good
AO84I-140 [1)]	Moderate-good
AO84I-150	Moderate-good
AO85I-101	Moderate-good
72/009	Moderate
72/010	Moderate
72/010A	Moderate
72/011	Moderate
72/013	Moderate
R29 [1)]	Poor
R30 [1)]	Poor
R31 [1)]	Poor
R32	Poor
R34	Poor
R35	Poor
R37	Poor
R38	Poor

[1)] Seismic section shown in this report

Several of the seismic lines had to be scanned and digitised from the original paper format. Afterward the scanned and digitized lines were loaded onto a seismic workstation. This procedure insures that the new interpretation can be integrated with earlier mapping efforts. This integration of all existing interpretations result in maps that are more consistent on a local scale compared to the earlier more regional maps, and the new maps prepared for this study are therefore more correct to use for evaluation of the continuity and the depth to the reservoirs in the study area.

5.1 Seismic interpretation and mapping (TWT maps)

Due to the lack of sufficient good-quality data near the areas of interest, it is difficult to map the location of major faults and to predict possible lateral changes in the lithology in the area of interest. Further, the moderate-poor quality of the seismic sections and the lack of a well tie reduce the number of identifiable horizons. In addition, tracing of seismic horizons is impeded by the lack of seismic details and further by the large fault running approx. between the Karlebo-1/1A and Lavø-1 wells (Fig. 3) which induces seismic noise in the vicinity of the fault. Five horizons are interpreted (see Figs. 14–20):

- Base Upper Cretaceous (i.e. Base Chalk = BUC)
- Near Top Gassum Formation
- Near Base Gassum Formation in parts of the study area
- Near Top Bunter Sandstone Formation
- Near Base Triassic

The identification and definition of these five horizons is based on an integration of stratigraphic well picks of the Karlebo-1/1A well with seismic reflections as interpreted from the seismic data. The subsequent seismic mapping comprises three horizons: Base Upper Cretaceous (BUC), Near Top Gassum Formation and Near Top Bunter Sandstone Formation (see also Enclosures 5, 6 and 7). As no high resolution seismic data is available in the area of interest, it is not possible to identify individual sandstone horizons with geothermal potential.

Accurate depth-conversion from time (seismic two-way travel time) to depth of the structural maps and the seismic sections is difficult due to limited velocity data. Available data only exist from the Margretheholm-1/1A and -2, Karlebo-1/1A and Stenlille wells. The Stenlille wells are situated too far from the areas of interest to be relevant (Fig. 1), and the Karlebo-1/1A well being located in a fault zone may show both structural and stratigraphical characteristics different from the areas of interest (Fig. 1). All maps are thus depth-converted based on a time-depth relationship (Depth = 1.888 * TWT – 79.752) derived from data from the Margretheholm-1/1A well and seismic velocities available from the seismic survey acquired in 2006 during the Margretheholm Geothermal Plant project (Fig. 22).

The three structural depth-converted maps are included in Enclosures 5-7. Due to lack of seismic data in the areas of interest total thickness maps of the Gassum and Bunter Sandstone Formations have not been constructed at this initial stage. Acquisition and interpretation of new seismic data is needed before more reliable thickness maps can be constructed. All maps presented herein are based on the current seismic interpretation and generated from 500x500 m grids; all maps are expected to have an uncertainty of more than ± 10–15%, increasing with depth.

It is important to remember that formations like the Gassum and Bunter Sandstone formations do not constitute individual and homogenous reservoirs; the formation is a stratigraphic interval composed of a mixture of alternating lithologies which is likely to include sandstone sections with reservoir potential. However, the seismic resolution in the study area is not good enough to define and correlate individual sandstone layers within the seismic sequences.

5.2 The Gassum Formation

The interpreted structural depth map (Enclosure 6) shows that in the greater Helsingør area the depth to the horizon named near Top Gassum Formation varies between approx. 1600 and 2800 m, being deepest towards the northwest. In the areas of interest the depth varies between approx. 2400 and 2600 m.

To the west of the areas of interest it is possible to assess the thickness of the Gassum Formation. In the seismic lines AO85I-100, AO85I-110, AO85I-120 and AO84I-140 (Figs. 14–17) the top and base of the Gassum Formation can be traced from the Norwegian-Danish Basin across the large fault and into the Höllviken Graben, providing relatively reliable information about formation thickness (Fig. 2). In general, the Gassum Formation is thicker in the Höllviken Graben compared to the Norwegian-Danish Basin with TWT thicknesses of 100–200 msec corresponding to real thicknesses of 190–380 m. In the seismic line AO84I-140 a slight thinning of the Gassum Formation towards the east is indicated.

5.3 The Bunter Sandstone Formation

Only three wells in Sjælland penetrate the Bunter Sandstone Formation: Margretheholm-1/1A, Margretheholm-2 and Slagelse-1 (Fig. 3). As the Slagelse-1 well is located in the Norwegian-Danish Basin far from the areas of interest and Sjælland in general lacks good quality seismic data, it is hard to produce a reliable tie from Slagelse-1 to the study area. Thus, the Margretheholm wells are the only source of information with respect to the Bunter Sandstone Formation. In addition, no direct seismic tie connects the

Margretheholm wells to the areas of interest (see seismic coverage in Figs. 1–2). There are, however, reasons to believe that the Bunter Sandstone Formation is present: 1) Both the Margretheholm wells and the areas of interest are situated in the deeper part of Höllviken Graben and expectedly share more or less the same geological history; 2) A thick sediment package (up to 4 km) is present beneath the Base Gassum Formation horizon and most likely includes the Bunter Sandstone Formation (Figs. 14–20). With no well tie, the seismic horizon interpreted as the near Top Bunter Sandstone Formation in Figs. 14–20 represents a qualified guess; the presence of the Bunter Sandstone Formation in the Helsingør area still remains unconfirmed.

The interpreted structural depth map (Enclosure 7) shows that the depth to the near Top Bunter Sandstone Formation varies between approx. 1600 and 4200 m in the greater Helsingør area, also being deepest towards the west. In the areas of interest the depth expectedly varies between approx. 2800 and 3200 m.

5.4 The three areas of interest

Based on the inadequate data available for this study it is not advisable to attempt to recommend one of the three areas of interest over the two others. However, possible trends can be extracted from the seismic data, and from considering more regional sedimentological aspects of the Øresund area. These trends are explained below and summarized in Table 11.

The Gassum Formation may be buried slightly deeper in the northern part of the study area (fig. 19), and is thus likely to contain a warmer geothermal reservoir. As mentioned before the burial depth of the Bunter Sandstone Formation is assumed to be around 3 km increasing the risk of diagenetic alterations considerably. There seems to be very little difference in the burial depth in the study area with a possible shallowing effect towards the northeast (fig. 19 and Encl. 7). Overall, the Triassic sediment package becomes thicker towards the fault running approx. between the Lavø-1 and Karlebo-1/1A wells (Figs. 13–18).

Generally, the paleo-coastline of the depositional basin, during deposition of the Triassic, Jurassic and Lower Cretaceous sediments, was located north and northeast of the Helsingør area with an assumed generally NW-SE trend. From a sedimentological point of view sediments closer to the coastline would expectedly be coarser-grained with more sandstones (higher net-to-gross ratios), which are poorly sorted. Moving away from the coastline into the deeper basin towards the southwest the sorting would probably improve, but the grain size on the other hand would be reduced and fewer sandstones would be present (lower net-to-gross ratio).

As the Sorgenfrei-Tornquist Zone (Fig. 3), running through the entire Øresund area is associated with pronounced faulting, fewer faults would be expected when moving in a westerly direction.

Table 11 Estimated reservoir parameters for the three areas of interest. The depths are based on grid values extracted from the depth structure maps (Enclosures 5–7); depth variations between the three areas of interest are within the uncertainty range. Note that the listed depths represent depths to reflectors near the formation tops – the actual depths to the individual sandstone horizons and units remain unknown. All listed depth and thickness values are approximate and expected to have an uncertainty of more than ± 10–15%, increasing with depth.

Reservoir parameter	**Area of interest 1**	**Area of interest 2**	**Area of interest 3**
Depth to near Top Gassum	2504	2498	2455
Thickness of Gassum Formation	130	140	150
Depth to near Top Bunter	3006	3077	3069
Grain size (relative)	Coarser	Finer	Finer
Net-to-gross ratio (relative)	Higher	Lower	Lower
Sorting (relative)	Poorer	Better	Better
Risk of faults (relative)	Higher	Higher	Lower

6 Temperature assessment

As the existing Danish onshore subsurface temperature database is limited and contains values from wells measured at different depths and at different times, estimated geothermal gradients are fairly uncertain. The database contains somewhat odd values, which are considered to be caused by measurement errors, poor corrections or local geological features e.g. salt structures, limiting the available number of reliable data points even further.

A low geothermal gradient often corresponds to positive structural basement elements, while high values are found in deep sedimentary basins. Therefore, an elongated zone of minimum gradients is found over the Ringkøbing-Fyn High, while maximum values are found in the North Sea area. Considering the onshore area, the gradient varies from 28ºC/km to less than 20ºC/km, and the temperature data have previously been evaluated by Balling et al. (1992, 1994). The wells with temperature data located in the vicinity of the study area are listed in Table 12 (Balling et al., 1994):

Table 12. Temperature data from Sjælland and Höllviken Graben areas

$Temp_{BHT}$	$Temp_{csm}$	$Temp_{Test}$	Top_m b.GL	Base_m b. GL	Well
	51,0		2439,0		Lavø-1
	97,0		2979,0		Slagelse-1
	44,0		322,0		Stenlille-1
	50,0		1495,0		Stenlille-1
	53,0		1405,0		Stenlille-1
	56,0		1558,0		Stenlille-1
52,7			2100,0		Karlebo-1
57,0			2000,0		Margretheholm-1
62,0			2486,0		Margretheholm-2
		73,0	2486,0		Margretheholm-1, Test
		62,0	2264,0		Margretheholm-2, Test

The $Temp_{BHT}$ value represents the bottom hole temperature, while the $Temp_{csm}$ value is a modelled value based on the “cylindrical source method” (see Balling et al., 1994).

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 8ºC. In Fig. 23 the slightly cooler temperature prognosis is compared to a regional gradient of ~28ºC/km.

No data exists near the Helsingør locations, the Lavø-1 well being the nearest data value. However, this value seems to be low compared to the other temperature data and is considered to be an outlier (Fig. 23).

Thus, assuming a depth to the middle of the Gassum Formation (2400-2600 m) of 2500 m, the formation temperature at this depth can be estimated to ~70ºC with an uncertainty of ±10%, using the Höllviken Graben gradient (Fig. 23). Likewise, a possible temperature of ~80ºC ±10% is expected in the Bunter Sandstone Formation (2800-3200 m) assuming a depth of 2900 m.

7 Conclusions and recommendations

The preliminary assessment of the geothermal potential in the Helsingør area is based on GEUS´s general knowledge of the geological development of the Danish subsurface in combination with the evaluation and interpretation of the existing datasets comprising from the seismic surveys located nearest to the areas of interest and data from four deep wells drilled on Sjælland. It should be stressed that the Helsingør area is situated in a zone of great tectonic complexity with limited seismic coverage and no wells nearby; the knowledge of the subsurface is therefore limited. The conclusions mentioned below are based on wells situated at a considerable distance from the area of interest which have been tied to the area of interest with available poor quality seismic data. Accepting the restricted conditions, the following conclusions can be made:

1. The Lower Cretaceous and Lower Jurassic units along with the Gassum Formation and the Bunter Sandstone Formation are expected to be present in the areas of interest. For most of these units and formations the depth is estimated to be within the economic prospective 800–3000 m depth interval in the investigated area, but the Bunter Sandstone Formation may be so deep that diagenetic processes have reduced the permeabilities considerably.

2. Based on the regional knowledge from the eastern part of the Höllviken Graben and Scania it is possible that the area of interest contains potential sandstone reservoirs other than those known from the Karlebo-1/1A, Lavø-1, Stenlille-1 and Margretheholm-1/1A wells. The extra potential units are the Lunda Sand, Arnager Greensand Formation and the Haldager Sand Formation.

3. The Lower Cretaceous Unit can be correlated between Karlebo-1/1A, Lavø-1, Stenlille-1 and Margretheholm-1. The petrophysical evaluation shows that the Lower Cretaceous Unit has a substantial net sand thickness in the Karlebo-1A of about 30 in case no porosity cut-off is applied.

4. The petrophysical evaluation of the Lower Jurassic Unit shows that the interval consists of a number of porous sandstone layers imbedded in mudstones. The Lower Jurassic Unit can be correlated between Karlebo-1/1A, Lavø-1, Stenlille-1 and Margretheholm-1. In e.g. Karlebo-1A the most pronounced layer (1984–2016 m MD) is about 30 m thick and the porosity is within the range of 15–25%.

5. The distribution and petrophysical properties of the Lower Cretaceous and Lower Jurassic units are less known compared to the Gassum and Bunter Sandstone Formations, since they probably only exist in the east and north-eastern Sjælland. The assessment of their geothermal potential is therefore more uncertain, but both units are situated at a shallower depth than the Gassum and Bunter Sandstone Formations, and drilling to either the Gassum or Bunter Sandstone level will pass through the units and a more detailed evaluation of their potential can thus be made in connection with testing of the deeper situated sandstone layers.

6. Both the Gassum and the Bunter Sandstone Formations contain sandstone layers with a net sand thickness that may be suitable for geothermal energy exploitation. The accumulated net sand thickness for each stratigraphic reservoir unit varies considerably within the study area. With respect to the Gassum Formation, for example, the accumulated net sand thickness varies from more than 26

m (in the logged section – more sand is probably present in the un-logged section; see Fig. 6 and Tables 6–9) in Karlebo-1A to more than 100 m in Stenlille-1, when applying a 15% porosity cut-off. However, it should be noted that the well data represent point data and that the distance between the area of interest and the nearest wells is large (Figs. 1 and 2). Thus, the specific reservoir parameters valid for the Helsingør area may deviate from those given here.

7. Evaluation of the sandstones in the Gassum Formation indicates relatively high average porosities. When considering the Gassum Formation in Margretheholm-1 and Stenlille-1, average porosities exceed 20%, whereas the porosity level for the Gassum Formation is slightly lower in the Karlebo-1A well. The lowermost part of the Gassum Formation was not logged in this well and a detailed evaluation based on log data cannot be performed.

8. The Bunter Sandstone Formation is only known from the Margretheholm-1, where a full modern log suite is available from the upper 255 m of the formation. The lack of log data from the lower 44 m of the formation prevents detailed evaluation of this part. Evaluation of the upper 255 m of the Bunter Sandstone Formation indicates that the average porosities of the sandstones are generally lower compared to the Gassum Formation.

9. Due to poor seismic data the presence of the Bunter Sandstone Formation reservoir cannot be verified directly in the Helsingør area. However, the same seismic data indicate a thick undifferentiated Triassic section in the Helsingør area which expectedly will include the Bunter Sandstone Formation. This potential reservoir may be buried so deeply that diagenesis has reduced its geothermal potential.

10. Due to poor seismic data the top of the Lower Cretaceous and Lower Jurassic sandstone has not been mapped. However, in the Karlebo-1/1A well the two tops occur 338 m and 186 m above the top of the Gassum Formation. If the thickness of the Top Gassum to the top Lower Cretaceous succession in the Helsingør area is identical to the thickness in the Karlebo-1/1A well the expected depth to the top of the Lower Cretaceous and Lower Jurassic sandstone will be approx. 2150 m and 2300 m. As these depths are estimates based on the combination of the depth to a seismic reflector (near Top Gassum) and an assumed succession thickness, the depths are subject to considerable uncertainty.

11. Based on the seismic interpretation and mapping combined with the assessment of the reservoir quality in the available well-sections, the depths to the near Top Gassum Formation in the areas of interest varies between approx. 2400 and 2600 m, being deepest towards the northwest. The depth to the near Top Bunter Sandstone Formation varies between approx. 2800 and 3200 m, being deepest towards the west.

12. Assuming a depth to the middle of the Gassum Formation of 2500 m, the formation temperature at this depth can be estimated to ~70ºC with an uncertainty of ±10%. Likewise, a possible temperature of ~80ºC ±10% is expected in the Bunter Sandstone Formation assuming a depth of 2900 m.

13. The lack of seismic data in the Helsingør area is crucial. Acquisition of new seismic data is crucial in order to: 1) identify the location and extent of possible faults; 2) better estimate the depth and thickness of the potential reservoirs; 3) better constrain the presence of the Bunter Sandstone Formation; 4) may help to describe possible variations in thickness and distribution of internal lithological changes.

14. Acquisition of new seismic data is needed before a differentiation between the three areas of interest can be performed with respect to their geothermal potential.

8 A stepwise general procedure for maturation of an area with geothermal potential

The data from the Danish subsurface have shown that large areas are suitable for geothermal exploitation. If a given area, a geothermal prospect or a local urban area is selected for possible exploitation of the subsurface geothermal energy, the following elements should be considered stepwise to minimize the exploration risks that are related to the geological uncertainties regarding the composition and the structures of the subsurface:

1) **Preliminary geological model.** Establishment of a preliminary geological model based on existing local data (to the extent they exist) combined with GEUS´s regional geological models.

1a) If non-released seismic data exists in or near the study area, it is recommended that the geothermal license holder investigate if access to the data can be obtained in order to strengthen the seismic mapping.

2) **Seismic Acquisition**. If the preliminary geological model is satisfying and predicts that the geothermal potential is sufficient for utilization, the next step will be to acquire a sufficient amount of new seismic data. Based on the integrated dataset comprising the previous and the new data, a new and updated detailed seismic mapping of the local area shall be carried out in order to investigate in more detail the reservoir continuity, presence of faults and, if the data resolution allows it, mapping of possible lateral and vertical variations in lithology. An updated geological model based on step 1 and 2 is then constructed.

3) **Preliminary Reservoir simulation**. If the updated geological model based on the previous and new data set predicts that potential reservoirs exist in the study area, a preliminary flow simulation of their production properties should be carried out. This will calculate the amount of water that may be exploited from the assumed reservoir(s).

4) **Well prognosis**. If the updated geological model and the reservoir simulation are satisfactory with respect to the presence of one or more reservoirs with high-quality sandstones and a sufficient geothermal potential, distance to faults etc., the next step should be to establish a proper drilling prognosis for a geothermal exploration well including depths, thickness, net-to-gross ratios and formation geochemistry.

5) **Exploration well**. If the exploration well encounters suitable reservoir(s) as prognosed, pumping tests should be conducted to clarify if enough warm water can be produced from the potential reservoir sandstones.

6) **Evaluation of exploration well**. The encountered stratigraphy should be evaluated with focus toward the reservoirs, and their quality should be assessed from log-evaluation and interpretation of test results. The results are compared with the geological model, well prognosis and the reservoir model; if necessary, the local geological model and the reservoir model is updated and adjusted. On this basis it is evaluated if the geothermal potential is satisfactory for a continuation of the project toward a geothermal plant.

7) **Detailed reservoir model**. If the project continues, a detailed reservoir model based on all available and relevant data should be established.

8) **Updating of the regional model**. All the new data is integrated and evaluated and GEUS´s regional models are adjusted, if needed, in order strengthening future evaluations.

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10 Figures

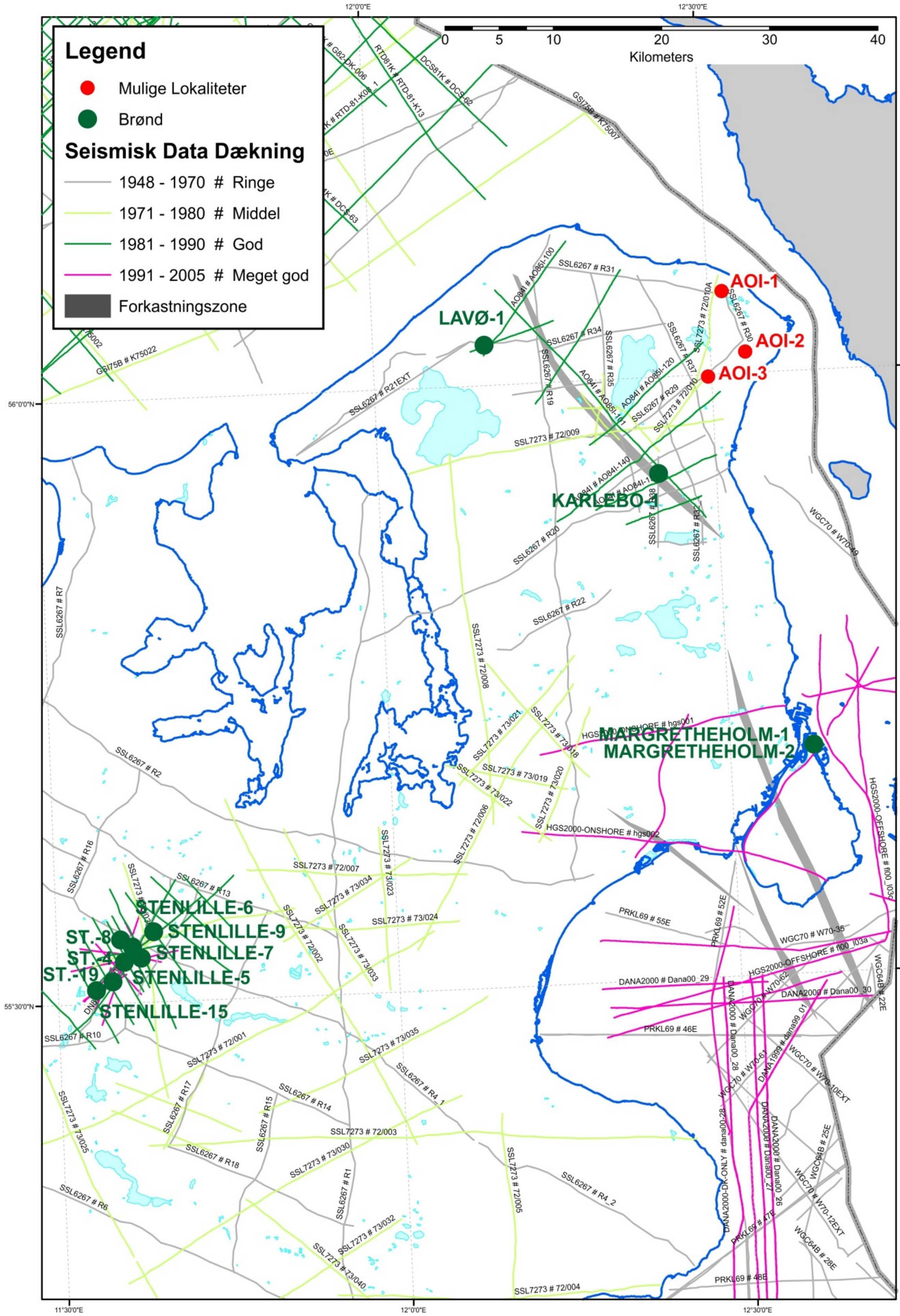


Fig. 1: Map of Sjælland showing seismic data coverage, well locations and areas of interest (AOI). The quality estimation of the seismic lines is based on age; the actual quality of single lines may deviate.

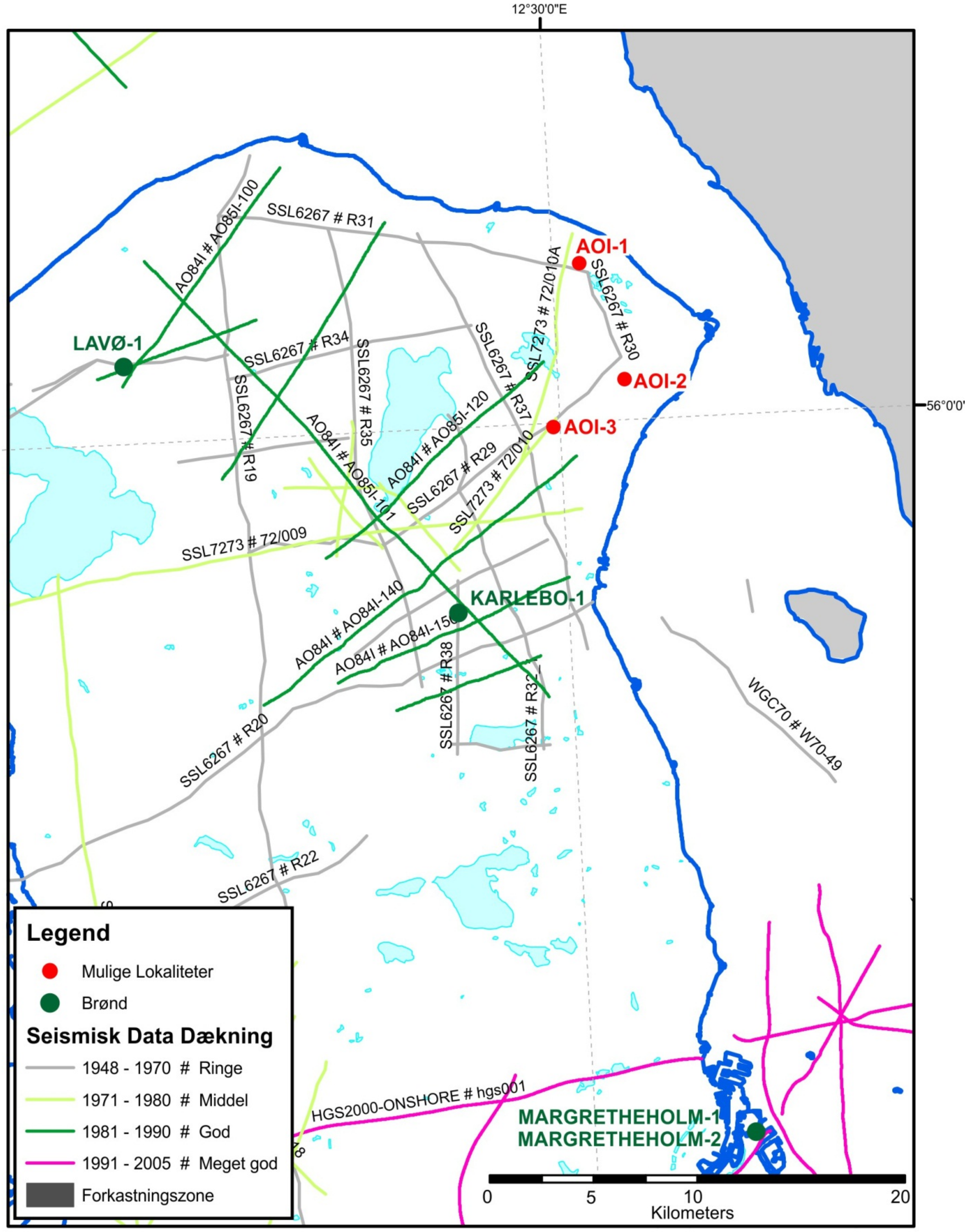


Fig. 2: Map of the greater Helsingør area illustrating the seismic data coverage; the quality estimation of the seismic lines is based on age; the actual quality of single lines may deviate. The locations of the Karlebo-1/1A, Lavø-1 and Margretheholm-1/1A and -2 wells used in this study are also indicated, while the location of the Stenlille-1 well is further to the southeast. The three areas of interest (AOI) are denoted with red dots.

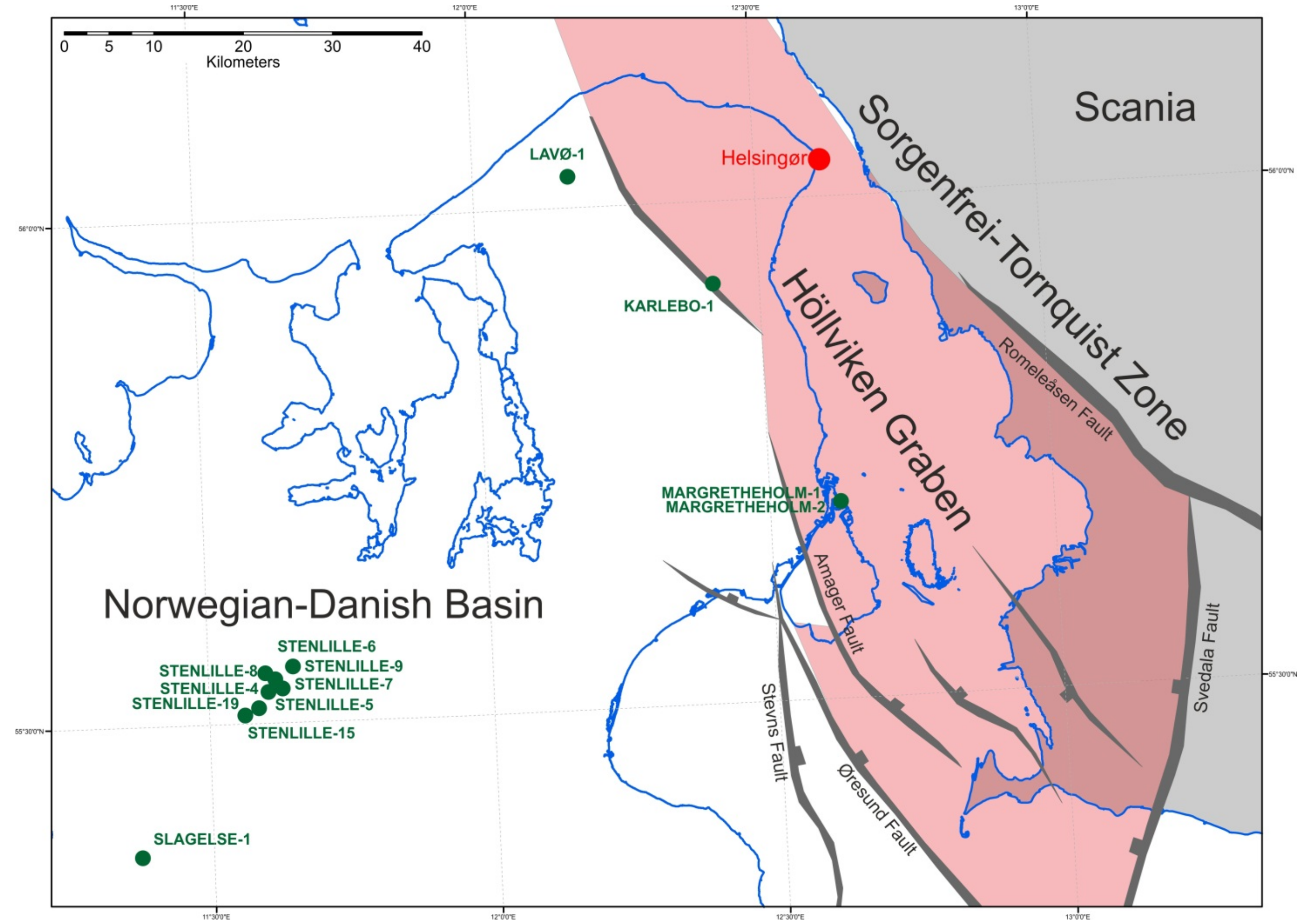


Fig. 3: Map showing major structural elements in the East Sjælland-West Scania area. Note the location of the downfaulted Höllviken Graben between the Norwegian-Danish Basin and the Sorgenfrei-Tornquist Zone and how the graben is bounded by faults. The Karlebo-1/1A and Margretheholm-1/1A wells are situated within the Höllviken Graben and expectedly provide the best well data for describing the subsurface of the Helsingør area.

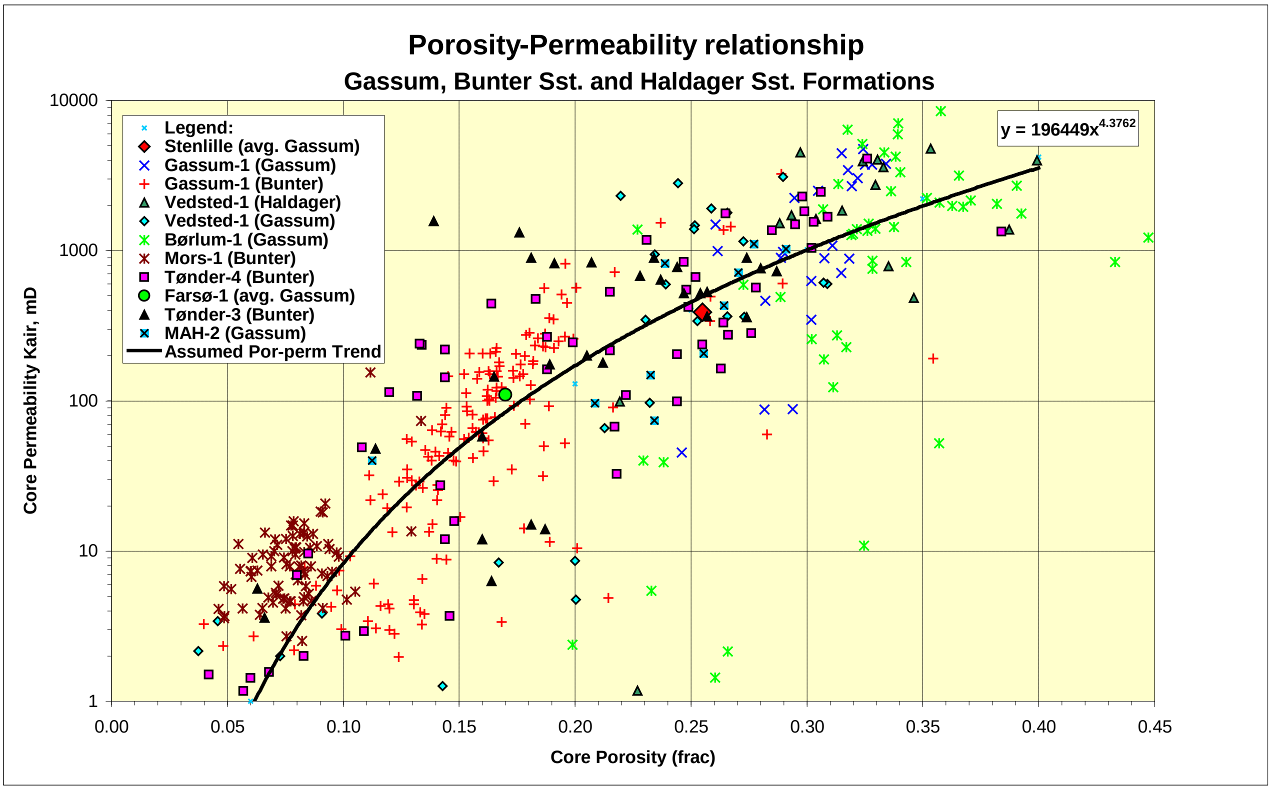


Fig. 4: Generalised relation between porosity and permeability for sandstones based on conventional core analysis data from selected Danish onshore wells in the Danish Basin. The underlying database includes core data from the Bunter Sandstone, Gassum and Haldager Sand formations. Note that the core permeability data are gas/air permeabilities.

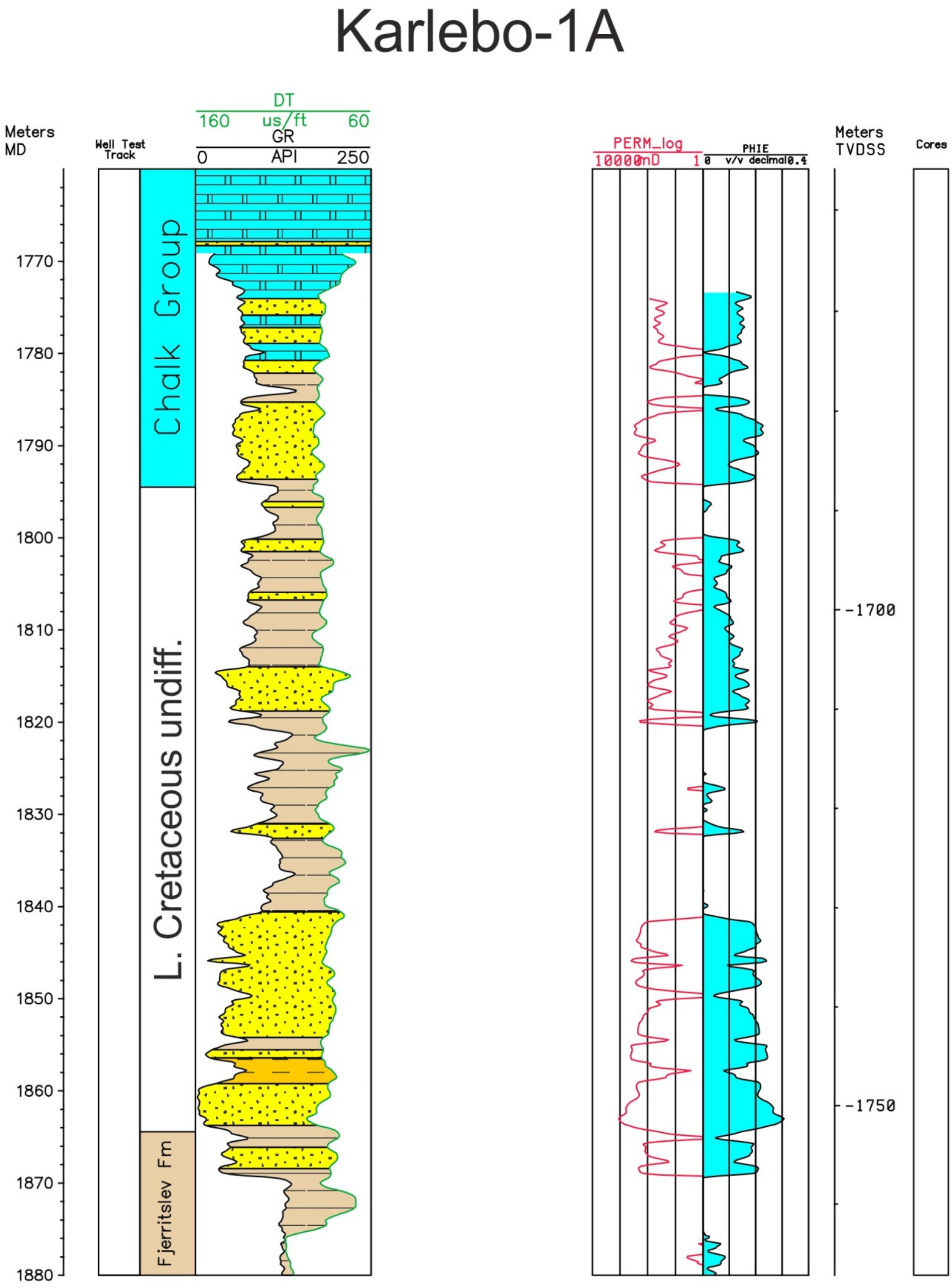


Fig. 5: Petrophysical evaluation of the Lower Cretaceous Unit in the Karlebo-1A well, including a lithological interpretation. The lithology column is bounded by the gamma-ray (GR) and sonic (DT) logs. The porosity determination (PHIE) is highlighted in blue colour fill, and the permeability estimate is plotted left of the porosity curve (PERM_log, in red). Colour code for lithology: Yellow: sandstone, brown: shale, orange: silt, blue: chalk. Abbreviations are explained in Table 1.

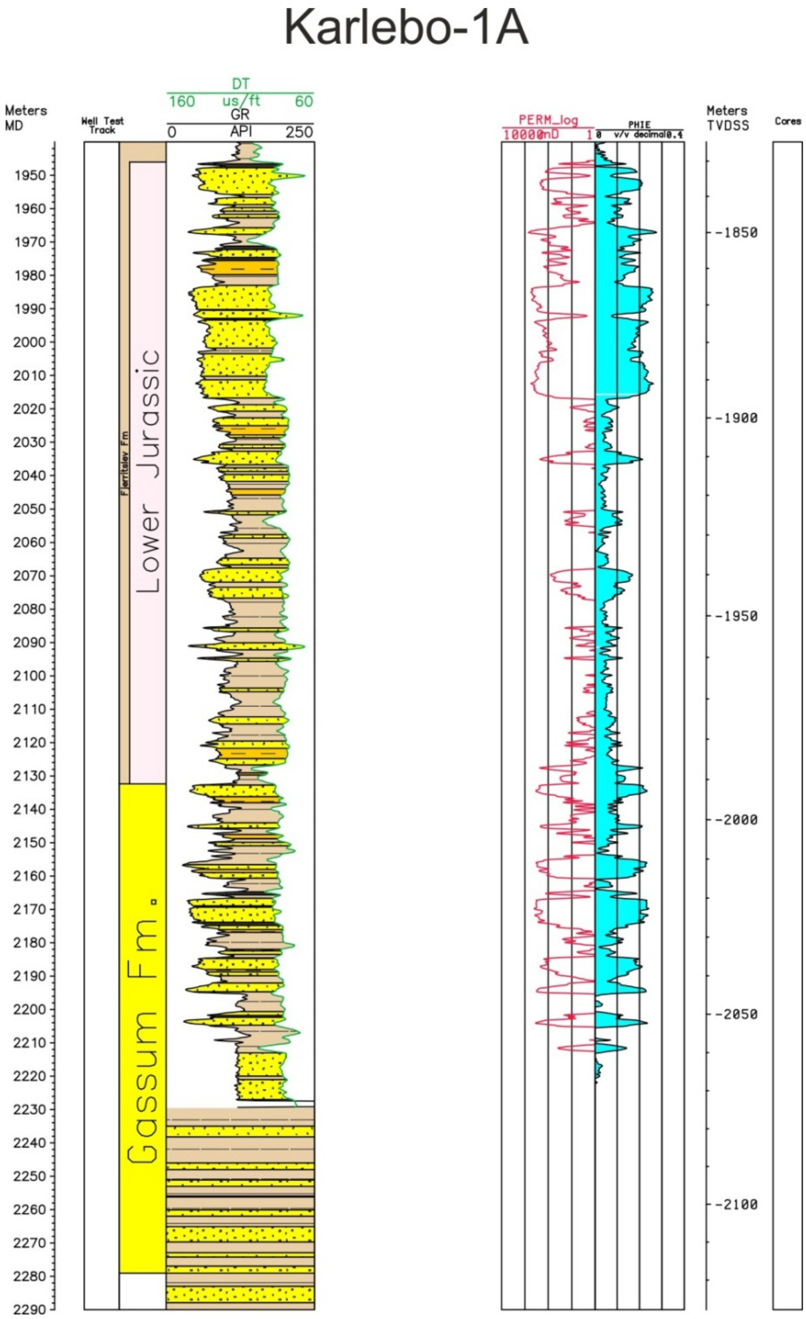


Fig. 6: Petrophysical evaluation of the Gassum Formation and the Lower Jurassic Unit in the Karlebo-1A well, including a lithological interpretation. The Gassum Formation is not fully logged; the base of the formation is defined based on cutting samples; also, the lithological description of the unlogged section is based on cutting samples. The lithology column is bounded by the gamma-ray (GR) and sonic (DT) logs. The porosity determination (PHIE) is highlighted in blue colour fill, and the permeability estimate is plotted left of the porosity curve (PERM_log, in red). Colour code for lithology: Yellow: sandstone, brown: shale, orange: silt, black: thin coal beds or coal debris. In the Karlebo-1A, Lavø-1 and Margretheholm-1A wells the "Lower Jurassic" is used as an informal acronym for a lower Jurassic succession containing sandstones and mudstones. Abbreviations are explained in Table 1.

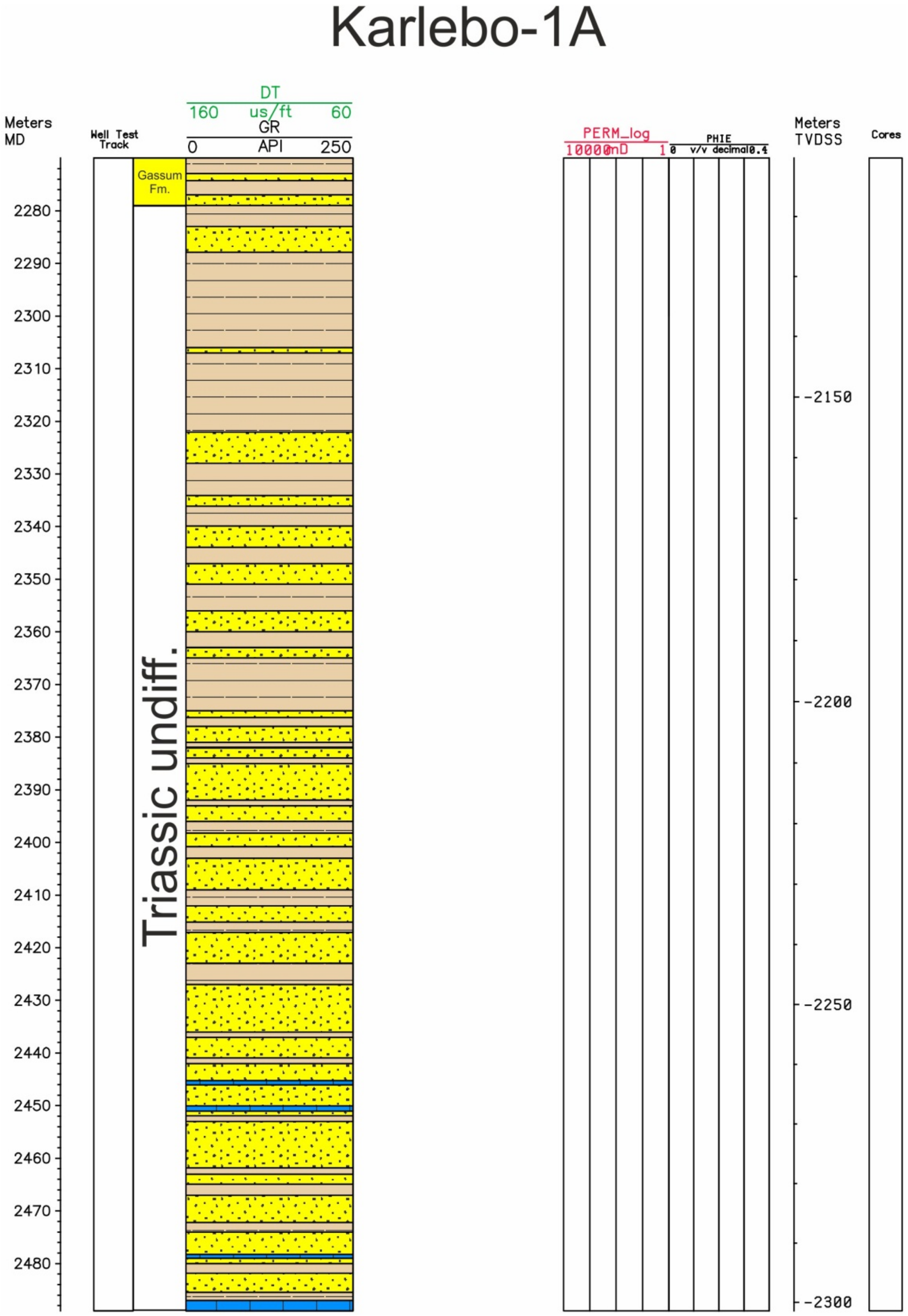


Fig. 7: Petrophysical evaluation of the Triassic undefined unit in the Karlebo-1A well, including a lithological interpretation based on cutting samples. The Triassic undefined unit is not logged; the top of the unit is defined based on cutting samples. Colour code for lithology: Yellow: sandstone, brown: shale, blue: chalk. Abbreviations are explained in Table 1.

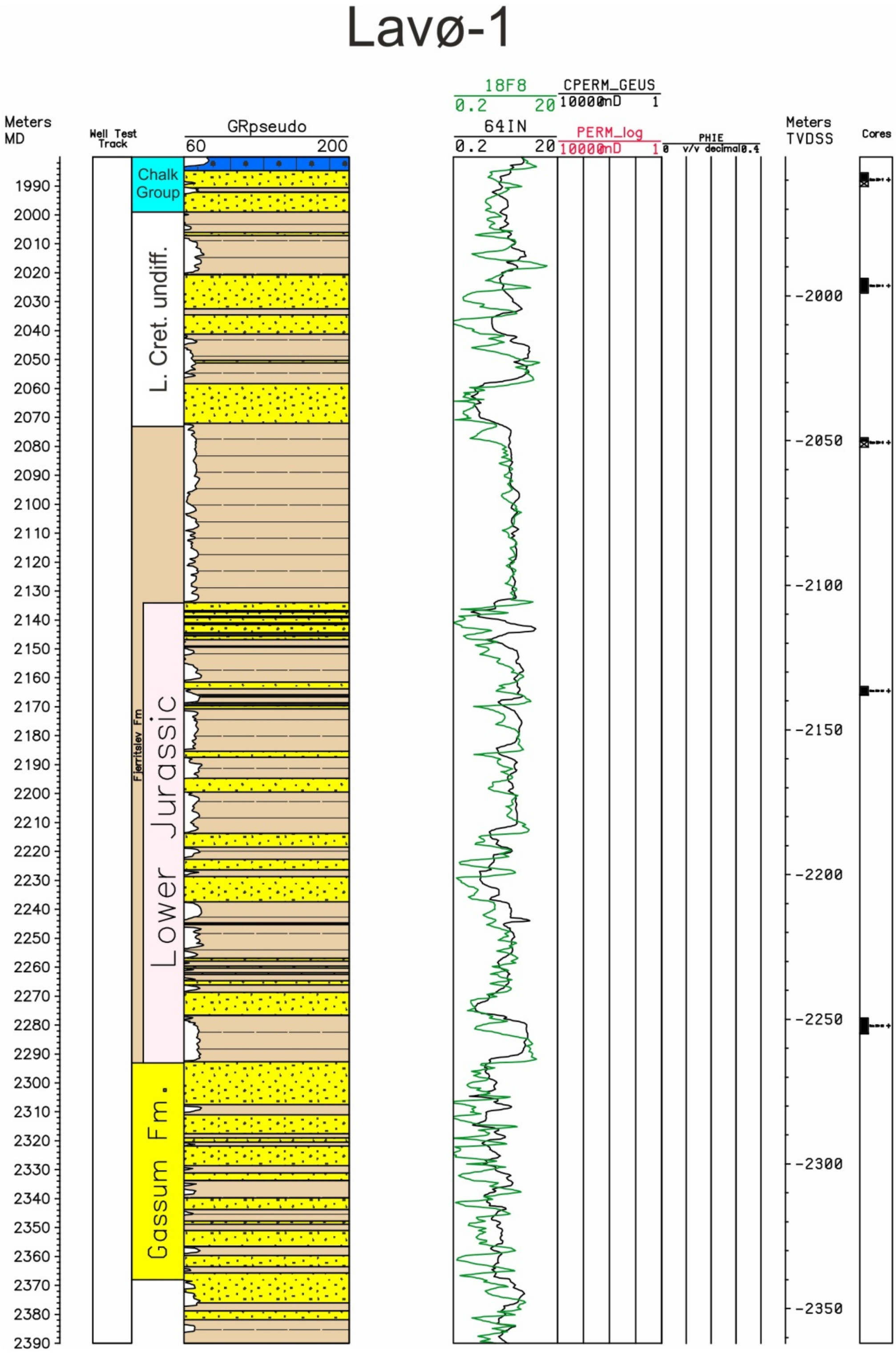


Fig. 8: Lithological interpretation of the Gassum Formation, the Lower Jurassic Unit and the Lower Cretaceous Unit in the Lavø-1 well. The lithology column is bounded by a re-scaled SP log. A porosity evaluation is not possible due to incomplete log set. Cored intervals indicated by black bars. Colour code for lithology: Yellow: sandstone, brown: shale, blue: chalk, black: thin coal beds or coal debris. Abbreviations are explained in Table 1.

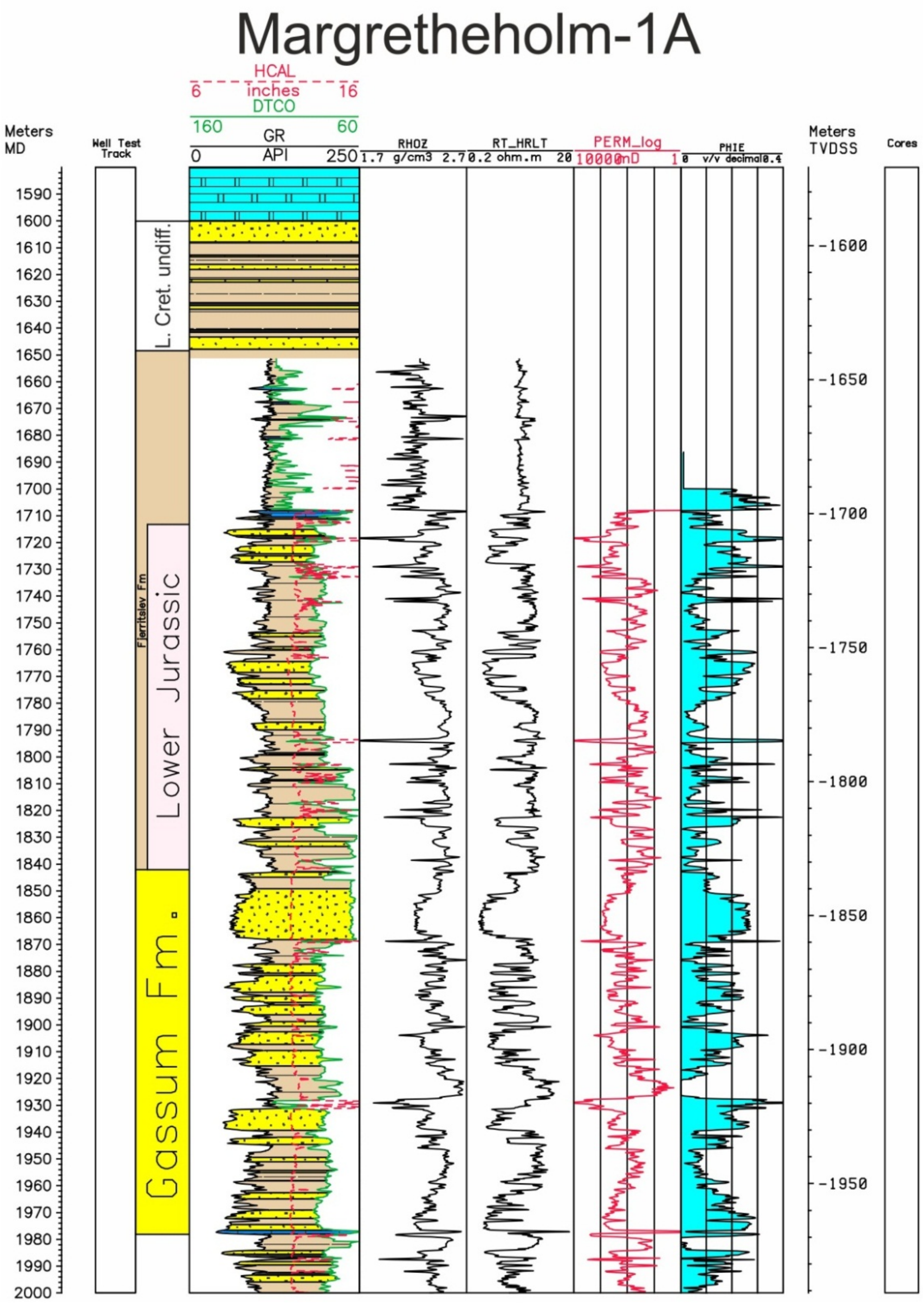


Fig. 9: Petrophysical evaluation of the Gassum Formation and the Lower Jurassic Unit in the Margretheholm-1A well, including a lithological interpretation. Only a lithological interpretation based on cuttings description of the Lower Cretaceous Unit is possible as no log data exist in this section. The lithology column is bounded by the gamma-ray (GR) and sonic (DTCO) logs. The porosity determination (PHIE) is highlighted in blue colour fill, and the permeability estimate is plotted left of the porosity curve (PERM_log, in red). Colour code for lithology: Yellow: sandstone, brown: Shale, blue: chalk.

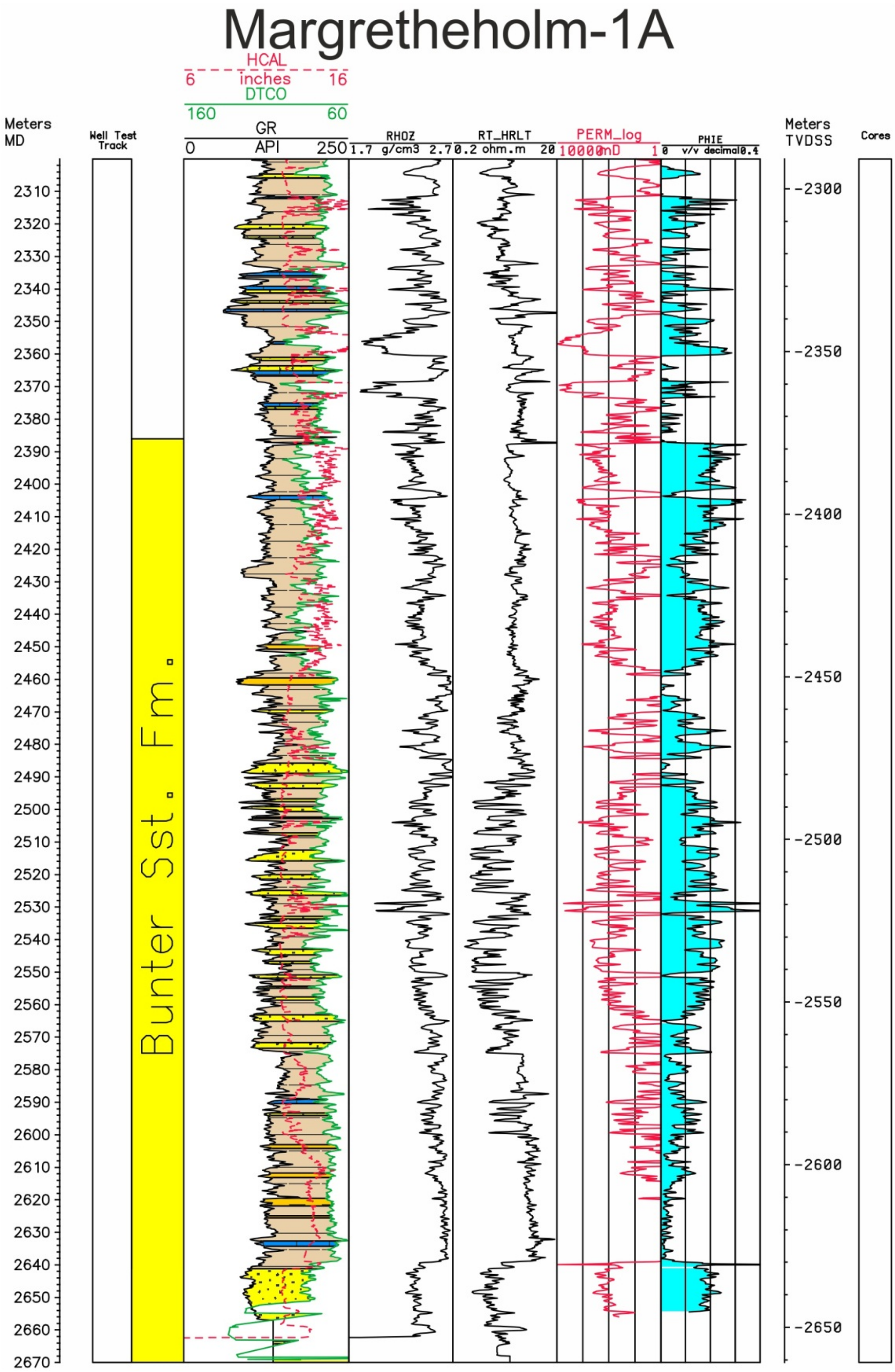


Fig. 10: Petrophysical evaluation of the Bunter Sandstone Formation in the Margretheholm-1A well, including a lithological interpretation. The lithology column is bounded by the gamma-ray (GR) and sonic (DTCO) logs. The porosity determination (PHIE) is highlighted in blue colour fill, and the permeability estimate is plotted left of the porosity curve (PERM_log, in red). Colour code for lithology: Yellow: sandstone, brown: Shale, orange: silt, blue: limestone.

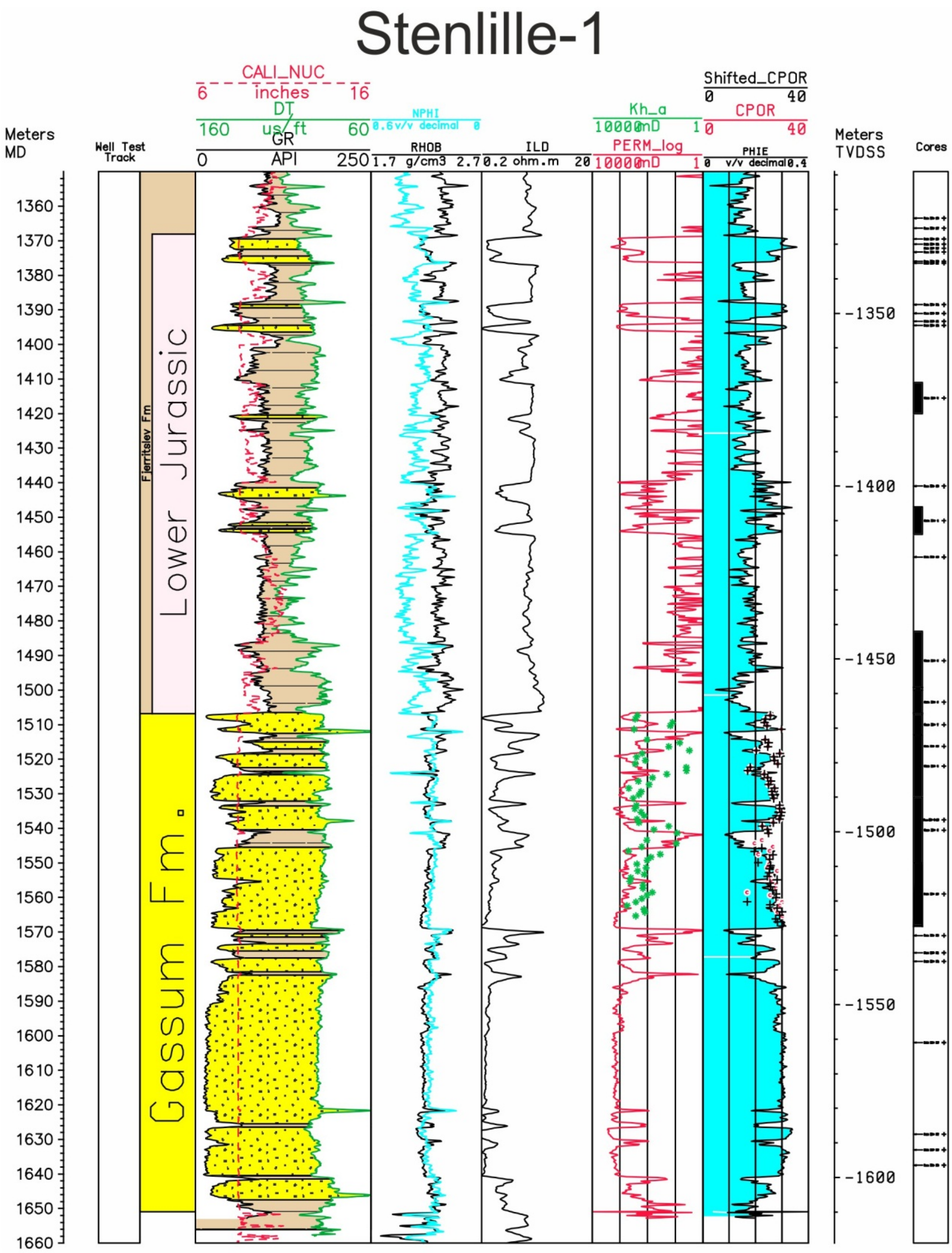


Fig. 11: Petrophysical evaluation of the Gassum Formation and the Lower Jurassic Unit in the Stenlille-1 well, including a lithological interpretation. The lithology column is bounded by the gamma-ray (GR) and sonic (DTCO) logs. The porosity determination (PHIE) is highlighted in blue colour fill, and the permeability estimate is plotted left of the porosity curve (PERM_log, in red). Colour code for lithology: Yellow: sandstone, brown: shale. Cored intervals indicated by black bars, red dots illustrate core porosity data.

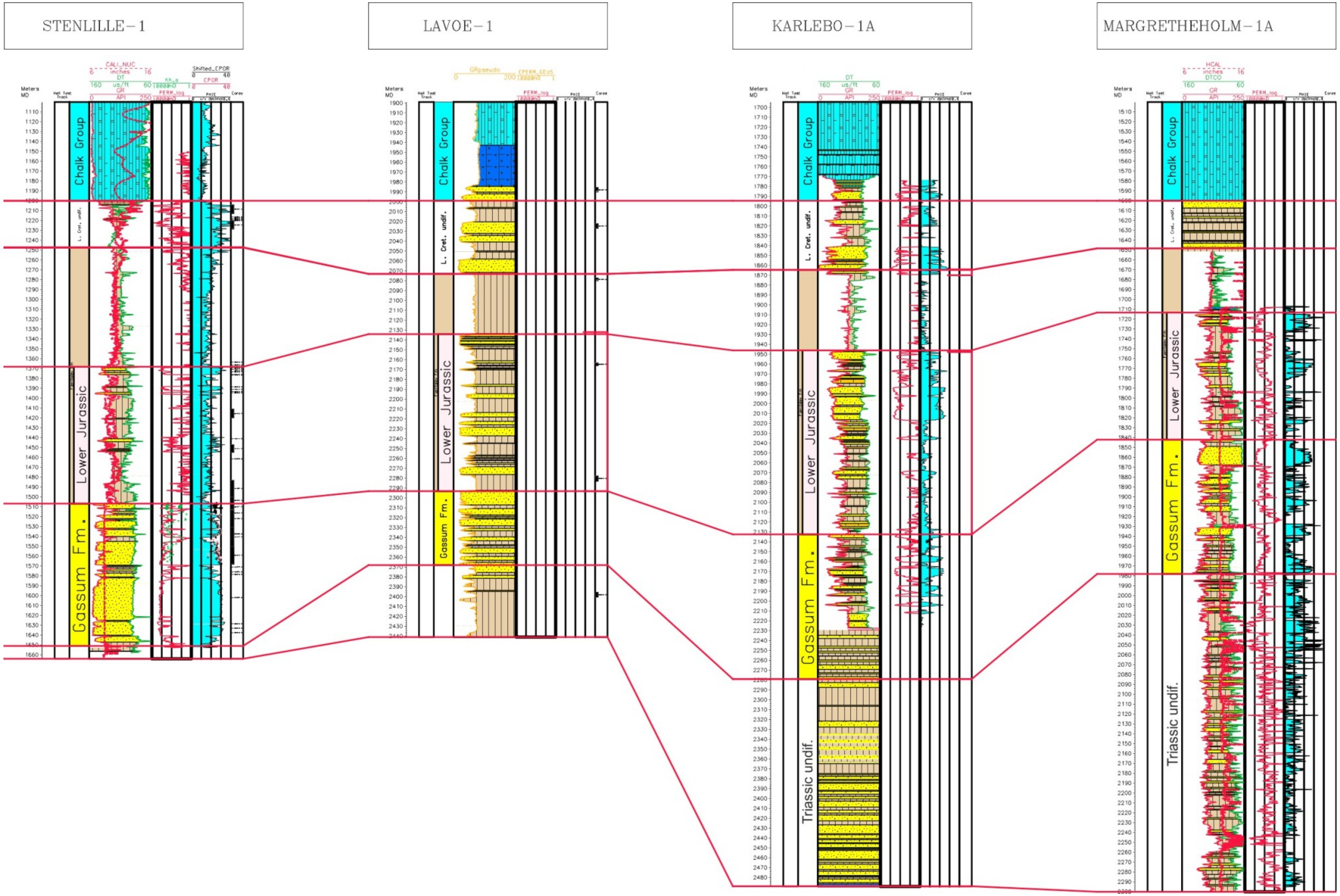


Fig. 12: Log based petrophysical correlation between the Karlebo-1/1A, Lavø-1, Margretheholm-1/1A and Stenlille-1 wells showing lateral variation of reservoir sections.

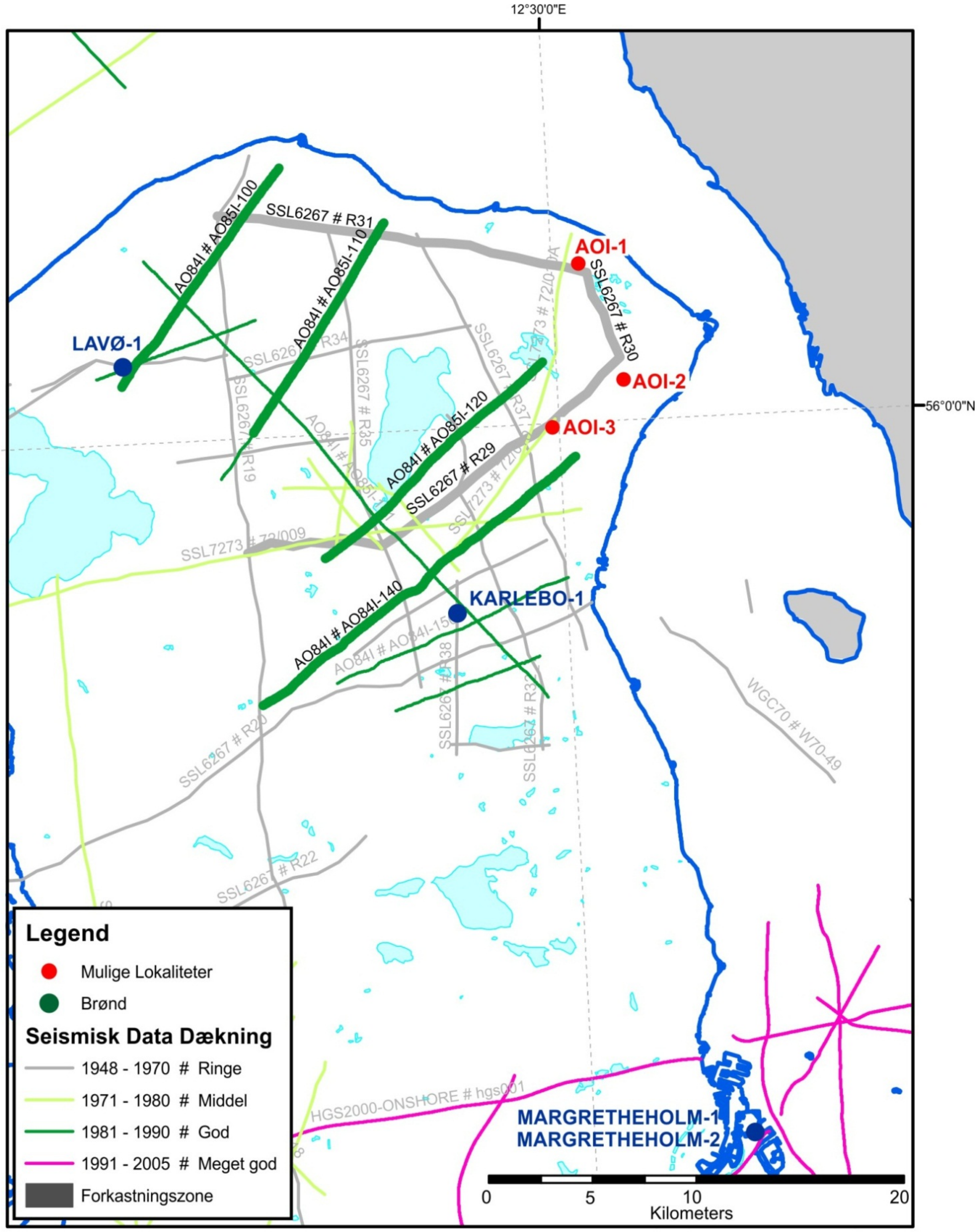


Fig. 13: Map showing the positions of the selected seismic sections shown in Figs. 14–20. Wells and areas of interest (AOI) are also shown. The quality estimation of the seismic lines is based on age; the actual quality of single lines may deviate

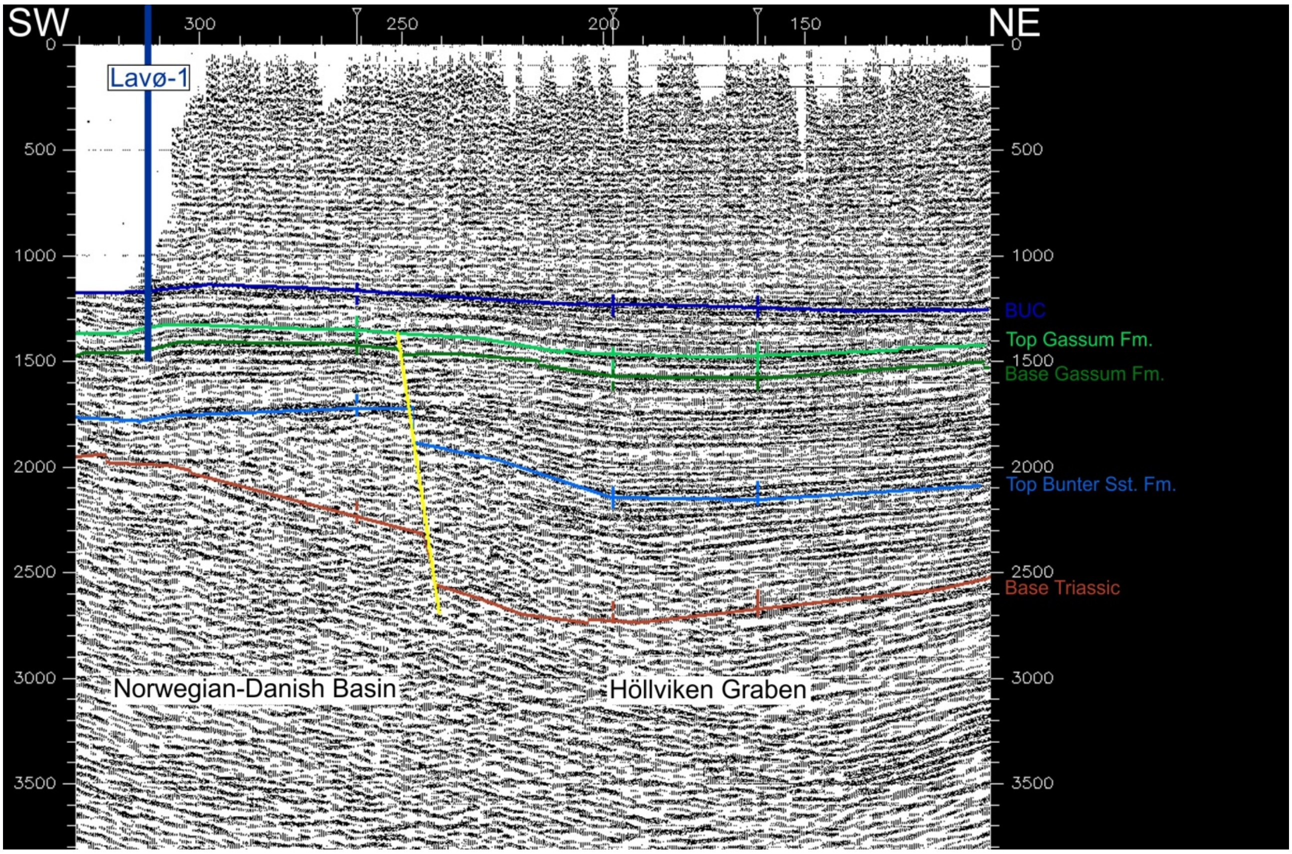


Fig. 14: Seismic section (AO85I-100) passing the Lavø-1 well (blue line); the location of the Lavø-1 well is only approximate. Depth is measured in time [msec]. The seismic data is old and of low quality; consequently, the number of identified seismic horizons is limited and subject to uncertainty; single reservoir sections cannot be identified. Further, the active, tectonic history of the Höllviken Graben and the Sorgenfrei-Tornquist Zone hints at significant fault activity, however, reliable identification of faults is not possible except for the large fault separating the Norwegian-Danish Basin and the Höllviken Graben (yellow line).

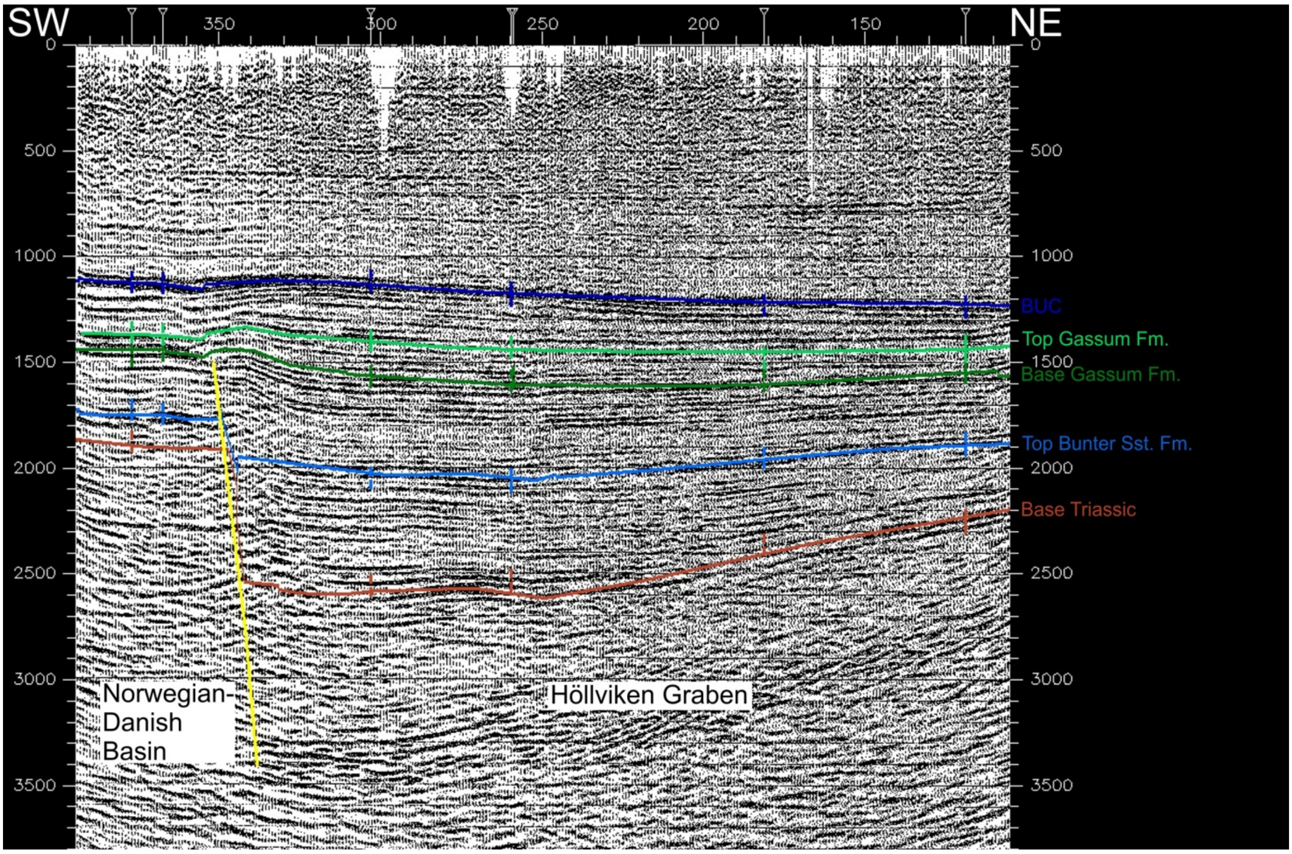


Fig. 15: Seismic section (AO85I-110), depth is measured in time [msec]. The seismic data is old and of low quality; consequently, the number of identified seismic horizons is limited and subject to uncertainty; single reservoir sections cannot be identified. Further, the active, tectonic history of the Höllviken Graben and the Sorgenfrei-Tornquist Zone hints at significant fault activity, however, reliable identification of faults is not possible except for the large fault separating the Norwegian-Danish Basin and the Höllviken Graben (yellow line).

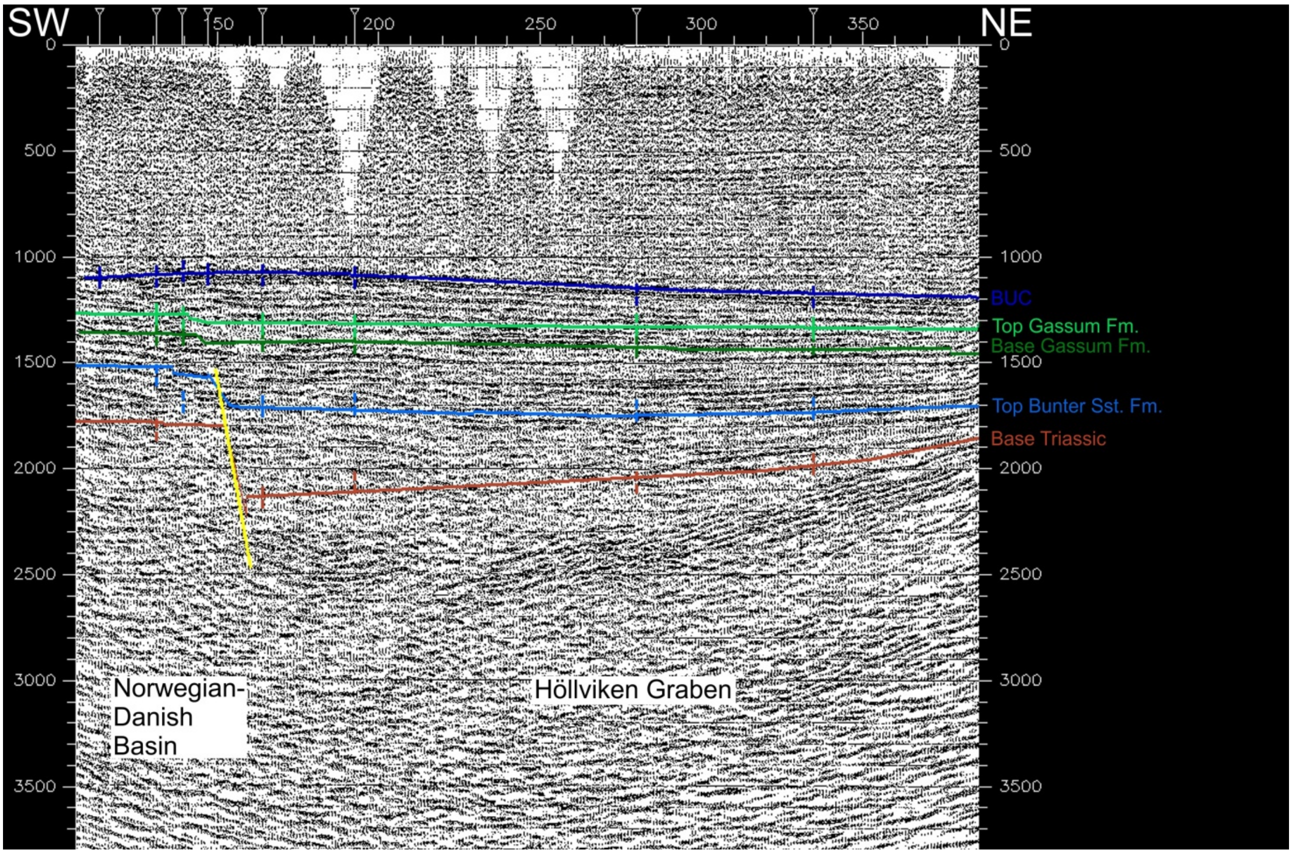


Fig. 16: Seismic section (AO85I-120), depth is measured in time [msec]. The seismic data is old and of low quality; consequently, the number of identified seismic horizons is limited and subject to uncertainty; single reservoir sections cannot be identified. Further, the active, tectonic history of the Höllviken Graben and the Sorgenfrei-Tornquist Zone hints at significant fault activity, however, reliable identification of faults is not possible except for the large fault separating the Norwegian-Danish Basin and the Höllviken Graben (yellow line).

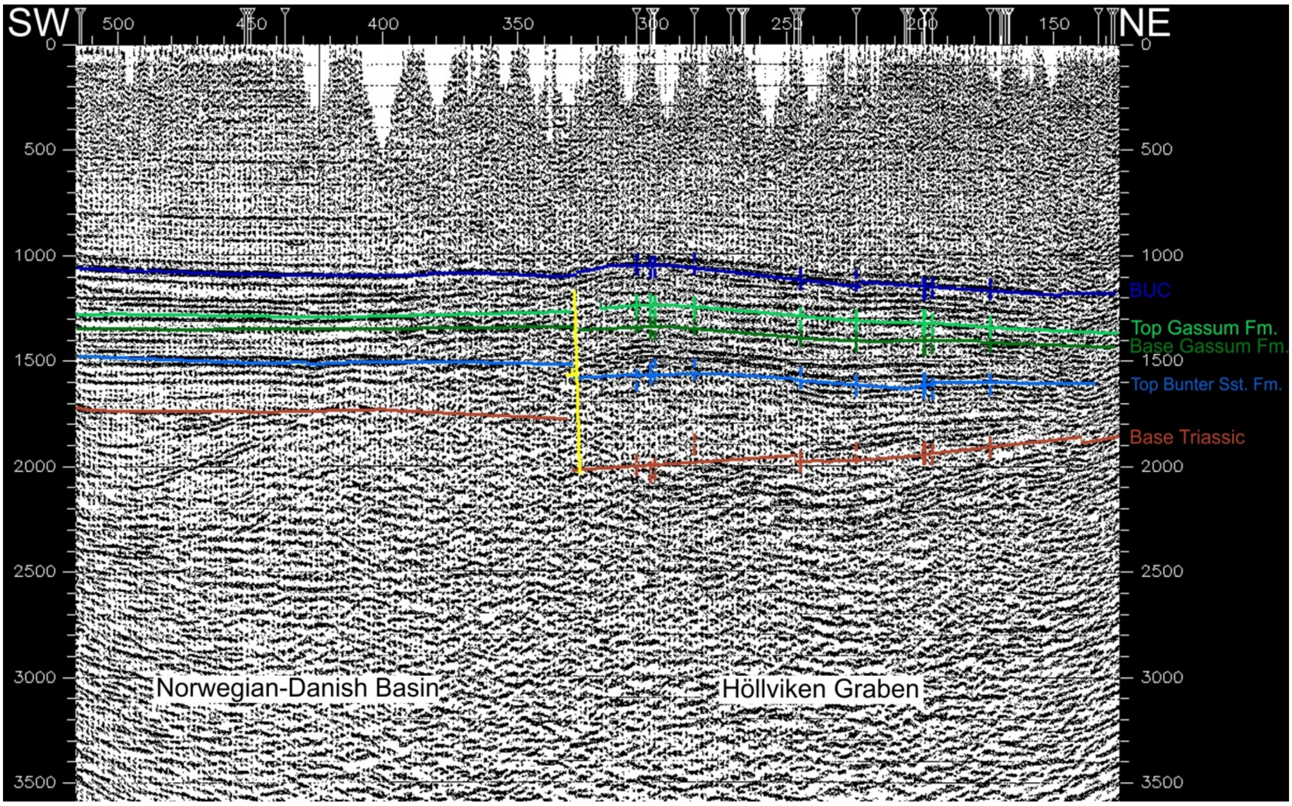


Fig. 17: Seismic section (AO84I-140), depth is measured in time [msec]. The seismic data is old and of low quality; consequently, the number of identified seismic horizons is limited and subject to uncertainty; single reservoir sections cannot be identified. Further, the active, tectonic history of the Höllviken Graben and the Sorgenfrei-Tornquist Zone hints at significant fault activity, however, reliable identification of faults is not possible except for the large fault separating the Norwegian-Danish Basin and the Höllviken Graben (yellow line). The offset of the fault decreases significantly from north to south (compare to figs. 14–16).

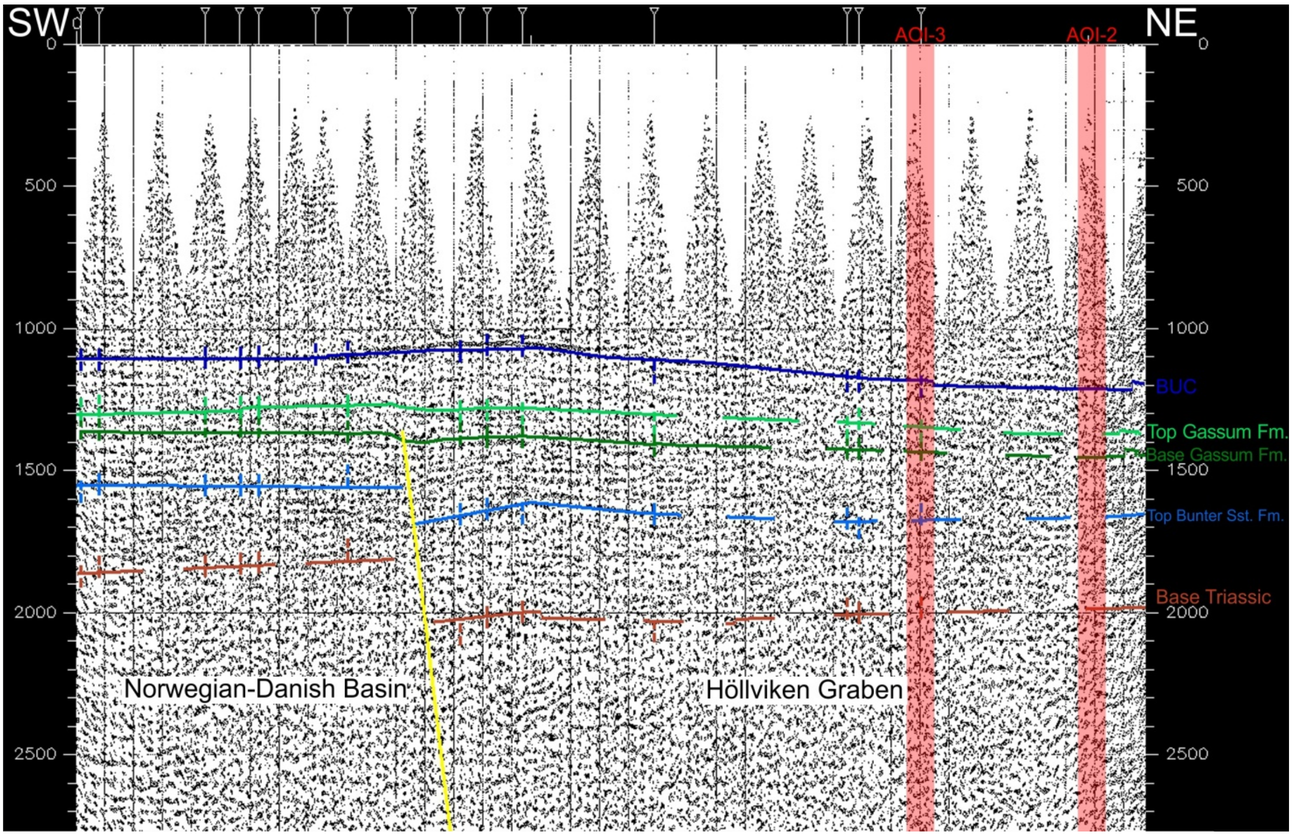


Fig. 18: Seismic section (R29), depth is measured in time [msec]. The seismic data is old and of low quality; consequently, the number of identified seismic horizons is limited and subject to uncertainty; single reservoir sections cannot be identified; hatched seismic horizons are particularly uncertain and largely based on GEUS' general knowledge. Further, the active, tectonic history of the Höllviken Graben and the Sorgenfrei-Tornquist Zone hints at significant fault activity, however, reliable identification of faults is not possible except for the large fault separating the Norwegian-Danish Basin and the Höllviken Graben (yellow line). AOI-3 is situated adjacent to the seismic line; AOI-2 is situated c. 1 km to the southeast.

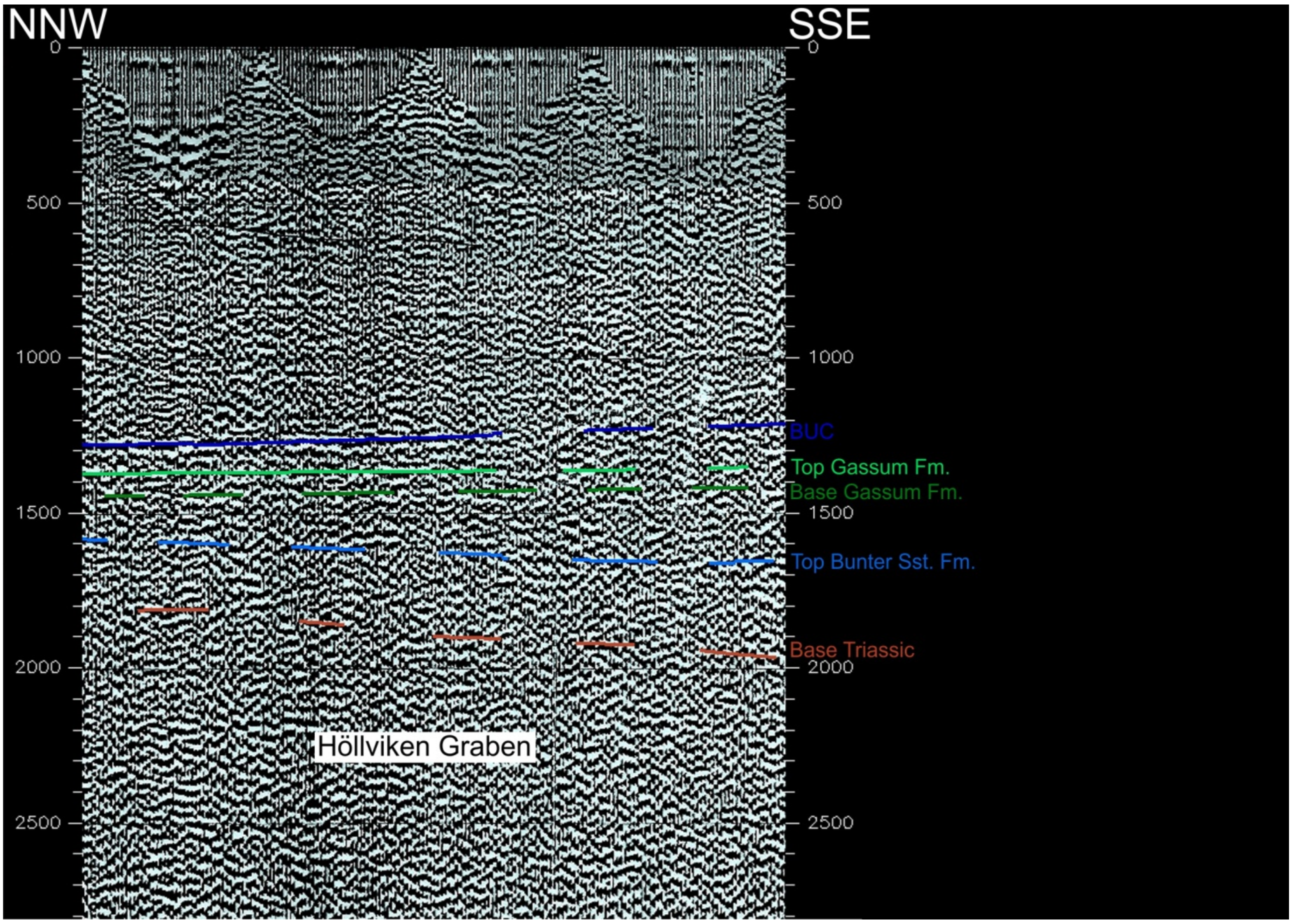


Fig. 19: Seismic section (R30) running approx. from AOI-1 (NNW) to AOI-2 (SSE), depth is measured in time [msec]. The seismic data is old and of low quality; consequently, the number of identified seismic horizons is limited and subject to uncertainty; hatched seismic horizons are particularly uncertain and largely based on GEUS' general knowledge; single reservoir sections cannot be identified. The interpreted depth to the Gassum Formation and to some degree the Top Bunter Formation remains nearly constant.

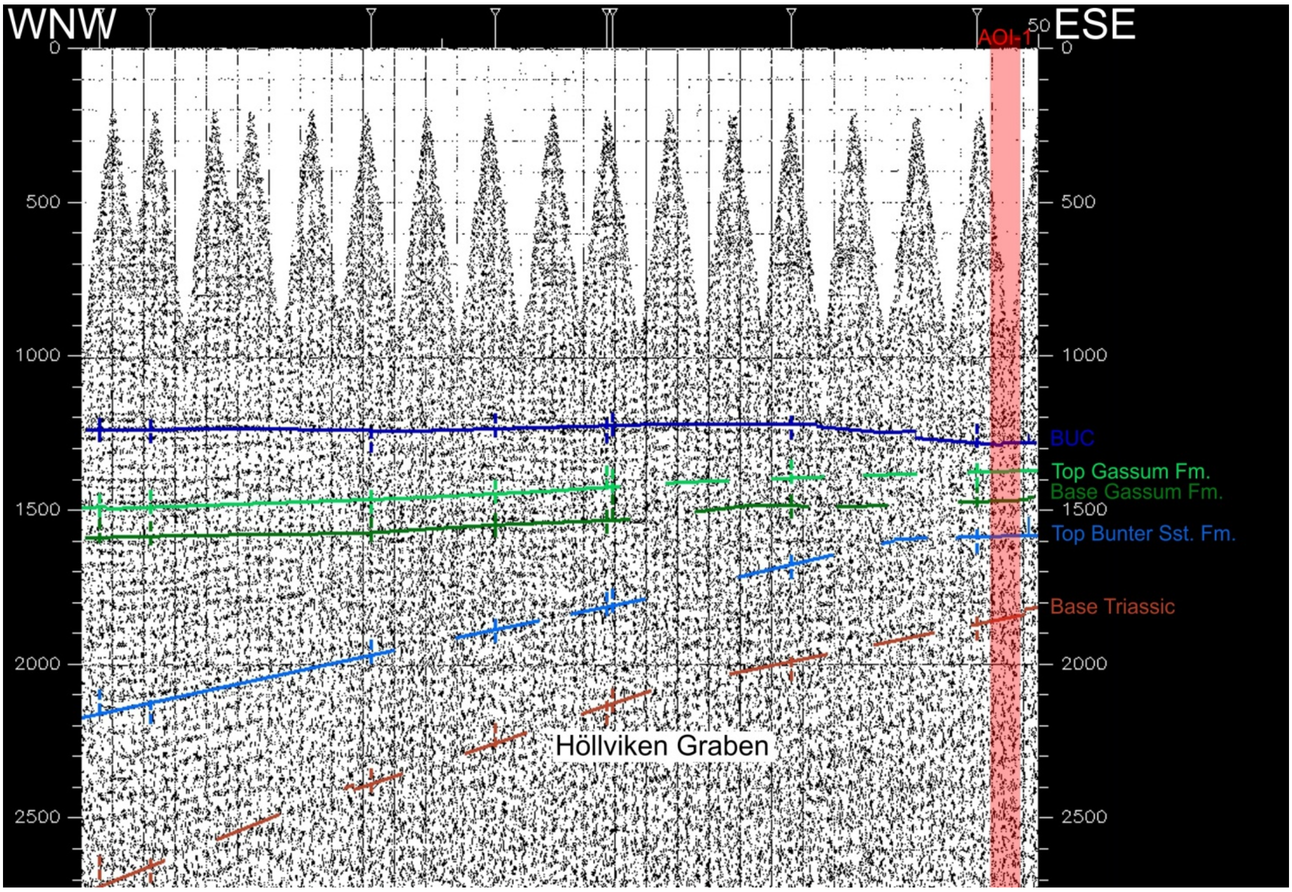


Fig. 20: Seismic section (R31), depth is measured in time [msec]. The seismic data is old and of low quality; consequently, the number of identified seismic horizons is limited and subject to uncertainty; hatched seismic horizons are particularly uncertain and largely based on GEUS' general knowledge; single reservoir sections cannot be identified. AOI-1 is situated close to the seismic line.

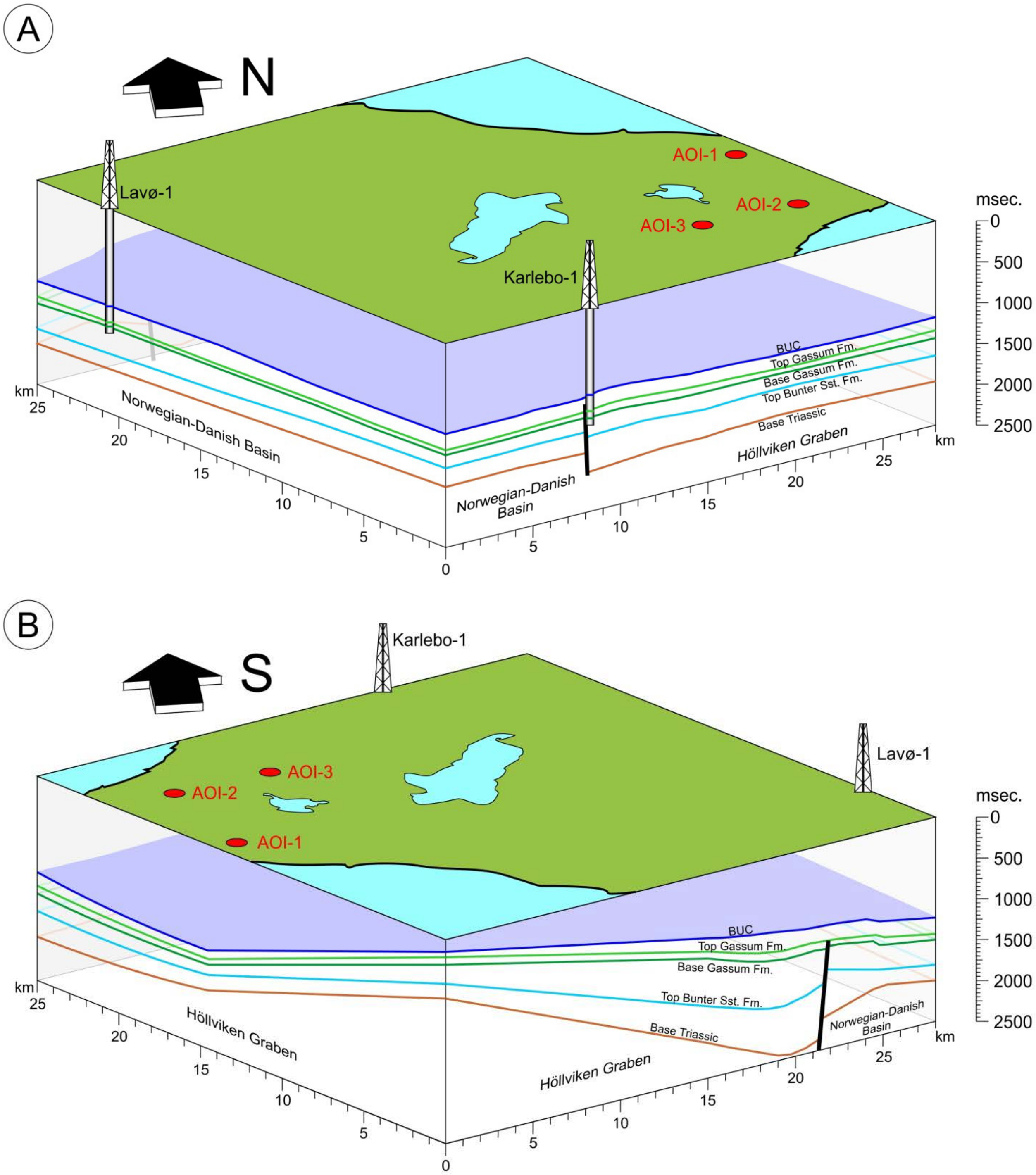


Fig. 21: Generalized geological model of the Helsingør area seen from South (A) and North (B) showing the Lavø-1 and Karlebo-1/1A wells, areas of interest (AOI) and the five identified seismic horizons. The model is based on seismic sections tied to the wells. Away from the wells the model becomes increasingly uncertain. The wells do not penetrate the Bunter Sandstone Formation; thus the Bunter Sandstone Formation is not confirmed in the Höllviken Graben but is expected to be present. Note in (B) that the steep ascent of the horizons has not been observed but is known to take place based on information from the wells related to the Helsingør-Helsingborg tunnel driving.

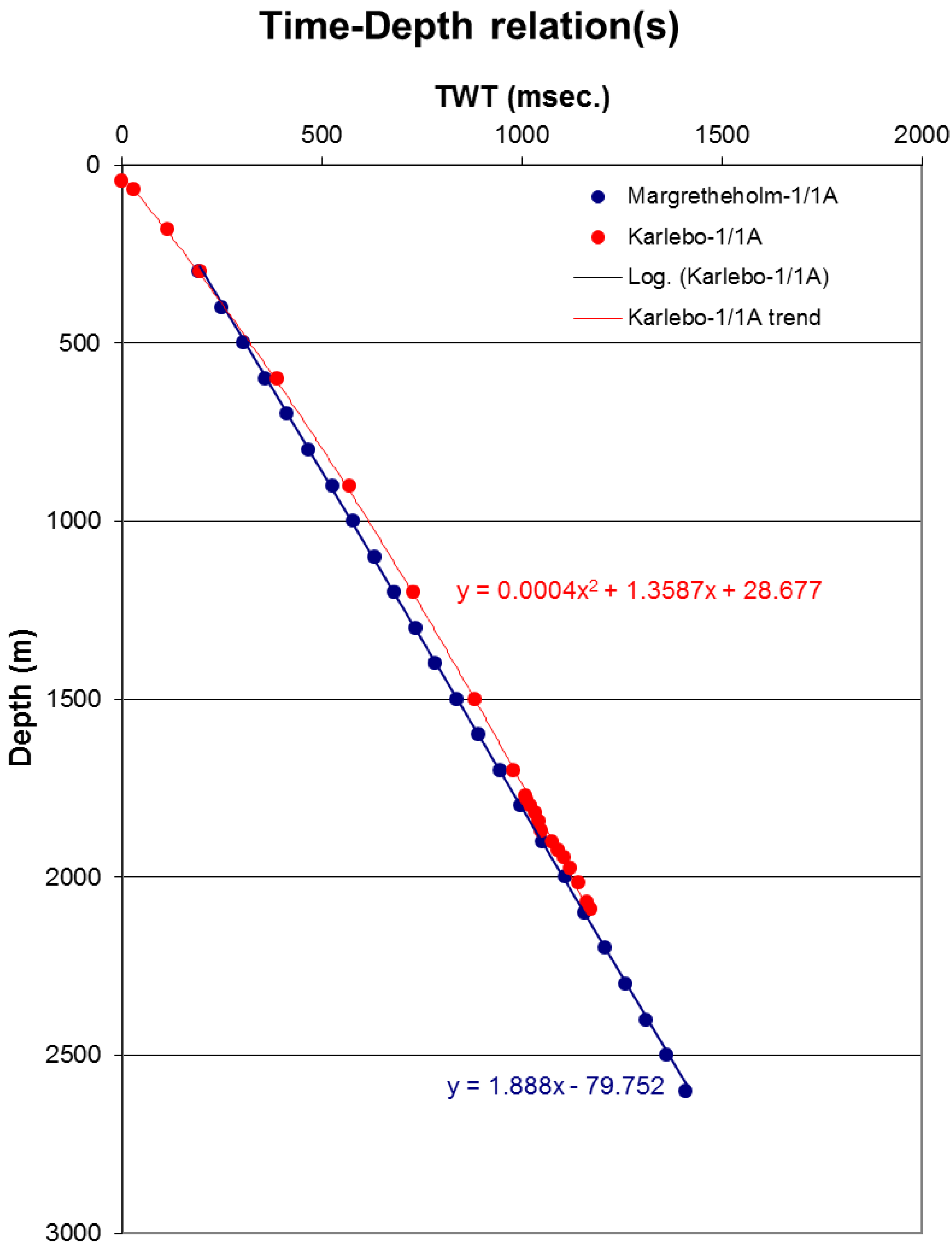


Fig. 22: Time-depth relation for the Margretheholm-1/1A and Karlebo-1/1A wells. The subsurface of the Margretheholm-1/1A well and the areas of interest is considered to be rather similar, while the subsurface of the Karlebo-1/1A being part of a fault zone is structurally and stratigraphically different from the areas of interest.

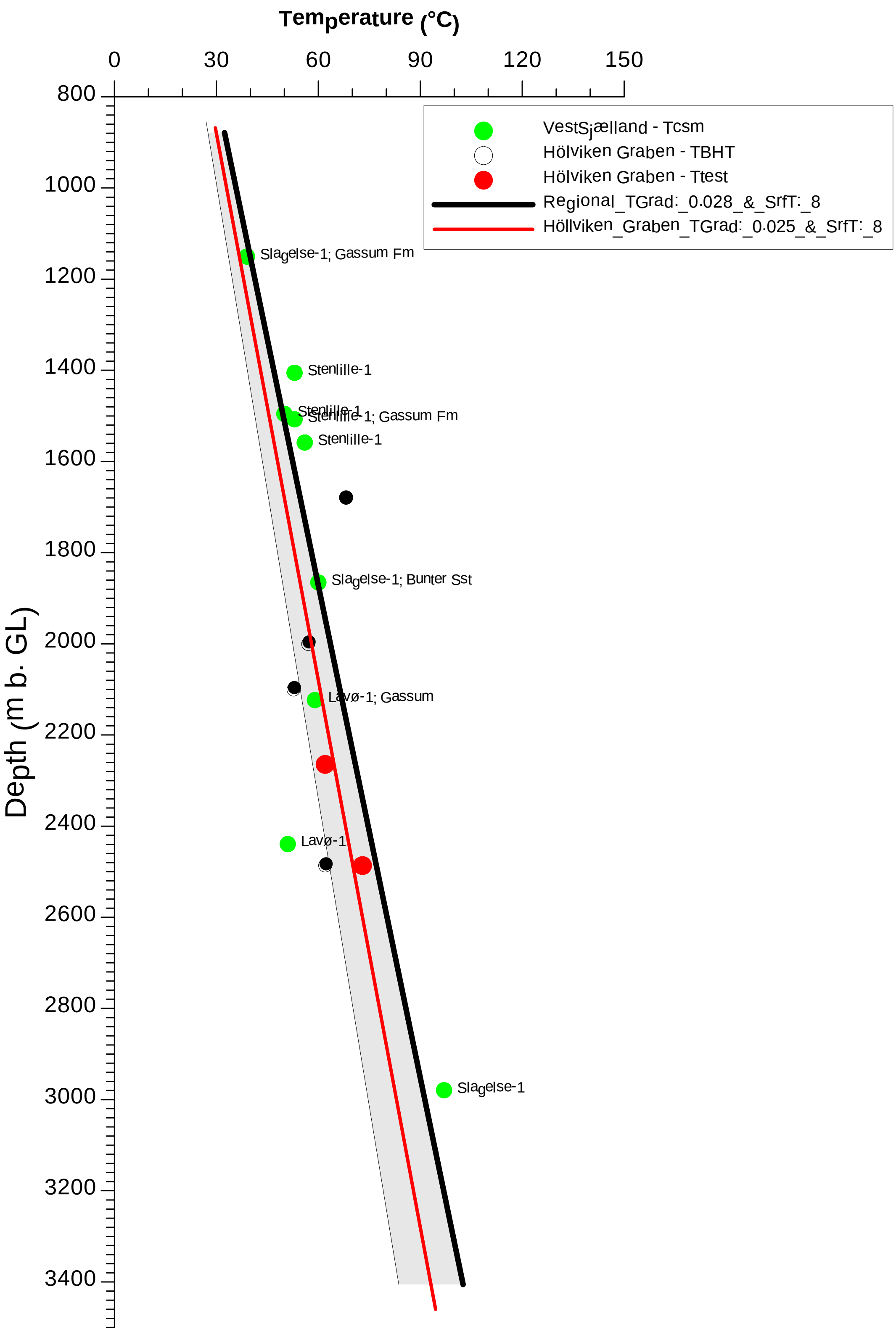


Fig. 23: Temperature prognosis based on available temperature data from Sjælland weighting the temperature test data from the Karlebo-1/1A and Margretheholm-1/1A wells highest (red line). The grey area represents a ± 10% uncertainty range, where the upper boundary coincides with the regional gradient (~28ºC/km; solid black line).

11 Enclosures

Enclosure 1: Lithology of formations containing possible reservoirs in the Karlebo-1A well.

Enclosure 2: Lithology of formations containing possible reservoirs in the Lavø-1 well.

Enclosure 3: Lithology of formations containing possible reservoirs in the Margretheholm-1/1A well.

Enclosure 4: Lithology of formations containing possible reservoirs in the Stenlille-1 well.

Enclosure 5: Base Upper Cretaceous (BUC) depth structure map, C.I. 200 m.

Enclosure 6: Near Top Gassum Formation depth structure map, C.I. 200 m.

Enclosure 7: Top Bunter Sandstone Formation depth structure map, C.I. 200 m.

Enclosure 1. Lithology of formations containing possible reservoirs in the Karlebo-1A well. Grain size, grain shape, sorting and cementation refer to sand/sandstone sections. The lithology data is extracted from the final well report of the Karlebo-1 well.

Age	**Formation**	**Formation depth interval** (m MD)	**Formation thickness** (m)	**Possible reservoir sections** (within formation/unit)	**Res. depth interval** (m MD)	**Grain size**	**Grain shape**	**Sorting**	**Cementation**
Cretaceous				Sandstones	1791 – 1808	Very fine – fine	subangular – subrounded	Well sorted	Calcareous
	Lower Cretaceous undiff.	1794 – 1865	71	Sandstones	1834 – 1843	Fine – medium	subangular – subrounded	Moderately – well sorted	Calcareous
Jurassic	Fjerritslev	1865 – 1946	81	Sandstone	1869 – 1911	Fine – coarse	subangular – rounded	Poorly sorted	Calcareous
	Lower Jurassic undiff.	1946 – 2132	186	Sandstones interbedded w. claystones and siltstones	1946 – 2229	Fine – medium (occ. coarse or very coarse)	subangular – subrounded (occ. rounded)	Moderately – well sorted	Calcareous silica
Triassic	Gassum	2132 – 2279	147	Sandstones interbedded w. claystones	2229 – 2298	Very fine – fine (occ. medium or coarse)	subangular – rounded	Moderately – poorly sorted	Calcareous silica
	Triassic undiff.	2279 – 2489	210	Interbedded sandstones and claystones	2298 – 2489	Fine – medium (occ. coarse or very coarse)	subangular – subrounded (occ. angular – rounded)	Moderately – poorly sorted	Calcareous
	Bunter Sst.	Not drilled							

Enclosure 2. Lithology of formations containing possible reservoirs in the Lavø-1 well. Grain size, grain shape, sorting and cementation refer to sand/sandstone sections. The lithology data is extracted from the completion report of the Lavø-1 well.

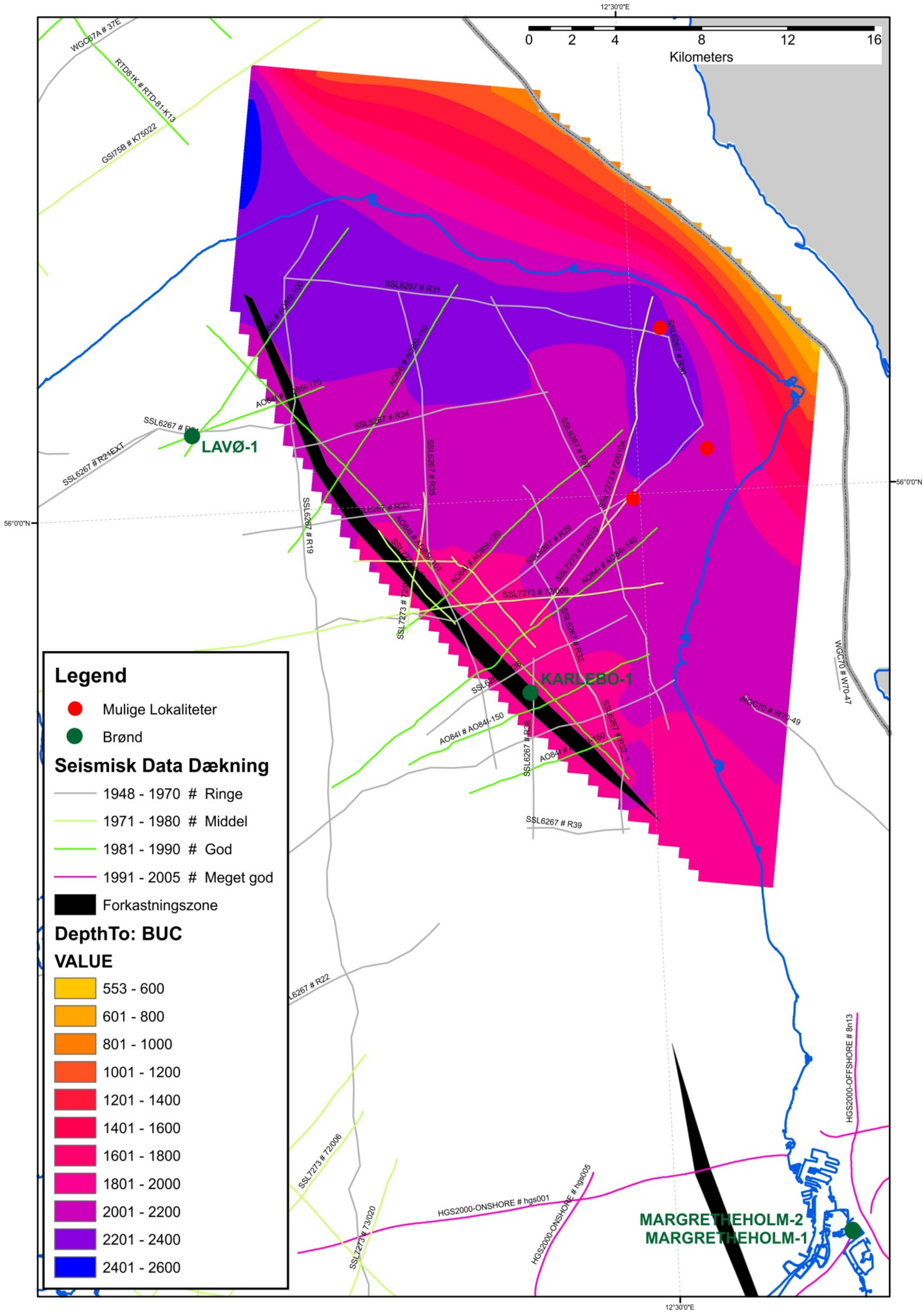
Age	**Formation**	**Formation depth interval** (m MD)	**Formation thickness** (m)	**Possible reservoir sections** (within formation/unit)	**Res. depth interval** (m MD)	**Grain size**	**Grain shape**	**Sorting**	**Cementation**
Cretaceous	Chalk Group			Siltstone/sandstone	1947 – 1952	Very fine	N/A	N/A	Calcareous
				Green sand	1985 – 1990	Very fine	N/A	N/A	N/A
	Lower Cretaceous undiff.	1999 – 2073	74	Sand w. shale in lower part	2022 – 2050	Fine – medium	N/A	N/A	N/A
				Sand w. some shale	2065 – 2077	Medium – coarse	N/A	N/A	N/A
Undiff.	Undiff.	2073 – 2134	61						
Jurassic	Lower Jurassic undiff.	2134 – 2293	159	Sandstones	2140 – 2155	Fine	N/A	N/A	N/A
				Sandstones	2212 – 2218	Fine	N/A	N/A	N/A
				Shales and sandstones	2283 – 8310	N/A	N/A	N/A	N/A
Triassic	Gassum	2293 – 2368	75	Shales and sandstones	8310 – 2376	Fine	N/A	N/A	N/A
	Undiff.	2368 – 2441	73	Sandstones and shales	2379 – 2395	Fine	N/A	N/A	N/A
	Bunter Sst.	Not drilled							

Enclosure 3. Lithology of formations containing possible reservoirs in the Margretheholm-1/1A well. Grain size, grain shape, sorting and cementation refer to sand/sandstone sections. The lithology data is extracted from the final well report of the Margretheholm-1/1A well.

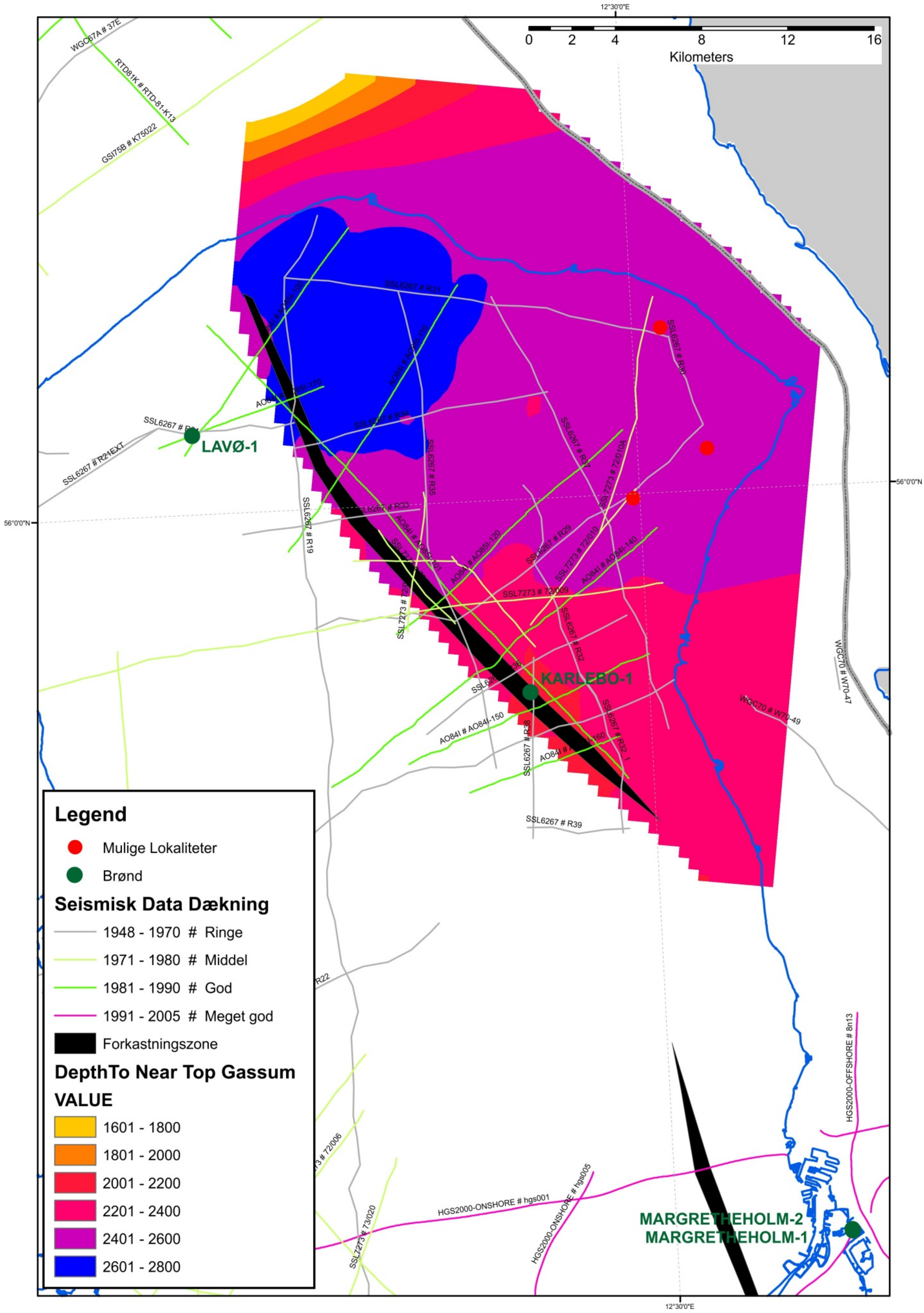
<table>
<tr><th>Age</th><th>Formation</th><th>Formation depth interval
(m MD)</th><th>Formation thickness
(m)</th><th>Possible reservoir sections
(within formation/unit)</th><th>Res. depth interval
(m MD)</th><th>Grain size</th><th>Grain shape</th><th>Sorting</th><th>Cementation</th></tr>
<tr><td rowspan="2">Cretaceous</td><td>Undiff.</td><td>1601 – 1623</td><td>22</td><td>Sandstones</td><td>1601 – 1608</td><td>Fine (occ. very fine, rarely coarse)</td><td>subangular – angular (occ. rounded)</td><td>Good</td><td>Calcite</td></tr>
<tr><td>Lower Cretaceous undiff.</td><td>1623 – 1648</td><td>25</td><td>Sandstones</td><td>1644 – 1648</td><td>Fine – medium (rarely coarse – very coarse)</td><td>subangular – angular (occ. subrounded – rounded)</td><td>Very poor</td><td>N/A</td></tr>
<tr><td>Undiff.</td><td>Undiff.</td><td>1648 – 1713</td><td>65</td><td rowspan="3">Sandstones interbedded w. claystones</td><td rowspan="3">1707 – 1977</td><td rowspan="3">Fine – medium (occ. silt and coarse)</td><td rowspan="3">subangular – subrounded</td><td rowspan="3">Moderately sorted</td><td rowspan="3">In places strongly calcareous or silica</td></tr>
<tr><td>Jurassic</td><td>Lower Jurassic undiff.</td><td>1713 – 1842</td><td>129</td></tr>
<tr><td rowspan="4">Triassic</td><td>Gassum</td><td>1842 – 1977</td><td>135</td></tr>
<tr><td rowspan="2">Undiff.</td><td rowspan="2">1977 – 2385</td><td rowspan="2">408</td><td>Interbedding of claystones, siltstones and sandstones</td><td>1977 – 2026</td><td>Fine – medium (occ. coarse)</td><td>subangular – subrounded</td><td>Moderately – poorly sorted</td><td>Calcite (variable)</td></tr>
<tr><td>Interbedding of claystones, siltstones and sandstones</td><td>2026 – 2368</td><td>Fine – very coarse</td><td>Angular – subrounded</td><td>Poor</td><td>In places calcite</td></tr>
<tr><td>Bunter Sst.</td><td>2385 – 2684</td><td>299</td><td>Sandstones</td><td>2640 – 2658</td><td>Fine – coarse</td><td>Angular – subangular</td><td>Poor</td><td>Calcite</td></tr>
</table>

Enclosure 4. Lithology of formations containing possible reservoirs in the Stenlille-1 well. Grain size, grain shape, sorting and cementation refer to sand/sandstone sections. The lithology data is extracted from the well summary report of the Stenlille-1 well.

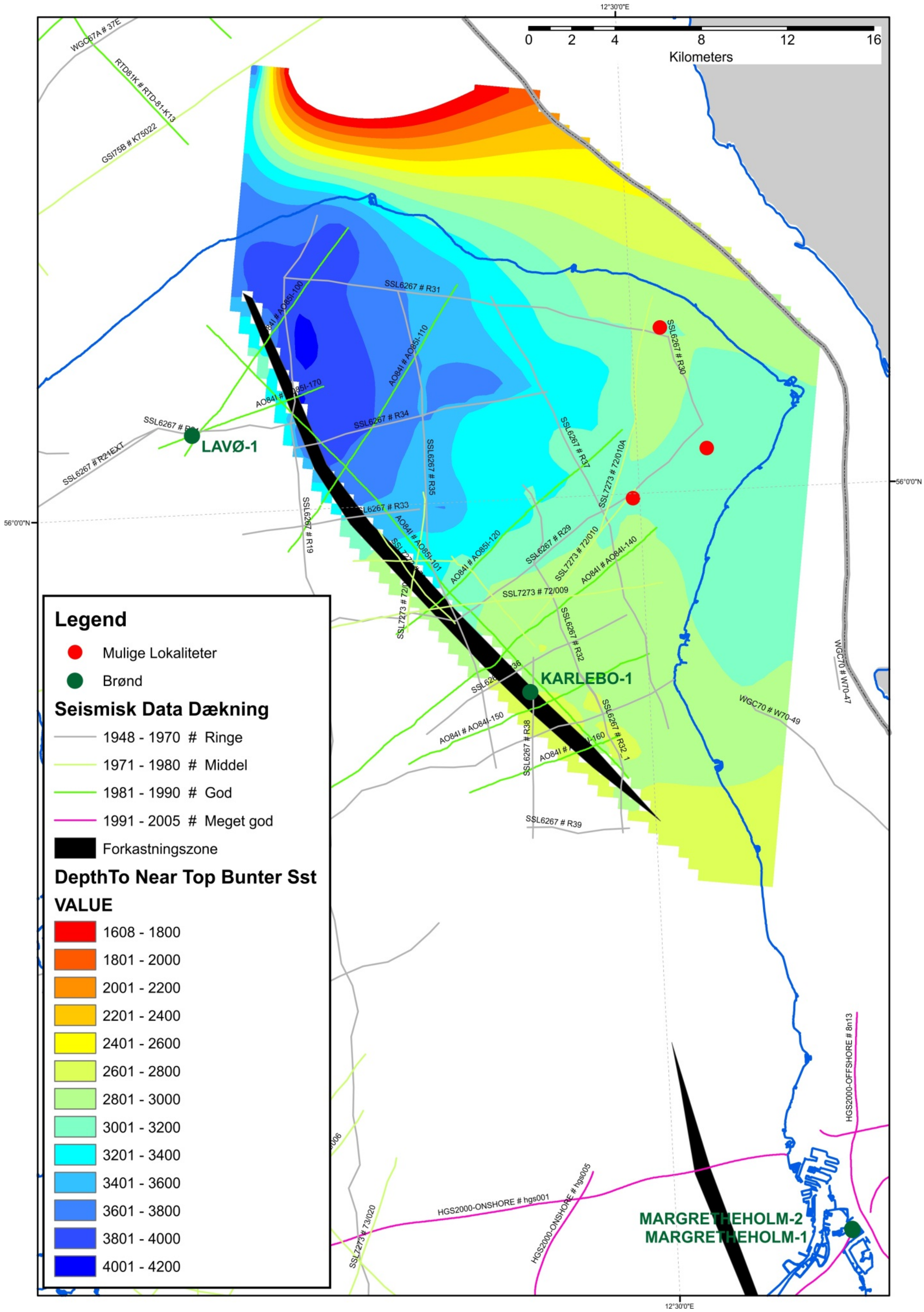
Age	**Formation**	**Formation depth interval** (m MD)	**Formation thickness** (m)	**Possible reservoir sections** (within formation/unit)	**Res. depth interval** (m MD)	**Grain size**	**Grain shape**	**Sorting**	**Cementation**
Jurassic	Lower Jurassic Unit	1368 – 1507	139	Sandstones	1369 – 1372	Fine		Good	
				Sandstones	1372 – 1374	Medium (fraction of coarse)		Well – moderate	
				Sandstones	1374 – 1376	Medium – coarse		Moderate – poor	Calcite (lower-most 40 cm)
				Sandstones	1388 – 1392	Fine		Well	
				Sandstones	1394 – 1395	Fine		Well	
				Sandstones	1440 – 1445	Fine		Well	Calcite
				Sandstones	1452 – 1455	Fine		Well	
Triassic	Gassum	1507 – 1651	144	Sandstones	1507 – 1508	Fine – medium		Well	
				Sandstones	1509 – 1511	Fine			
				Sandstones	1511 – 1512				
				Sandstones	1519 – 1522	Fine		Well	
				Sandstones	1524 – 1541	Fine		Well	
				Sandstones	1546 – 1569				
				Interbedding of claystones, siltstones and sandstones	1569 – 1574	Fine			
				Sandstones	1574 – 1576	Fine			
				Sandstones	1578 – 1582	Fine			
				Sandstones	1583 – 1625	Medium – coarse		Well	Calcite (1 m in lower part)
				Sandstones	1627 – 1641	Medium – coarse		Well	
				Sandstones	1642 – 1647	Fine – medium			



Enclosure 5: Base Upper Cretaceous (BUC) depth structure map, C.I. 200 m. Well locations, areas of interest, coast line, position of seismic lines and fault zones are included.



Enclosure 6: Near Top Gassum Formation depth structure map, C.I. 200 m. Well locations, areas of interest, coast line, position of seismic lines and fault zones are included.



Enclosure 7: Top Bunter Sandstone Formation depth structure map, C.I. 200 m. Well locations, areas of interest, coast line, position of seismic lines and fault zones are included. Note that the depth to Near Top Bunter Sandstone Formation is around 3 km in the areas of interest.