DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2014/34

# Evaluation of possible geothermal reservoirs in The Brønderslev area

## Contribution to an evaluation of the geothermal potential

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# Preface

This report is prepared by GEUS for Brønderslev Varme A/S based on a local dataset and GEUS' regional geological models of the Danish subsurface. The report is a contribution to the assessment of the geothermal potential for possible geothermal reservoirs in the Northern Jutland area. The area of interest was defined by the client and with special focus on an evaluation of the Gassum and Skagerrak formations, however, the Frederikshavn and Haldager Sand formations, though shallowly buried, may constitute potential geothermal reservoirs and are considered as well.

GEUS has conducted studies of the regional development and geothermal potential of the prospective formations (Mathiesen et al. 2009), and has recently assessed the geothermal potential at several local areas in Denmark including the Hjørring area.

This report builds on available and released data that are relevant to an evaluation of the geothermal potential in the area of interest. The results of the study reported here show no discrepancies from the regional trends that GEUS has observed previously for the Danish area.

The report contains a quantitative petrophysical interpretation of the potential reservoirs based on the existing conventional cores and well logs in order to estimate the net/gross ratio including porosity permeability and transmissivity. Furthermore, an interpretation of the existing 2D seismic data in the Northern Jutland area has been carried out in order to map the depth to the formations and to investigate the presence of faults.

Focus will be on the Gassum and Skagerrak formations, both of which are buried deeply enough in the Fjerritslev Trough (i.e. above ~1000 m) to have geothermal potential in the Brønderslev area. As mentioned, the shallow Frederikshavn and Haldager Sand formations are considered possible geothermal reservoirs. The extent of the sand intervals in the Flyvbjerg Formation in itself is insufficient in terms of geothermal exploitation, however these intervals may contribute to the geothermal potential of the adjacent Haldager Sand Formation.

The report includes:

1. An assessment of the geological evolution of the Permian-Mesozoic succession in the licence area based on the Børglum-1, Flyvbjerg-1, Vedsted-1, Haldager-1 and Sæby-1 wells and GEUS' regional and general geological model for the Northern Jutland area.
2. An interpretation of relevant and available seismic data in the licence area in order to identify faults and map the distribution, depth and lateral continuity of possible reservoir-bearing formations.

3. A petrophysical interpretation based on available well logs from the Børglum-1, Flyvbjerg-1, Vedsted-1, Haldager-1 and Sæby-1 wells in order to assess the net/gross ratio, porosity and permeability of the potential reservoirs.

# CONTENT

# 1 Dansk resumé

Den foreliggende rapport er udarbejdet af GEUS for Brønderslev Varme A/S med det formål at bidrage til en vurdering af muligheden for etablering af et geotermisk anlæg ved Brønderslev med særligt henblik på den udpegede prognoselokalitet på Virksomhedsvej i byens sydlige del.

## 1.1 Datagrundlag

Datagrundlaget for den geologiske vurdering udgøres af alle relevante, tilgængelige og frigivne data omfattende 2D-seismiske data, brønddata (logs) samt kerneanalyser og kerne- og cuttings-beskrivelser fra boringerne Børglum-1, Flyvbjerg-1, Vedsted-1, Haldager-1 og Sæby-1. De foreliggende data (seismiske linjer og boringer) vedrørende undergrundens geologiske opbygning i Vendsyssel er sparsomme og muliggør kun generelle vurderinger i områder uden dybe boringer. Der findes således ikke for indeværende data, der muliggør en tilbundsgående beskrivelse af reservoirernes tykkelse og vandledende egenskaber på specifikke lokaliteter i Brønderslev by.

## 1.2 Geologi

Området ved Brønderslev by ligger geologisk set i Fjerritslev Truget tæt på en stor forkastningszone kaldet Børglum Forkastningen, som adskiller Fjerritslev Truget fra Skagerrak-Kattegat Platformen mod nordøst. Den præcise placering af forkastningen kendes ikke, idet den kun krydses af få seismiske linjer af ældre dato og ringe kvalitet. På baggrund af de foreliggende data forventer GEUS, at forkastningen ligger under udkanten af byens nordlige del. Forkastningen har haft stor betydning for den geologiske udvikling, hvilket fx betyder, at de potentielle geotermiske reservoirer Haldager Sand, Gassum og Skagerrak Formationerne er væsentlig tykkere syd for forkastningen end på platformen mod nordøst. Den primære information vedrørende reservoirernes beskaffenhed syd for forkastningen kommer fra Børglum-1 (1951), Flyvbjerg-1 (1958), Haldager-1 (1950) og Vedsted-1 (1958), mens den primære kilde på platformen er Sæby-1 boringen (boret i 1985).

## 1.3 kontinuiteten af mulige reservoirer

Den seismiske kortlægning omfatter alle tilgængelige linjer ved Brønderslev by og et godt stykke uden for denne. Den seismiske linje DNJ-100 udgør den vigtigste seismiske linje, da den med ca. 1.5 km passerer forholdsvis tæt på den udpegede prognoselokalitet og danner derved grundlaget for estimeringen af dybden til potentielle reservoirer. Syv seismiske horisonter er blevet identificeret, heriblandt formationstoppene for Frederikshavn, Haldager Sand, Gassum og Skagerrak formationerne, hvoraf sidstnævnte tillige udgør basis af Gassum Formation. Ud fra de seismiske horisonter vurderes den mulige tilstedeværelse af forkastninger, og horisonterne udgør grundlaget for generering af dybdekort.

Tre store forkastninger eller forkastningszoner er blevet identificeret. De to NV-SØ forløbende forkastninger, Børglum Forkastningen og Haldager Forkastningen, ligger henholdsvis ca. 10 km NØ og ca. 20 km SV for Brønderslev by og influerer antageligvis ikke på kontinuiteten af potentielle reservoirer på prognoselokaliteten. En unavngiven forkastning (kaldet Brønderslev Forkastningen i rapporten) beliggende ca. 3 km SV for Brønderslev by og ligeledes med et NV-SØ orienteret forløb antages heller ikke at påvirke kontinuiteten af de mulige reservoirer. Dog kan indflydelsen fra Børglum Forkastningen og eventuelle følgeforkastninger først afklares med indsamlingen af ny højkvalitet-seismik. Derudover kan forekomsten af mindre forkastninger ikke udelukkes, men for nærværende forbliver disse uidentificeret grundet den generelt ringe kvalitet af de seismiske data.

## 1.4 Dybden til mulige reservoirer

Med udgangspunkt i borehulslogs, kerneanalyse og beskrivelse af borespåner er fire formationer med geotermisk potentiale identificeret. Det drejer sig om Frederikshavn Formationen, Haldager Sand Formationen, Gassum Formationen og Skagerrak Formationen. Dybden til toppen af disse formationer på den planlagte brøndlokalitet er estimeret ud fra den seismiske linje DNJ-100 og præsenteret i **Tabel 1**. Dybdekort antyder en 400–700 m dybere placering af Gassum Formationen ca. 5 km sydvest for den nuværende prognoselokalitet, hvilket svarer til en temperaturgevinst i størrelsesordenen 11–19 °C, men også en formodet lavere permeabilitet.

## 1.5 Reservoirkvalitet

På den udpegede prognoselokalitet er reservoiregenskaber og tykkelser for formationer med geotermisk potentiale baseret på reservoiregenskaberne for boringerne Børglum-1, Flyvbjerg-1, Vedsted-1 og Haldager-1 samt i nogen udstrækning seismiske linjer, fortrinsvist DNJ-100 og DNJ-200. En række faktorer komplicerer overførslen af boringernes reservoiregenskaber til prognoselokaliteten:

- Boringerne er placeret i forskellig afstand fra prognoselokaliteten
- Prognoselokaliteten er adskilt fra Vedsted-1 og Haldager-1 af Brønderslev Forkastningen og fra Vedsted-1 af Haldager Forkastningen
- Ikke alle boringer når ned til Gassum og Skagerrak formationerne
- Kun de øverste ca. 200 m af Skagerrak Formationen er anboret
- Boringernes logsuiter er af varierende kvalitet eller mangelfulde
- Log-udledte reservoirparametre understøttes ikke af kerneanalysedata i alle boringer

På grund af forskellige geologiske forhold på dannelsestidspunktet varierer formationernes laterale udbredelse og tykkelse i Brønderslev-området, og de fire relevante formationer kan ikke vurderes ud fra de samme forudsætninger på prognoselokaliteten. Således vægtes de eksisterende boringer efter deres geografiske placering samt mængden og kvaliteten af den information, de yder, i forbindelse med bedømmelsen af de enkelte formationers reservoiregenskaber på prognoselokalitet. I **Tabel 1** præsenteres reservoirparametrene for lokaliteten på Virksomhedsvej.

**Tabel 1:** Estimerede reservoirparametre for net sand i formationer med geotermisk potentiale ved prognoselokaliteten (Virksomhedsvej). Net sand defineres som sandsten med mindre end 30% lerskifer og en porøsitet over 15%.

| Formation | Estimerede reservoirparametre | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Formations-interval** (m MD) | **Formations-tykkelse** (m) | **Gross sand-tykkelse** (m) | **Net sand-tykkelse** (m) | **N/G** | **Middel porøsitet** (%) | **Estimeret gasperm.** (mD) | **Estimeret res.perm.** (mD) | **Transmissivitet** (Dm) |
| **Frederikshavn** | 778–989 | 211 | 79 | 24 | 0.10 | 21 | 469 | 586 | 14 |
| **Haldager Sand** | 1052–1118 | 66 | 52 | 44 | 0.61 | 25 | 748 | 935 | 41 |
| **Gassum** | 1337–1455 | 118 | 77 | 53 | 0.45 | 24 | 609 | 762 | 40 |
| **Skagerrak** | 1455–3000[1)] | 1545/200 [2)] | 61 | 26 | 0.42 | 25 | 390 | 488 | 13 |

[1)] En betragtelig del (425 m) af den nedre Skagerrak Formation falder udenfor det geotermale dybdevindue (800–3000 m) og indgår ikke i formationsintervallet.
[2)] Kun de øverste 200 m af formationen er evalueret med udgangspunkt i data fra Flyvbjerg-1 and Vedsted-1

På prognoselokaliteten vurderes temperaturerne for de fire formationer med geotermisk potentiale således:

- Frederikshavn Formation: 32 °C
- Haldager Sand Formation: 37 °C
- Gassum Formation: 46 °C
- Skagerrak Formation: 50 °C.

## 1.6 Konklusion

Med udgangspunkt i det eksisterende datagrundlag vurderes undergrunden ved Brønderslev by at indeholde flere sandstensformationer med geotermisk potentiale. I særdeleshed Gassum Formationen udviser en lovende kombination af transmissivitet og temperatur. Skagerrak Formationen må formodes at have et større potentiale end angivet i **Tabel 1**, da der kun er datagrundlag for vurdering af formationens øverste 200 m. Frederikshavn og Haldager Sand formationerne er mere grundt begravet med lavere temperaturer til følge; Haldager Sand Formationen har dog et geotermisk potentiale grundet den høje transmissivitet. En 400–700 m dybere placering af Gassum Formationen ca. 5 km sydvest for den nuværende prognoselokalitet antyder en betragtelig temperaturgevinst på 11–19 °C, som dog skal sammenholdes med en formodet permeabilitetsforringelse.

Behovet for indsamling af nye seismiske data vurderes at være betydeligt, hvis kortlægningen af undergrunden og vurderingen af det geotermiske potentiale skal forbedres. Formålet med indsamling af nye seismiske data er i høj grad at sikre, at lokale forkastninger ikke bryder reservoirernes kontinuitet; især ønskes en afklaring om, hvorvidt Brønderslev Forkastningens udbredelse i undergrunden udgør et kontinuitetsproblem for en geotermisk boring på Virksomhedsvej. Desuden vil ny seismik kunne præcisere, hvor meget dybere Gassum Formationens er begravet ca. 5 km sydvest for den nuværende prognoselokalitet. Endvidere forventes en væsentligt forbedret kortlægning af lagene i undergrunden, end tilfældet er i dag.

# 2 Introduction

The general guidelines for suitable geothermal reservoirs in the subsurface fulfilling the requirements for safe, sustainable and economical 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 thickness of a reservoir needs to be at least 25 m thick and should be situated at a depth of 800–3000 m. The lower depth limit is selected due to the 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 the reservoirs at depths shallower than c. 800 meters (i.e. 20–30 ºC) is too cold for geothermal production depending on the method for production, e.g. if electricity-powered heat pumps are used to extract heat energy from the formation water.

This report presents an evaluation of the reservoir quality of the potential geothermal reservoirs with focus on the Gassum and Skagerrak formations – and to some degree the Frederikshavn and Haldager Sand formations – and the lateral continuity of the formations by analysing the existing cores, well logs, cuttings samples and seismic sections that are available from the archives at GEUS. The study is based on the relatively limited available relevant geological and geophysical information from the greater Brønderslev area which mainly includes the Fjerritslev Trough, but also the Skagerrak-Kattegat Platform north of the Børglum Fault (**Figure 1**).

The available 2D seismic data in the area of interest is mainly old and of poor to moderate quality (**Figure 1**). The Børglum-1 and Flyvbjerg-1 wells (from 1951 and 1958) are the primary data source in the Fjerritslev Trough south of the Børglum Fault zone. The Vedsted-1 and Haldager-1 wells south of the area of interest provide supporting data. The Sæby-1 well provides data from the Skagerrak-Kattegat Platform. The exact location of the Børglum Fault is not known due the sparse seismic data, of which most are old and of poor quality. The Børglum-1, Flyvbjerg-1, Vedsted-1 Haldager-1 and Sæby-1 wells were drilled to investigate whether sandstone layers from the Triassic–Jurassic section were hydrocarbon-bearing, but none of the wells encountered hydrocarbons with economic potential.

The Børglum-1 and Flyvbjerg-1 wells confirmed the presence of sandstones, in the Frederikshavn Formation (224 and 171 m), the Haldager Sand Formation (29 and 54 m) and the Gassum Formation. The Børglum-1 well reached total depth (TD) in the lower Gassum Formation (156+ m) without penetrating the entire formation, and the Flyvbjerg-1well drilled 178 m Gassum Formation and reached TD in the upper Skagerrak Formation (194+ m), proving the existence of potential geothermal reservoirs in the Fjerritslev Trough (**Figure 1**). The wells also encountered sandstones in the Flyvbjerg Formation between the Frederikshavn and Haldager Sand formations. However, the most promising reservoir sandstones in terms of exploitation of geothermal energy are the Gassum and Skagerrak formations (Mathiesen et al. 2009).

The more distant Vedsted-1 and Haldager-1 wells also encountered sandstones, in the Frederikshavn Formation (235 and 243 m) and the Haldager Sand Formation (75 and 155 m). Haldager-1 reached total depth before the Gassum Formation. Vedsted-1 drilled through the Gassum Formation (194 m) before entering total depth in the Skagerrak Formation (>36 m).

On the Skagerrak-Kattegat Platform, the presence of sandstones in the Frederikshavn Formation (105 m), the Haldager Sand Formation (20 m), the Gassum Formation (34 m) and in the Skagerrak Formation (538 m) was confirmed by the Sæby-1 well, proving the existence of potential geothermal reservoirs in the north of the Fjerritslev Trough (**Figure 1**).

# 3 Geological background

The Danish Basin and the Sorgenfrei-Tornquist Zone with the Fjerritslev Trough contains an Upper Permian–Mesozoic succession which is up to c. 9 km thick. The basin was formed by Late Carboniferous–Early Permian stretching of the crust and after deposition of syn-rift prisms of Rotliegendes coarse-grained clastic sediments followed a phase with thermal contraction, which lead to deposition of thick Zechstein salts overlain by Triassic sandstones, mudstones, carbonates and salts. These are overlain by Lower Jurassic mudstones, Middle Jurassic sandstones, Upper Jurassic–Lower Cretaceous mudstones and siltstones with few sandstones. The Mesozoic succession is terminated by carbonates and chalks up to c. 220 m thick on the Skagerrak-Kattegat Platform and up to approx. 400 m thick in the Fjerritslev Trough.

Geologically, the town of Brønderslev and the Flyvbjerg-1, Børglum-1, Vedsted-1 and Haldager-1 wells are located in the NW-SE running Fjerritslev Trough, Flyvbjerg-1and Børglum-1 in the northern part of the trough, and Vedsted-1 and Haldager-1 c. 25 km to the south in the central part of the trough (**Figure 1**). Vedsted-1 and Haldager-1 are structurally separated by the Haldager Fault. A major fault zone termed the Børglum Fault separates the Fjerritslev Trough from the Skagerrak-Kattegat Platform to the north where the Sæby-1 well is located (**Figure 1**). The fault zone plays an important role in the geological development of the licence area which is stressed by the fact that the potential geothermal reservoirs are significantly thicker in the trough than on the platform.

The five wells have proved sandstones of Late Triassic and Jurassic age distributed between the Frederikshavn, Haldager Sand, Gassum and Skagerrak formations. In the Fjerritslev Trough the Gassum Formation is located at a depth of 1300–1500 m with a total thickness close to 200 m (i.e. the Børglum-1 and Flyvbjerg-1 wells). The Skagerrak Formation was found below ~1500 m in the Flyvbjerg-1 well, which penetrated the upper 194 m of the formation, but seismic data indicates a total thickness of c. 2000 m. The composition of the Gassum Formation is well-known and consists mostly of interbedded sandstones, siltstones, mudstones and thin coal beds (Nielsen 2003). In the Børglum-1 and Flyvbjerg-1 wells sandstones are the dominating lithology. The composition of the Skagerrak Formation is less known due to much fewer well sections, but it is very variable consisting of sandstones, mudstones, conglomerates, siltstones and mixtures hereof.

In the Sæby-1 well situated on the Skagerrak-Kattegat Platform the Gassum Formation is located at 1077–1111 m with a total thickness of 34 m, while the Skagerrak Formation was found just below the Gassum Formation at 1111–1649 m with at total thickness of 538 m.

# 4 The lateral continuity of the potential reservoirs in the Northern Jutland area

The seismic data available in and around the Brønderslev area (see **Figure 1**) has mainly been acquired as part of previous hydrocarbon exploration activities. Most of these data were produced before 1970 and in the mid-eighties. The quality of these older seismic data is mostly poor to moderate (**Figure 1**).

The interpreted seismic data have been used 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 and the planned well site (**Figure 2**–**Figure 5**).

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.

## 4.1 Seismic interpretation and mapping (TWT maps)

As the quality of the seismic lines in the greater Brønderslev area mostly are poor the generation of depth maps and assessments of formation thicknesses involve significant uncertainty (+/- 10%); this is also true for the planned well site. Great effort has been invested in minimizing the uncertainty by scrutinizing relations between seismic lines and well data, thereby obtaining as precise an understanding of the subsurface as possible. The most important seismic lines are:

- DNJ-100
- DNJ-200
- DNJ-300
- DNJ-500

DNJ-100 (**Figure 2**) constitutes the most important seismic line as it connects the Flyvbjerg-1 and Haldager-1 wells and passes relatively close to the planned well site (c. 1.5 km). DNJ-200 connects the Børglum-1 and Flyvbjerg-1 wells, DNJ-500 connects the Vedsted-1 and Haldager-1 wells and DNJ-300 originates at the Flyvbjerg-1 well and crosses the Børglum Fault in the general direction of the Sæby-1 well.

Tracing of seismic horizons is impeded by the lack of seismic details. Seven horizons, however, have been identified and interpreted (see **Figure 2**–**Figure 5**):

- Base Upper Cretaceous (BUC, i.e. Base Chalk)
- Near Top Frederikshavn Formation
- Near Top Haldager Sand Formation
- Mid Cimmerian Unconformity (MCU, i.e. Base Haldager Sand Fm/Top Fjerritslev Fm)
- Near Top Gassum Formation
- Near Top Skagerrak Formation (=near Base Gassum Formation)
- Near Top Pre-Zechstein

The identification and definition of these seven horizons is based on an integration of stratigraphic well picks of the Børglum-1, Flyvbjerg-1, Vedsted-1, Haldager-1 and Sæby-1 wells with seismic reflections as interpreted from the seismic data. The subsequent seismic mapping comprises four horizons: Base Upper Cretaceous (BUC), Mid-Cimmerian Unconformity (MCU), Near Top Gassum Formation and Near Top Skagerrak Formation (see also **Enclosure 1**–**Enclosure 4**). Formation top and base has only been defined for the Gassum Formation; vertical extent of other formations with geothermal potential is not available.

It is important to be aware of the fact that the Gassum Formation does not constitute a single and homogenous reservoir; the formation is a stratigraphic interval composed of a mixture of alternating lithologies which is likely to include sandstones with reservoir potential. However, the seismic resolution in the study area is not good enough to define and correlate individual sandstone units within the seismic sequences. As no high resolution seismic data is available at the planned well site, it is not possible to identify individual sandstone horizons with geothermal potential within the Gassum Formation.

## 4.2 Identification of faults

Three major faults or fault zones have been identified, all of which are part of the Sorgenfrei-Tornquist Zone (**Figure 1**). The well-known NW-SE trending *Børglum Fault zone* separates the Fjerritslev Trough from the Skagerrak-Kattegat Platform and is clearly depicted in **Figure 4**. The Børglum fault zone is situated c. 10 km NE of the planned well site and is assumed to have no impact on lateral continuity of the potential reservoirs. Expectedly, the NW-SE trending *Haldager Fault* situated c. 20 km SW of the planned well site will not inflict on reservoir continuity either.

An *unnamed fault* clearly visible on the seismic line DNJ-100 is situated c. 3 km SW of the planned well site. This fault (informally termed the *Brønderslev Fault* in this report) is also interpreted to be present west of Brønderslev town based on the seismic lines AA4 and B9, both of which are of poor quality. Further west and east of Brønderslev town the Brønderslev Fault cannot be traced which may be due to the poor quality of the seismics and/or that the vertical displacement (throw) has died away. The Brønderslev Fault follows a NW-SE trend as the Brønderslev and Haldager faults and possibly does not inflict on reservoir continuity, however new seismic data with higher resolution are needed to determine the importance of the fault.

Minor faults were not identified within or close to the license area. However, the lack of good quality seismic data impedes the degree of seismic details and thus prohibits identification of lateral seismic variations. Thus, the presence of more faults cannot be ruled out.

## 4.3 Depth to and thickness of potential reservoirs at the planned well site

Accurate depth-conversion from time (seismic two-way travel time, TWT) to depth of the structural maps and seismic sections is difficult due to limited velocity data. Available TWT data only exist from the Børglum-1 and Haldager-1 wells. Haldager-1 is situated further away from the planned well site than Børglum-1 (**Figure 1**) and a pronounced fault separates Haldager-1 from the planned well site (**Figure 1**). All maps are thus depth-converted based on a time-depth relationship (Depth = 1.3423 * TWT – 53.995) derived from data from the Børglum-1 well (**Figure 6**).

Depth mapping of BUC, MCU, Near Top Gassum Formation and Near Top Skagerrak Formation (**Enclosure 1**–**Enclosure 4**) is hampered by the poor velocity data and it is thus not possible to generate precise depth structure maps. In this context gridding the interpreted surfaces with identified faults introducing "jumps" of contour intervals across faults or fault zones is of reduced value due to the uncertainty of the location and orientation of the contour intervals. For the Brønderslev Fault this uncertainty is further enlarged as the fault is only properly represented in the seismic line DNJ-100 and the orientation is uncertain. New seismic data is needed in order to map faults more precisely and in order to generate precise depth structure maps.

Despite the uncertainties in mapping exact depths the spatial representation of structural surfaces (e.g. formation tops) is believed to be fairly accurate and in correspondence with regional mapping. Thus, the SW deepening trend of the near Top Gassum Formation surface (**Enclosure 3**) and the near Top Skagerrak Formation surface (**Enclosure 4**) indicates deeper burial and higher temperatures of these two formations. If the currently planned well location is moved c. 5 km to the SW the expected burial increase of the Gassum Formation may be in the range of c. 400–700 m corresponding to a temperature increase in the range of c. 11–19 °C. However, moving into more distal parts of the depositional basin may cause a slight reduction in grain size and net sand thickness and increasing depth leads to reduced permeability.

Shot Point 1360 of the seismic line DNJ-100 is located c. 1.5 km away from the planned well site (**Figure 1**). The TWT of the identified seismic horizons in shot point 1360 are depth-converted based on the mentioned Børglum-1 time-depth relationship (**Table 1**). From the identified formation tops and bases the thickness of the Gassum and Skagerrak formations can be estimated (**Table 2**). Identification of the base (and thus formation thickness) of the Frederikshavn and Haldager Sand formations has not been done as the relevant reflectors are hard to recognize and trace.

**Table 1:** TWT converted to depths for identified seismic horizons of the seismic line DNJ-100 at shot point 1360.

| **Seismic horizon** | **Two way travel time** (msec) | **Depth** (m) |
|---|---|---|
| Base Upper Cretaceous | 436 | 531 |
| Near Top Frederikshavn Fm. | 620 | 778 |
| Near Top Haldager Sand Fm. | 824 | 1052 |
| Mid Cimmerian Unconformity | 864 | 1106 |
| Near Top Gassum Fm. | 1036 | 1337 |
| Near Top Skagerrak Fm. | 1124 | 1455 |
| Near Top Pre-Zechstein | 2592 | 3425 |

**Table 2:** Estimated formation thicknesses based on the seismic line DNJ-100.

| **Formation** | **Formation thickness** (m) |
|---|---|
| Frederikshavn | – |
| Haldager Sand | – |
| Gassum | 118 |
| Skagerrak | 1970 |

It is worth noting that the seismic-derived formation thickness of the Gassum Formation at the planned well site (**Table 2**) is considerably smaller than the measured formation thickness in the nearest well, Flyvbjerg-1 (**Table 15**–**Table 18**); c. 118 m compared to 178 m. From the interpretation of the seismic line DNJ-100 (**Figure 2**) a thickening of the Gassum Formation from the planned well site towards the Flyvbjerg-1 well is indicated corresponding to a TWT increase from 88 msec to 138 msec. As the proportion between TWT thickness (88 msec/138 msec = 0.64) is almost identical to proportion between TWT thickness in meters (88 msec/138 msec = 0.66) it is concluded that the expected formation thickness of 118 m at the planned well site is likely.

# 5 Assessment of the reservoir quality in the Brønderslev area

The evaluation of the reservoir quality in the study area is based on the data presently available. The data primarily comprises well logs, cuttings samples, conventional cores and seismic data that have been acquired over a long time span during hydrocarbon exploration activities. The investigated Frederikshavn, Haldager Sand, Gassum and Skagerrak formations are also known from other areas owing to activities related to geothermal energy and gas storage.

The most promising geothermal reservoirs in the Northern part of Jutland are considered to be sandstones of the Gassum Formation an in part the Skagerrak Formation. The distribution and petrophysical properties of the more shallowly buried formations in the area (i.e. the Haldager Sand, Flyvbjerg and Frederikshavn formations) are less known and the assessment of their geothermal potential is more uncertain and considered of less importance due their low temperatures; these shallow formations may, however, be of interest and have been evaluated.

In the Fjerritslev Trough the Børglum-1 and Flyvbjerg-1 wells are the primary data source with additional data input from the more distant Vedsted-1 and Haldager-1 wells. North of the Børglum Fault zone, on the Skagerrak-Kattegat Platform, the primary information concerning the potential reservoirs is based on the Sæby-1 well.

## 5.1 Reservoir quality controlling parameters

Based on the well log interpretation a set of parameters controlling reservoir quality is defined (**Table 3**). Good reservoir properties are defined on the basis of two criteria: a $V_{shale}$ cut-off and a porosity cut-off. The net sand thickness, net-to-gross ratio (N/G) and average porosity are calculated by the use of different cut-off values in order to estimate and document the sensitivity of the quantitative log interpretation. Sand/sandstone is defined as 'sand' with an acceptable clay content of up to 30%, which is standard praxis within reservoir evaluations.

The 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. The reservoir parameters have been calculated for four different minimum porosity values (0, 10, 15 and 20%) in order to illustrate the sensitivity of net sand thickness when applying constraints to the porosity (the 0% scenario corresponds to no porosity cut-off).

In **Sections 5.2–5.6** the principles behind determining the reservoir parameters are discussed in detail. The results of the petrophysical evaluation are listed in **Table 7**–**Table 22**.

**Table 3:** Definition of reservoir parameters

| Reservoir parameter | Definition |
|---|---|
| *Formation thickness* | The distance between the upper and lower boundary of a formation |
| *Sand/sandstone* | Sand/sandstone with a maximum clay content of 30% |
| *Gross sand thickness* | The total (cumulative) thickness of all identified *Sand/sandstone* layers in a given formation |
| *Net sand* | *Sand/sandstone* layers exhibiting good reservoir quality properties (controlled by porosity cut-off) |
| *Net sand thickness* | The total (cumulative) thickness of all layers of *Net sand* |
| *Net-to-gross ratio (N/G)* | *Net sand thickness* divided by *Formation thickness*; N/G is calculated for each formation separately |
| *Average porosity* | The average effective porosity determined by averaging of all porosity values defined for every *Net sand* layer |
| *Estimated gas permeability* | The average gas permeability of all sandstone layers in the net sand section |
| *Estimated reservoir permeability* | Multiplication of *Estimated gas permeability* with an upscaling factor of 1.25 |
| *Transmissivity* | Multiplication of *Estimated reservoir permeability* with *Net sand thickness* |

## 5.2 Database, log quality and petrophysical evaluation

The petrophysical evaluation of the wells is based on the various logs acquired in the wells (**Table 4**), and it encompasses assessment of the porosity and permeability based on the amount of clay in the formation, if possible on the basis of the available logs. Log quality is therefore of great importance when assessing reservoir parameters. Results from the well log analysis are combined with lithological descriptions of the rock samples and core analysis data to strengthen the overall petrophysical evaluation. **Table 5** shows the availability of cores and sidewall cores for analysis.

A standard porosity log has not been acquired for the Børglum-1 (**Figure 7**–**Figure 8**), Vedsted-1 (**Figure 11**–**Figure 12**) and Haldager-1 (**Figure 13**) wells, and instead the porosity was determined from a combined use of a deep-reading resistivity log and core porosity data. A full petrophysical evaluation of the Flyvbjerg-1 well (**Figure 9**–**Figure 10**) is not possible due to an incomplete log suite and a very limited amount of core analysis data – thus, the evaluation is based mainly on the lithology description available from the Well Completion Report (DAPCO 1958a). The thickness of the reservoir sand (net sand) is also assessed, and is based on a minimum porosity and maximum clay content for the reservoir sand. The petrophysical logs recorded in the Sæby-1 well are generally of good and reliable quality, and include gamma ray, caliper, neutron, sonic, density and resistivity logs (**Table 4** and **Figure 14**–**Figure 15**). The results of the petrophysical evaluation are listed in **Table 7**–**Table 22**.

**Table 4:** List of raw logs and interpreted log curves for the Flyvbjerg-1, Børglum-1, Vedsted-1, Haldager-1 and Sæby-1 wells

| Log name | Description | Unit | Application |
|---|---|---|---|
| GR | Gamma ray log | API | Measured natural radioactivity |
| GRnorm | Gamma ray log | API | Measured natural radioactivity |
| DT | Sonic log | microsec/ft | Acoustic log measured travel time (/velocity) |
| CALI | Caliper log | inches | Measured borehole size (diameter) |
| CALI_nuc | Caliper log | inches | Measured borehole size (diameter) |
| ILD | Deep-reading resistivity log | ohm | Induction log |
| LLS | Shallow-reading resistivity log | ohm | Laterolog |
| LLD | Deep-reading resistivity log | ohm | Laterolog |
| 16ft | Older resistivity log | ohm | |
| 38in | Older resistivity log | ohm | |
| 10in | Older resistivity log | ohm | |
| 18F8 | Older resistivity log | ohm | |
| 64in | Older resistivity log | ohm | |
| NPHI | Neutron log | fraction | Measured apparent porosity |
| RHOB | Density log | $g/cm^3$ | Measured bulk density |
| PERM_log | Log-derived permeability | mD | Interpreted/calculated log curve |
| Kh_a | Core permeability | mD | Measured horizontal gas permeability |
| CPERM_GEUS | Core permeability | mD | Measured gas permeability |
| PHIE | Log-derived *effective* porosity | fraction | Interpreted/calculated log curve |
| CPOR | Core porosity | % | Measured effective porosity |
| CPOR_GEUS | Core porosity | % | Measured effective porosity at GEUS |

**Table 5:** Stratigraphic reservoir units, depth intervals and cored sections

| Well | Stratigraphic reservoir unit | Depth interval [m MD] | Cores | Sidewall cores |
|---|---|---|---|---|
| **Børglum-1** | Frederikshavn Fm | 755–979 | 838.1–844.3<br>914.4–917.5 | No sidewall cores were cut |
| | Haldager Sand Fm | 1047–1076 | 1043.3–1045.5<br>1046.4–1048.2 | No sidewall cores were cut |
| | Gassum Fm | 1371–1518 | 1371.0–1375.6<br>1431.7–1437.7<br>1462.4–1467.6<br>1492.9–1499.0 | No sidewall cores were cut |
| | Skagerrak Fm | [1] | – | – |
| **Flyvbjerg-1** | Frederikshavn Fm | 750–921 | 804.0–810.0<br>879.0–885.0 | No sidewall cores were cut |
| | Haldager Sand Fm | 990–1044 | No cores were cut | No sidewall cores were cut |
| | Gassum Fm | 1308–1504 | 1316.0–1322.0<br>1396.0–1402.0<br>1483.0–1489.0 | No sidewall cores were cut |
| | Skagerrak Fm | 1504–1698 [2] | – | – |
| **Vedsted-1** | Frederikshavn Fm | 841–1076 | 1034.0–1040.0 | No sidewall cores were cut |
| | Haldager Sand Fm | 1149–1224 | 1149.0–1157.0 | No sidewall cores were cut |
| | Gassum Fm | 1749–2037 | 1775.0–1780.0<br>1865.0–1870.0<br>2006.0–2012.0 | 1788.0<br>1821.2<br>1920.8<br>1926.2 |
| | Skagerrak Fm | 2037–2073 [2] | 2062.0–2068.0 | No sidewall cores were cut |
| **Haldager-1** | Frederikshavn Fm | 785–1028 | 785.0–993.3 | 908.3 |
| | Haldager Sand Fm | 1125–1280 | 1153.7–1159.8<br>1201.8–1204.9<br>1219.8–1222.9<br>1271.9–1277.4 | 1127.8<br>1170.7<br>1171.3<br>1230.5<br>1261.9 |
| | Gassum Fm | [3] | – | – |
| | Skagerrak Fm | [1] | – | – |
| **Sæby-1** | Frederikshavn Fm | 606–711 | No cores were cut | 610.0<br>623.0<br>652.0 |
| | Haldager Sand Fm | 801–821 | No cores were cut | 820.0 |
| | Gassum Fm | 1077–1111 | No cores were cut | 1079.0 |
| | Skagerrak Fm | 1111–1649 | 1612.2–1630.0 | 1167.0<br>1169.0<br>1298.0<br>1305.0<br>1328.0<br>1441.0<br>1525.0<br>1601.0<br>1603.0<br>1609.0<br>1641.0<br>1643.0 |

[1] Total depth reached before entering the Skagerrak Formation
[2] Total depth reached within the Skagerrak Formation; formation thickness unknown
[3] Total depth reached before entering the Gassum Formation

## 5.3 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. For each studied well a lithology column, bounded by the gamma-ray and sonic logs (if available), is generated for all formations with geothermal potential (**Figure 7**–**Figure 15**). In **Enclosure 5**–**Enclosure 9** a more precise lithologic description is given for potential sandstone sections in each well based on descriptions of core and cuttings samples.

## 5.4 Distinguishing between sand/sandstones and silt/siltstones in well logs

Sand and silt are identical sediment types distinguished by grain size. Sand/sandstones constitute potential reservoirs whereas silt/siltstones do not. This fact poses a challenge with respect to well log interpretation as sand and silt in general respond similarly to log signals. The gamma ray reading is not able to distinguish sand from silt; consequently, a logged well section with low gamma reading may be interpreted either as a potential reservoir (sand) or as a non-reservoir (silt). To identify the actual lithology behind the gamma ray reading lithology descriptions (cuttings, cores, sidewall cores) available from the well completion report should be included.

In general, sand occurs significantly more frequently compared to silt and the challenge of separating sand from silt may only be relevant on few occasions. However, the effects of interpreting silt as sand (non-reservoir as reservoir) is potentially potent, and it is recommendable to use the means available to secure a correct lithological interpretation.

## 5.5 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 6**. The shale volume ($V_{shale}$) is then calculated as follows:

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

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.

The log-derived effective porosity (PHIE) is determined from a clay corrected density log. A correct determination of the amount of clay is essential, because the clay volume directly affects the porosity and permeability interpretations.

**Table 6:** Response parameters for the gamma-ray (GR) log.

| Formation | Well | Formation interval (m MD) | GR_clean (API) | GR_clay (API) | Clay density (g/cc) |
|---|---|---|---|---|---|
| Frederikshavn | **Børglum-1** | 755–979 | 32 | 120 | 2.40 |
| | **Flyvbjerg-1** | 750–921 | 37 | 150 | 2.40 |
| | **Vedsted-1** | 841–1076 | 65 | 150 | 2.40 |
| | **Haldager-1** | 785–1028 | 48 | 150 | 2.40 |
| | **Sæby-1** | 606–711 | 30 | 120 | 2.40 |
| Haldager Sand | **Børglum-1** | 1047–1076 | 32 | 120 | 2.40 |
| | **Flyvbjerg-1** | 990–1044 | 37 | 150 | 2.40 |
| | **Vedsted-1** | 1149–1224 | 65 | 150 | 2.40 |
| | **Haldager-1** | 1125–1280 | 48 | 150 | 2.40 |
| | **Sæby-1** | 801–821 | 30 | 120 | 2.40 |
| Gassum | **Børglum-1** | 1371–1518 | 32 | 120 | 2.40 |
| | **Flyvbjerg-1** | 1308–1504 | 37 | 150 | 2.40 |
| | **Vedsted-1** | 1749–2037 | 65 | 150 | 2.40 |
| | **Haldager-1** | [1] | – | – | 2.40 |
| | **Sæby-1** | 1077–1111 | 30 | 150 | 2.40 |
| Skagerrak | **Børglum-1** | [2] | – | – | 2.40 |
| | **Flyvbjerg-1** | 1504–1698 [3] | 37 | 150 | 2.40 |
| | **Vedsted-1** | 2037–2073 [3] | 65 | 150 | 2.40 |
| | **Haldager-1** | [2] | – | – | 2.40 |
| | **Sæby-1** | 1111–1444 | 40 | 200 | 2.40 |
| | | 1444–1639 | 70 | 400 | 2.40 |
| | | 1639–1649 | | | 2.40 |

1) Total depth reached before entering the Gassum Formation
2) Total depth reached before entering the Skagerrak Formation
3) Total depth reached within the Skagerrak Formation; formation thickness unknown

## 5.6 Evaluation of permeability

Technically, it is not possible to log the permeability in a well; however, a permeability estimate can be derived from the estimated porosity 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; as a rule of thumb the gas permeability is approx. twice the size of the liquid permeability.

Most porosity and permeability measurements conventional core analysis were performed at standard conditions, i.e. with a sleeve pressure of 400 psi and not at formation pressure where grains and particles are squeezed closer together resulting in reduction of porosity and permeability. Thus, the measured porosities and permeabilities presented in Springer & Haslund (1985) may overestimate porosities and permeabilities at reservoir conditions.

### 5.6.1 The regional porosity-permeability relation

GEUS has established a porosity-permeability relation using a regional dataset, which encompasses core analysis data from several Danish onshore wells and including the Bunter Sandstone, Gassum and Haldager Sand formations (**Figure 16**). 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 = $a\cdot(\text{PHIE})^b$, 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:

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

where PHIE is a fraction and the log-derived gas permeability (PERM_log) is measured in mD. This expression has been used for calculating PERM_log in the Frederikshavn, Haldager Sand and Gassum formations. The regional porosity-permeability relation fits the distribution of Skagerrak Formation data points poorly and is replaced by an adjusted relation (**Figure 19**) using the following mathematical expression:

$$\textbf{PERM\_log} = 4\cdot 10^{6}\cdot(\text{PHIE})^{7.070}$$

### 5.6.2 The depth-porosity relationship

The Gassum Formation is the main geothermal target in the Danish subsurface and has been investigated more thoroughly than other sandstone reservoirs. A total of 35 onshore wells have encountered the Gassum Formation and provided well log data from which net sand and the average effective porosity for net sand have been estimated. Plotting depth (defined as top of formation) against average porosity provide a regional depth-porosity trend (**Figure 18**) that may be used for estimating porosity when formation depths are known.

The depth-porosity values of Børglum-1, Vedsted-1 and Sæby-1 have been emphasized in **Figure 18**; Note that in Børglum-1 the porosity seems overestimated compared to the trend whereas in Vedsted-1 and Sæby-1 the porosity seem underestimated. It is resolved that a more reliable porosity assessment is obtained for the planned well site based on the expression for the regional trend (y = -0.0033 x depth + 28.474).

### 5.6.3 Upscaling

In core analysis permeability measurements are made on flawless plugs and e.g. cracks and larger inhomogeneities occurring on reservoir scale are not accounted for in the porosity-permeability relation (**Figure 16**). Such upscaling phenomena may influence critically on permeability and thus the porosity-permeability relation and ultimately the log-derived permeability estimate are affected. In fact, comparing log-derived permeability estimates with well pumping tests has proven the permeability estimates to be somewhat conservative in general. In order to solve the issue of upscaling and also converting gas permeability to liquid permeability GEUS has, based on extensive datasets and general experience, developed an upscaling factor with the value of 1.25; multiplying 1.25 with the log-derived gas permeability estimate provides a liquid permeability estimate scaled for the reservoir (see **Table 7**–**Table 23**).

It should be born in mind that both the porosity-permeability relation and the upscaling factor are based on the study and evaluation of regional datasets. Locally, particular geological conditions may control the magnitude of porosity and permeability and cause significant deviations from the regional porosity-permeability relation.

## 5.7 Petrophysical evaluation of the Frederikshavn Formation

The Frederikshavn Formation has been encountered in the Børglum-1, Flyvbjerg-1, Vedsted-1, Haldager-1 and Sæby-1 wells. The results of the petrophysical evaluation are listed in **Table 7**–**Table 10**.

**Table 7:** Reservoir parameters of the Frederikshavn Formation for net sand: Shale cut-off applied, porosity cut-off applied. Net sand defined as sandstone with < 30% shale, and porosity > 0%.

| **Well** | **Formation interval** (m MD) | **Formation thickness** (m) | **Gross sand thickness** (m) | **Net sand thickness** (m) | **N/G** | **Avg. porosity** (%) | **Estimated gas perm.** (mD) | **Estimated res. perm.** (mD) |
|---|---|---|---|---|---|---|---|---|
| **Børglum-1** | 755–979 | 224 | 74.3 | 74.3 | 0.33 | 14 | 65 | 80 |
| **Flyvbjerg-1** | 750–921 | 171 | 115.3 | 115.3 | 0.67 | 1) | 1) | 1) |
| **Vedsted-1** | 841–1076 | 235 | 38.1 | 38.1 | 0.16 | 13 | 35 | 45 |
| **Haldager-1** | 785–1028 | 243 | 56.4 | 56.4 | 0.23 | 28 | 1400 | 1750 |
| **Sæby-1** | 606–711 | 105 | 53.2 | 53.2 | 0.51 | 30 | 1250 | 1560 |

1) Parameter cannot be estimated due to incomplete log suite in the Flyvbjerg-1 well

**Table 8:** Reservoir parameters of the Frederikshavn Formation for net sand: Shale cut-off applied, porosity cut-off applied. Net sand defined as sandstone with < 30% shale, and porosity > 10%.

| **Well** | **Formation interval** (m MD) | **Formation thickness** (m) | **Gross sand thickness** (m) | **Net sand thickness** (m) | **N/G** | **Avg. porosity** (%) | **Estimated gas perm.** (mD) | **Estimated res. perm.** (mD) |
|---|---|---|---|---|---|---|---|---|
| **Børglum-1** | 755–979 | 224 | 74.3 | 71.2 | 0.32 | 15 | 70 | 90 |
| **Flyvbjerg-1** | 750–921 | 171 | 115.3 | 1) | 1) | 1) | 1) | 1) |
| **Vedsted-1** | 841–1076 | 235 | 38.1 | 30.8 | 0.13 | 14 | 40 | 50 |
| **Haldager-1** | 785–1028 | 243 | 56.4 | 54.1 | 0.22 | 29 | 1450 | 1813 |
| **Sæby-1** | 606–711 | 105 | 53.2 | 52.3 | 0.50 | 31 | 1300 | 1625 |

1) Parameter cannot be estimated due to incomplete log suite in the Flyvbjerg-1 well

**Table 9:** Reservoir parameters of the Frederikshavn Formation for net sand: Shale cut-off applied, porosity cut-off applied. Net sand defined as sandstone with < 30% shale, and porosity > 15%.

| Well | Formation interval (m MD) | Formation thickness (m) | Gross sand thickness (m) | Net sand thickness (m) | N/G | Avg. porosity (%) | Estimated gas perm. (mD) | Estimated res. perm. (mD) |
|---|---|---|---|---|---|---|---|---|
| Børglum-1 | 755–979 | 224 | 74.3 | 22.4 | 0.10 | 19 | 160 | 200 |
| Flyvbjerg-1 | 750–921 | 171 | 115.3 | [1)] | [1)] | [1)] | [1)] | [1)] |
| Vedsted-1 | 841–1076 | 235 | 38.1 | 8.5 | 0.04 | 16 | 65 | 80 |
| Haldager-1 | 785–1028 | 243 | 56.4 | 43.6 | 0.18 | 34 | 1800 | 2250 |
| Sæby-1 | 606–711 | 105 | 53.2 | 52.3 | 0.50 | 31 | 1300 | 1625 |

[1)] Parameter cannot be estimated due to incomplete log suite in the Flyvbjerg-1 well

**Table 10:** Reservoir parameters of the Frederikshavn Formation for net sand: Shale cut-off applied, porosity cut-off applied. Net sand defined as sandstone with < 30% shale, and porosity > 20%.

| Well | Formation interval (m MD) | Formation thickness (m) | Gross sand thickness (m) | Net sand thickness (m) | N/G | Avg. porosity (%) | Estimated gas perm. (mD) | Estimated res. perm. (mD) |
|---|---|---|---|---|---|---|---|---|
| Børglum-1 | 755–979 | 224 | 74.3 | 8.8 | 0.04 | 21 | 235 | 295 |
| Flyvbjerg-1 | 750–921 | 171 | 115.3 | [1)] | [1)] | [1)] | [1)] | [1)] |
| Vedsted-1 | 841–1076 | 235 | 38.1 | 0 | 0 | – | – | – |
| Haldager-1 | 785–1028 | 243 | 56.4 | 43.6 | 0.18 | 34 | 1800 | 2250 |
| Sæby-1 | 606–711 | 105 | 53.2 | 50.5 | 0.48 | 31 | 1325 | 1650 |

[1)] Parameter cannot be estimated due to incomplete log suite in the Flyvbjerg-1 well

## 5.8 Petrophysical evaluation of the Haldager Sand Formation

The Haldager Sand Formation has been encountered in the Børglum-1, Flyvbjerg-1, Vedsted-1, Haldager-1 and Sæby-1 wells. The results of the petrophysical evaluation are listed in **Table 11**–**Table 14**.

**Table 11:** Reservoir parameters of the Haldager Sand Formation for net sand: Shale cut-off applied, porosity cut-off applied. Net sand defined as sandstone with < 30% shale, and porosity > 0%.

| Well | Formation interval (m MD) | Formation thickness (m) | Gross sand thickness (m) | Net sand thickness (m) | N/G | Avg. porosity (%) | Estimated gas perm. (mD) | Estimated res. perm. (mD) |
|---|---|---|---|---|---|---|---|---|
| Børglum-1 | 1047–1076 | 29 | 16 | 16 | 0.54 | 22 | 65 | 82 |
| Flyvbjerg-1 | 990–1044 | 54 | 46 | 46 | 0.85 | [1)] | [1)] | [1)] |
| Vedsted-1 | 1149–1224 | 75 | 65 | 65 | 0.86 | 29 | 950 | 1200 |
| Haldager-1 | 1125–1280 | 155 | 126 | 126 | 0.81 | 26 | 730 | 913 |
| Sæby-1 | 801–821 | 20 | 11 | 11 | 0.53 | 27 | 870 | 1090 |

[1)] Parameter cannot be estimated due to incomplete log suite in the Flyvbjerg-1 well

**Table 12:** Reservoir parameters of the Haldager Sand Formation for net sand: Shale cut-off applied, porosity cut-off applied. Net sand defined as sandstone with < 30% shale, and porosity > 10%.

| Well | Formation interval (m MD) | Formation thickness (m) | Gross sand thickness (m) | Net sand thickness (m) | N/G | Avg. porosity (%) | Estimated gas perm. (mD) | Estimated res. perm. (mD) |
|---|---|---|---|---|---|---|---|---|
| Børglum-1 | 1047–1076 | 29 | 16 | 16 | 0.54 | 22 | 65 | 82 |
| Flyvbjerg-1 | 990–1044 | 54 | 46 | [1)] | [1)] | [1)] | [1)] | [1)] |
| Vedsted-1 | 1149–1224 | 75 | 65 | 65 | 0.86 | 29 | 950 | 1200 |
| Haldager-1 | 1125–1280 | 155 | 126 | 125 | 0.81 | 26 | 730 | 913 |
| Sæby-1 | 801–821 | 20 | 11 | 11 | 0.53 | 27 | 870 | 1090 |

[1)] Parameter cannot be estimated due to incomplete log suite in the Flyvbjerg-1 well

**Table 13:** Reservoir parameters of the Haldager Sand Formation for net sand: Shale cut-off applied, porosity cut-off applied. Net sand defined as sandstone with < 30% shale, and porosity > 15%.

| Well | Formation interval (m MD) | Formation thickness (m) | Gross sand thickness (m) | Net sand thickness (m) | N/G | Avg. porosity (%) | Estimated gas perm. (mD) | Estimated res. perm. (mD) |
|---|---|---|---|---|---|---|---|---|
| **Børglum-1** | 1047–1076 | 29 | 16 | 14 | 0.48 | 23 | 660 | 825 |
| **Flyvbjerg-1** | 990–1044 | 54 | 46 | 1) | 1) | 1) | 1) | 1) |
| **Vedsted-1** | 1149–1224 | 75 | 65 | 64 | 0.85 | 29 | 960 | 1200 |
| **Haldager-1** | 1125–1280 | 155 | 126 | 116 | 0.75 | 27 | 800 | 1000 |
| **Sæby-1** | 801–821 | 20 | 11 | 11 | 0.53 | 27 | 900 | 1125 |

1) Parameter cannot be estimated due to incomplete log suite in the Flyvbjerg-1 well

**Table 14:** Reservoir parameters of the Haldager Sand Formation for net sand: Shale cut-off applied, porosity cut-off applied. Net sand defined as sandstone with < 30% shale, and porosity > 20%.

| Well | Formation interval (m MD) | Formation thickness (m) | Gross sand thickness (m) | Net sand thickness (m) | N/G | Avg. porosity (%) | Estimated gas perm. (mD) | Estimated res. perm. (mD) |
|---|---|---|---|---|---|---|---|---|
| **Børglum-1** | 1047–1076 | 29 | 16 | 8 | 0.28 | 27 | 1050 | 1313 |
| **Flyvbjerg-1** | 990–1044 | 54 | 46.8 | 1) | 1) | 1) | 1) | 1) |
| **Vedsted-1** | 1149–1224 | 75 | 65 | 62 | 0.82 | 29 | 990 | 1238 |
| **Haldager-1** | 1125–1280 | 155 | 126 | 103 | 0.66 | 28 | 880 | 1100 |
| **Sæby-1** | 801–821 | 20 | 11 | 9 | 0.45 | 29 | 1015 | 1269 |

1) Parameter cannot be estimated due to incomplete log suite in the Flyvbjerg-1 well

## 5.9 Petrophysical evaluation of the Gassum Formation

The Gassum Formation has been encountered in the Børglum-1, Flyvbjerg-1, Vedsted-1 and Sæby-1 wells. The Haldager-1 well does not reach the Gassum Formation. In the Fjerritslev Trough the Gassum Formation is encountered in the depth interval 1308–1518 m in Børglum-1 and Flyvbjerg-1, and somewhat deeper, 1749–2037 m, in Vedsted-1. On the Skagerrak-Kattegat Platform the Gassum Formation is located more shallowly at 1077–1111 m. The development of the Gassum Formation in the four wells varies considerably, both with respect to thickness, clay content and porosity. In Flyvbjerg-1 and Vedsted-1 the Gassum Formation appears at 2 and 3 depth intervals due to the geological evolution in this area; this implies a sedimentation pattern alternating between deposition of sediments belonging to the Gassum and Fjerritslev formations. The results of the petrophysical evaluation are listed in **Table 15**–**Table 18**.

### 5.9.1 The Børglum-1 well

A rather thick and almost homogeneous reservoir interval has been interpreted from the log data in the Børglum-1 well (**Figure 8**). Interpreted porosities are quite high but subject to some uncertainty because a standard porosity log is not available from the well. On the other hand, the core-porosity measurements, which form the basis of calibrating the log porosity, are generally high and range from 22–40%, and the core data thus support and guide the log interpretation. The cored sandstones are described as predominantly fine-grained (DAPCO & DGU 1951). Variations in lithology are summarized in **Enclosure 5**.

Similarly, a limited number of core permeability measurements in the range 5–5000 mD are available from the Børglum-1 well, indicating that in general a high permeability level apply to the Gassum Formation in this well. The permeability has not been logged, and the estimated permeability values listed in **Table 15**–**Table 18** are modelled from a combined use of core analysis data and the regional GEUS permeability model for the Gassum Formation, which presumes the existence of a robust relationship between porosity, permeability and grain size. The regional model includes core analysis data from the Børglum-1, Vedsted-1, Gassum-1, Farsø-1, but not from the Sæby-1 well as this well was not cored in the Gassum Formation.

### 5.9.2 The Flyvbjerg-1 well

In the Flyvbjerg-1 well, the Gassum Formation sandstones are predominantly medium-grained, but occasionally coarse-grained (DAPCO 1958a). In **Enclosure 6** the variations in lithology are summarized. The Flyvbjerg-1 well is cored in the Gassum Formation, but no original core analysis data exist in GEUS' archive from this well. Very recently, however, GEUS analyzed six core plugs from the interval 1316–1487 m MD, and these samples point to porosity and permeability values that are very similar to those found in the Børglum-1 core.

### 5.9.3 The Vedsted-1 well

Compared to the Børglum-1, Flyvbjerg-1 and Sæby-1 wells the Gassum Formation of Vedsted-1 is thicker, but a relatively higher content of shale keeps the net sand thickness and N/G values low. The sandstones are predominantly fine-grained, frequently medium-grained and occasionally coarse-grained (DAPCO 1958b). Variations in lithology are summarized in **Enclosure 8**.

### 5.9.4 The Sæby-1 well

In the Sæby-1 well, the Gassum Formation is thin with relatively high clay content, and only a minor net reservoir interval is encountered in the well. The sandstones of the interval 1090–1100 m MD are described as medium to coarse-grained (see Dansk Olie og Gas Produktion A/S 1985). Variations in lithology are summarized in **Enclosure 9**.

### 5.9.5 Combining well information

The petrophysical evaluation of the Gassum Formation indicates that the reservoir sand thickness is quite large in the Børglum-1 well, in contrast to the Sæby-1 well in which only a thin interval having reasonably high reservoir quality has been interpreted from the log data.

The Gassum Formation in the Børglum-1 well is characterized by high porosities – and in general also high permeabilities. Despite that the log data from the Børglum-1 well are incomplete, the available log and core analysis data indicates that the Gassum Formation has a geothermal potential. If a minimum porosity of 20% is required, the reservoir sand thickness is about 75 m in the Børglum-1 well. The well did not reach the base of the formation, and additional sandstones are assumed to be present below TD in the well (Nielsen 2003).

It has not been possible to evaluate the old and very incomplete log data acquired in the Flyvbjerg-1 well. Nevertheless, information on the lithology of the Gassum Formation – including grain size assessments – is presented in the Well Completion Report (DAPCO 1958a). Based on this information and the log patterns it may be concluded that the Gassum Formation in Flyvbjerg-1 is thicker (178 m) than in Børglum-1 (min.147 m; **Table 15**–**Table 18**), but the proportion of non-reservoir mudstones and muddy sandstones are higher in Flyvbjerg-1. However, due to larger gross thickness of the formation it is assumed that the net sand thickness in Flyvbjerg-1 is comparable to the estimated values for Børglum-1. The Gassum Formation is thus considered to constitute a good to excellent reservoir in the Børglum-1 and Flyvbjerg-1 wells (Nielsen 2003).

**Table 15:** Reservoir parameters of the Gassum Formation for net sand: Shale cut-off applied, porosity cut-off applied. Net sand defined as sandstone with < 30% shale, and porosity > 0%.

| **Well** | **Formation interval** (m MD) | **Formation thickness** (m) | **Gross sand thickness** (m) | **Net sand thickness** (m) | **N/G** | **Avg. porosity** (%) | **Estimated gas perm.** (mD) | **Estimated res. perm.** (mD) |
|---|---|---|---|---|---|---|---|---|
| **Børglum-1** | 1371–1518 | 147 [1)] | 86 [1)] | 86 [1)] | 0.59 | 29 | 1100 | 1375 |
| **Flyvbjerg-1** | 1308–1330<br>1348–1504 | 178 | 122 | 122 | 0.69 | [2)] | [2)] | [2)] |
| **Vedsted-1** | 1749–1799<br>1818–1823<br>1898–2037 | 194 | 109 | 109 | 0.56 | 14 | 50 | 63 |
| **Sæby-1** | 1077–1111 | 34 | 23 | 23 | 0.68 | 20 | 250 | 313 |

[1)] The entire Gassum Formation has not been penetrated; Thus *Formation thickness* is a minimum value and *Gross sand thickness* and *Net sand thickness* may be larger, *N/G* may be higher or lower
[2)] Parameter cannot be estimated due to incomplete log suite in the Flyvbjerg-1 well

**Table 16:** Reservoir parameters of the Gassum Formation for net sand: Shale cut-off applied, porosity cut-off applied. Net sand defined as sandstone with < 30% shale, and porosity > 10%.

| **Well** | **Formation interval** (m MD) | **Formation thickness** (m) | **Gross sand thickness** (m) | **Net sand thickness** (m) | **N/G** | **Avg. porosity** (%) | **Estimated gas perm.** (mD) | **Estimated res. perm.** (mD) |
|---|---|---|---|---|---|---|---|---|
| **Børglum-1** | 1371–1518 | 147 [1)] | 86 [1)] | 86 [1)] | 0.59 | 29 | 1100 | 1375 |
| **Flyvbjerg-1** | 1308–1330<br>1348–1504 | 178 | 122 | [2)] | [2)] | [2)] | [2)] | [2)] |
| **Vedsted-1** | 1749–1799<br>1818–1823<br>1898–2037 | 194 | 109 | 88 | 0.45 | 15 | 65 | 81 |
| **Sæby-1** | 1077–1111 | 34 | 23 | 21 | 0.62 | 20 | 260 | 325 |

[1)] The entire Gassum Formation has not been penetrated; Thus *Formation thickness* is a minimum value and *Gross sand thickness* and *Net sand thickness* may be larger, *N/G* may be higher or lower
[2)] Parameter cannot be estimated due to incomplete log suite in the Flyvbjerg-1 well

**Table 17:** Reservoir parameters of the Gassum Formation for net sand: Shale cut-off applied, porosity cut-off applied. Net sand defined as sandstone with < 30% shale, and porosity > 15%.

| Well | Formation interval (m MD) | Formation thickness (m) | Gross sand thickness (m) | Net sand thickness (m) | N/G | Avg. porosity (%) | Estimated gas perm. (mD) | Estimated res. perm. (mD) |
|---|---|---|---|---|---|---|---|---|
| Børglum-1 | 1371–1518 | 147 [1)] | 86 [1)] | 82 [1)] | 0.56 | 29 | 1200 | 1500 |
| Flyvbjerg-1 | 1308–1330<br>1348–1504 | 178 | 122 | [2)] | [2)] | [2)] | [2)] | [2)] |
| Vedsted-1 | 1749–1799<br>1818–1823<br>1898–2037 | 194 | 109 | 46 | 0.24 | 18 | 110 | 138 |
| Sæby-1 | 1077–1111 | 34 | 23 | 17 | 0.50 | 22 | 320 | 400 |

[1)] The entire Gassum Formation has not been penetrated; Thus *Formation thickness* is a minimum value and *Gross sand thickness* and *Net sand thickness* may be larger, *N/G* may be higher or lower
[2)] Parameter cannot be estimated due to incomplete log suite in the Flyvbjerg-1 well

**Table 18:** Reservoir parameters of the Gassum Formation for net sand: Shale cut-off applied, porosity cut-off applied. Net sand defined as sandstone with < 30% shale, and porosity > 20%.

| Well | Formation interval (m MD) | Formation thickness (m) | Gross sand thickness (m) | Net sand thickness (m) | N/G | Avg. porosity (%) | Estimated gas perm. (mD) | Estimated res. perm. (mD) |
|---|---|---|---|---|---|---|---|---|
| Børglum-1 | 1371–1518 | 147 [1)] | 86 [1)] | 74 [1)] | 0.50 | 30 | 1300 | 1625 |
| Flyvbjerg-1 | 1308–1330<br>1348–1504 | 178 | 122 | [2)] | [2)] | [2)] | [2)] | [2)] |
| Vedsted-1 | 1749–1799<br>1818–1823<br>1898–2037 | 194 | 109 | 3 | 0.02 | 22 | 250 | 313 |
| Sæby-1 | 1077–1111 | 34 | 23 | 10 | 0.29 | 24 | 470 | 588 |

[1)] The entire Gassum Formation has not been penetrated; Thus *Formation thickness* is a minimum value and *Gross sand thickness* and *Net sand thickness* may be larger, *N/G* may be higher or lower
[2)] Parameter cannot be estimated due to incomplete log suite in the Flyvbjerg-1 well

## 5.10 Petrophysical evaluation of the Skagerrak Formation

The Skagerrak Formation has been encountered in the Flyvbjerg-1, Vedsted-1 and Sæby-1 wells. The Børglum-1 and Haldager-1 wells do not reach the Skagerrak Formation.

### 5.10.1 The Flyvbjerg-1 well

The upper part of the Skagerrak Formation (194 m) was encountered in the Flyvbjerg-1 well (**Figure 10**), but it is not possible to evaluate the reservoir quality due to the lack of logs of sufficient quality. The acquired SP-log, however, shows together with cuttings descriptions the presence of several sandstone beds with thicknesses up to c. 15 m. The two cores taken were in shale sections; thus no core descriptions or core analysis data exist.

### 5.10.2 The Vedsted-1 well

In Vedsted-1 only the upper 36 m of the Skagerrak Formation was penetrated thus providing little information of potential reservoirs in the formation. However, 6 m of core consisting of conglomerate, fine–coarse grained fluvial sand and shale was recovered and porosity-permeability analysis performed. The results indicate good reservoir qualities with high porosities (23–29%) and high gas permeabilities (341–3112 mD). It is noteworthy that the porosity-permeability trend of the Skagerrak Formation in Vedsted-1 follows the corresponding regional trend for the Bunter Sandstone Formation (**Figure 17**). One data point is excluded from the trend due to very low permeability (5 mD), but despite fair porosity (20%). Assuming that the Skagerrak Formation below total depth contains continuous sandstone intervals with reservoir properties comparable to those of the recovered core the Skagerrak Formation at the Vedsted-1 well may prove exploitable.

### 5.10.3 The Sæby-1 well

In the Sæby-1 well, the Skagerrak Formation (1111–1649 m) consists of a variety of lithologies: sandstones, claystones, siltstones and conglomerates, which complicates the interpretation of the logs in intervals containing a mixture of these lithologies. The petrophysical evaluation is based on the gamma ray log-response integrated with information from the density-neutron log combination (see **Table 6** and **Figure 15**); further, lithological information from the Sæby-1 well completion report and core inspection are included (**Enclosure 9**).

The upper part of the Skagerrak Formation (1111–1444 m MD) is here regarded as mainly non-reservoir with low net-to-gross ratio. However, as indicated in **Table 19**–**Table 22** a number of thin intervals has reasonable reservoir quality potential.

Much of the lower part of the Skagerrak Formation (1444–1639 m MD) contains fairly thick sandstones as indicated by the separation between the neutron-density logs. A small number of shale intervals have, however, been interpreted from the log data supported by the information from the mud log. Interpreted log porosity (PHIE), core analysis data (Springer & Haslund 1985) and core inspection indicate that the apparent sandstone unit contains conglomeratic intervals and may include various amounts of silt and partly calcite cemented intervals (**Figure 15**). The sandstones are composed predominantly of medium to coarse grained quartz (Dansk Olie og Gas Produktion A/S 1985). Sorting is very poor and silt particles may have infiltrated the pore space of the sandstone reducing the porosity and permeability.

Much of the lower Skagerrak Formation is porous documented by the porosity data available from the cored interval (1612–1630 m MD); in this interval porosities vary between 15 and 30% which corresponds well with log porosity (15–30%). Furthermore, permeability values are available from core plugs taken in the same interval (Springer & Haslund 1985). It is notable that the core permeability measurements cover an unusually wide range, i.e. 0.1–1000 mD following a high and a low trend (**Figure 17**). The concentration of data points along two trends may be explained by the presence of pure sandstone sections alternating with either cemented sections, siltstone sections or sandstone sections with infiltrated silt particles in the pore space.

To ensure a sufficiently large database the core measurements are integrated with data from the Skagerrak Formation encountered in the Thisted-2, Vedsted-1, Gassum-1 and Mors-1 wells to establish the most reliable porosity-permeability relationship for the Skagerrak Formation in the Brønderslev area (**Figure 19**). However, the sandstones of the Skagerrak Formation seen in the Thisted-2, Gassum-1 and Mors-1 wells were deposited more distally, i.e. in a more basinward depositional environment, and are of higher quality than more proximally deposited sandstones accumulated in alluvial fans (as seen in Sæby-1). Thus, the sandstone permeabilities of the formation in especially the Gassum-1 and Mors-1 wells are higher for a given porosity compared to Sæby-1 (**Figure 19**). Likewise, the higher sandstone permeabilities of Vedsted-1 compared to Sæby-1 may also be controlled by depositional environment. The porosity-permeability relation of the Skagerrak Formation at the planned well site is assumed to follow trend in between the Sæby-1 and Vedsted-1 trends corresponding to the trend established for the Gassum Formation sandstones in the Stenlille area.

With a minimum porosity of 15% the lowermost part of the Skagerrak Formation in Sæby-1 (1444–1639 m MD) is interpreted to have good reservoir properties indicating a high geothermal potential (**Figure 15**). Even if a minimum porosity of 20% is required, the reservoir sand thickness is quite large (approx. 130 m, see **Table 22**). However, the presence of silt (Dansk Olie og Gas Produktion A/S 1985) reduces permeability, especially if present in the sandstones. Further, cores (1612–1630 m) demonstrate very poor sorting, a high degree of heterogeneity over short vertical intervals and cemented intervals with thicknesses below well log resolution. This information provided by the completion report, core analysis and core description (Michelsen & Nielsen 1993) is not identifiable in the well logs; the reservoir properties presented in **Figure 15** and **Table 19**–**Table 22** may thus be highly optimistic.

**Table 19:** Reservoir parameters of the Skagerrak Formation for net sand: Shale cut-off applied, porosity cut-off applied. Net sand defined as sandstone with < 30% shale, and porosity > 0%.

| Well | Formation interval (m MD) | Formation thickness (m) | Gross sand thickness (m) | Net sand thickness (m) | N/G | Avg. porosity (%) | Estimated gas perm. (mD) | Estimated res. perm. (mD) |
|---|---|---|---|---|---|---|---|---|
| **Flyvbjerg-1** | 1504–1698 | >194 [1] | 61 [1] | 61 [1] | 0.31 | [2] | [2] | [2] |
| **Vedsted-1** | 2037–2073 | >36 [1] | 16 [1] | 16 [1] | 0.43 | 24 | 290 | 363 |
| **Sæby-1** | 1111–1444 | 333 | 196 | 196 | 0.59 | 12 | 80 | 100 |
| | 1444–1639 | 195 | 192 | 192 | 0.98 | 22 | 300 | 375 |
| | 1639–1649 | 10 | 0 | 0 | – | – | – | – |

[1] The entire Skagerrak Formation has not been penetrated; Thus *Formation thickness* is a minimum value and *Gross sand thickness* and *Net sand thickness* may be larger, *N/G* may be higher or lower
[2] Parameter cannot be estimated due to incomplete log suite in the Flyvbjerg-1 well

**Table 20:** Reservoir parameters of the Skagerrak Formation for net sand: Shale cut-off applied, porosity cut-off applied. Net sand defined as sandstone with < 30% shale, and porosity > 10%.

| Well | Formation interval (m MD) | Formation thickness (m) | Gross sand thickness (m) | Net sand thickness (m) | N/G | Avg. porosity (%) | Estimated gas perm. (mD) | Estimated res. perm. (mD) |
|---|---|---|---|---|---|---|---|---|
| **Flyvbjerg-1** | 1504–1698 | >194 [1] | 61 [1] | [2] | [2] | [2] | [2] | [2] |
| **Vedsted-1** | 2037–2073 | >36 [1] | 16 [1] | 15 [1] | 0.43 | 25 | 300 | 375 |
| **Sæby-1** | 1111–1444 | 333 | 196 | 120 | 0.36 | 17 | 125 | 156 |
| | 1444–1639 | 195 | 192 | 191 | 0.98 | 22 | 300 | 375 |
| | 1639–1649 | 10 | 0 | 0 | – | – | – | – |

[1] The entire Skagerrak Formation has not been penetrated; Thus *Formation thickness* is a minimum value and *Gross sand thickness* and *Net sand thickness* may be larger, *N/G* may be higher or lower
[2] Parameter cannot be estimated due to incomplete log suite in the Flyvbjerg-1 well

**Table 21:** Reservoir parameters of the Skagerrak Formation for net sand: Shale cut-off applied, porosity cut-off applied. Net sand defined as sandstone with < 30% shale, and porosity > 15%.

| Well | Formation interval (m MD) | Formation thickness (m) | Gross sand thickness (m) | Net sand thickness (m) | N/G | Avg. porosity (%) | Estimated gas perm. (mD) | Estimated res. perm. (mD) |
|---|---|---|---|---|---|---|---|---|
| **Flyvbjerg-1** | 1504–1698 | >194 [1] | 61 [1] | [2] | [2] | [2] | [2] | [2] |
| **Vedsted-1** | 2037–2073 | >36 [1] | 16 [1] | 15 [1] | 0.42 | 25 | 300 | 375 |
| **Sæby-1** | 1111–1444 | 333 | 196 | 63 | 0.19 | 20 | 200 | 250 |
| | 1444–1639 | 195 | 192 | 189 | 0.97 | 22 | 320 | 400 |
| | 1639–1649 | 10 | 0 | 0 | – | – | – | – |

[1] The entire Skagerrak Formation has not been penetrated; Thus *Formation thickness* is a minimum value and *Gross sand thickness* and *Net sand thickness* may be larger, *N/G* may be higher or lower
[2] Parameter cannot be estimated due to incomplete log suite in the Flyvbjerg-1 well

**Table 22:** Reservoir parameters of the Skagerrak Formation for net sand: Shale cut-off applied, porosity cut-off applied. Net sand defined as sandstone with < 30% shale, and porosity > 20%.

| Well | Formation interval (m MD) | Formation thickness (m) | Gross sand thickness (m) | Net sand thickness (m) | N/G | Avg. porosity (%) | Estimated gas perm. (mD) | Estimated res. perm. (mD) |
|---|---|---|---|---|---|---|---|---|
| **Flyvbjerg-1** | 1504–1698 | >194 [1] | 61 [1] | [2] | [2] | [2] | [2] | [2] |
| **Vedsted-1** | 2037–2073 | >36 [1] | 16 [1] | 14 [1] | 0.39 | 26 | 325 | 406 |
| **Sæby-1** | 1111–1444 | 333 | 196 | 20 | 0.06 | 25 | 485 | 606 |
| | 1444–1639 | 195 | 192 | 134 | 0.69 | 24 | 400 | 500 |
| | 1639–1649 | 10 | 0 | 0 | – | – | – | – |

[1] The entire Skagerrak Formation has not been penetrated; Thus *Formation thickness* is a minimum value and *Gross sand thickness* and *Net sand thickness* may be larger, *N/G* may be higher or lower
[2] Parameter cannot be estimated due to incomplete log suite in the Flyvbjerg-1 well

# 6 Assessed reservoir parameters for the planned well site

Assessing the reservoir quality for potential geothermal reservoirs at the planned well site is based on extrapolation of interpreted reservoir parameters for the relevant wells guided by depth and thickness information from seismic lines.

For each formation the reservoir quality in the planned well site is assessed by the following general procedure:

1. Reservoir parameters are interpreted for the 5 wells (see **Section 5**)
2. The depth to the formation top is assessed from the seismic line DNJ-100 (see **Section 4.1**)
   a. If this is not possible the depth is assessed from well data
3. The formation thickness is assessed from the seismic line DNJ-100 (see **Section 4.1**)
   a. If this is not possible the thickness is assessed from well data
4. The importance (weight) of each well in relation to the planned well site is evaluated based on:
   a. Distance between well and planned well site
   b. Geological location of the well (Fjerritslev Trough, Skagerrak versus Kattegat Platform)
   c. Geological evolution in the greater Brønderslev area
   d. Quality of well data
   e. Whether formation depth and thickness can be evaluated from the seismic line DNJ-100
5. Reservoir parameters are assessed for the planned well site (see **Section 6**)

As mentioned in **Section 4** seismic information in the greater Brønderslev area and at the planned well site is limited, as is the quality of well log data. In addition, the reservoir parameters for all interpreted formations in the five wells (as presented in **Section 5.7–5.10**) show both similarities and significant variations depending on formation, well location and availability of log data. Assessing reservoir parameters at the planned well site thus involves significant uncertainties. In order to produce the best possible assessments careful considerations are needed with respect to identifying the most reliable method of combining well log and seismic data. Below, the considerations behind all assessed reservoir parameters for each formation are explained and the results are listed in **Table 23**.

The porosities, permeabilities and transmissivities presented in **Table 23** indicate fairly good reservoirs, but the significant uncertainties connected to these values should be born in mind. This is especially true for the Skagerrak Formation where the lack of sufficient data from wells in the Fjerritslev Trough is compensated by the use of data from the more distant Sæby-1 well which in addition is situated in a very different geological setting. Furthermore, the lower part of the Skagerrak Formation is buried deeper than the geothermal depth window (800–3000 m). At depths approaching 3000 m the effects of e.g. diagenesis may inflict significantly on reservoir quality, which may cause assessments based on the Sæby-1 well where the formation is more shallowly buried to be of limited value.

**Table 23:** Assessed reservoir parameters of the potential geothermal formations for net sand at the planned well site (Virksomhedsvej): Shale cut-off applied, porosity cut-off applied. Net sand defined as sandstone with < 30% shale, and porosity > 15%.

| **Potential geothermal formations** | **Assessed reservoir parameters** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Formation interval** (m MD) | **Formation thickness** (m) | **Gross sand thickness** (m) | **Net sand thickness** (m) | **N/G** | **Avg. porosity** (%) | **Estimated gas perm.** (mD) | **Estimated res. perm.** (mD) | **Transmissivity** (Dm) |
| **Frederikshavn** | 778–989 | 211 | 79 | 24 | 0.10 | 21 | 469 | 586 | 14 |
| **Haldager Sand** | 1052–1118 | 66 | 52 | 44 | 0.61 | 25 | 748 | 935 | 41 |
| **Gassum** | 1337–1455 | 118 | 77 | 53 | 0.45 | 24 | 609 | 762 | 40 |
| **Skagerrak** | 1455–3000[1)] | 1545/200 [2)] | 61 | 26 | 0.42 | 25 | 390 | 488 | 13 |

[1)] A significant part (425 m) of the lower Skagerrak Formation is outside the geothermal depth window (800–3000 m) and has been removed.
[2)] Only the upper 200 m of the formation is evaluated based on data from Flyvbjerg-1 and Vedsted-1

## 6.1 The Frederikshavn Formation

Sæby-1 is situated on the Skagerrak-Kattegat Platform and is considered irrelevant for assessing the reservoir parameters of the Frederikshavn Formation at the planned well site and will not be further considered in relation to this formation.

### Formation thickness

Formation thickness at the planned well site ($FT_{\text{Virksomhedsvej}}$) is difficult to estimate from the seismic line DNJ-100 (see **Section 4.1**); instead it is estimated from the Børglum-1, Flyvbjerg-1, Vedsted-1 and Haldager-1 wells. Børglum-1 and Flyvbjerg-1 are weighted double compared to Vedsted-1 and Haldager-1:

$$
\begin{aligned}
FT_{\text{Virksomhedsvej}} &= (2\text{x}FT_{\text{Børglum-1}} + 2\text{x}FT_{\text{Flyvbjerg-1}} + FT_{\text{Vedsted-1}} + FT_{\text{Haldager-1}})/6 \\
&= (2\text{x}224 \text{ m} + 2\text{x}171 \text{ m} + 235 \text{ m} + 243 \text{ m})/6 \\
&= 211 \text{ m}
\end{aligned}
$$

### Formation interval

Formation depth at the planned well site ($FD_{\text{Virksomhedsvej}}$) is estimated to be c. 778 m from the seismic line DNJ-100 (**Table 1**) and formation thickness ($FT_{\text{Virksomhedsvej}}$) is estimated to be 211 m. The formation interval ($FI_{\text{Virksomhedsvej}}$) then is c. 778–989 m.

### Gross sand thickness

Gross sand thickness at the planned well site ($GST_{\text{Virksomhedsvej}}$) is estimated from the Børglum-1, Flyvbjerg-1, Vedsted-1 and Haldager-1 wells. Børglum-1 and Flyvbjerg-1 are weighted double compared to Vedsted-1 and Haldager-1:

$$GST_{Virksomhedsvej} = (2xGST_{Børglum-1} + 2xGST_{Flyvbjerg-1} + GST_{Vedsted-1} + GST_{Haldager-1})/6$$
$$= (2x74.3 \text{ m} + 2x115.3 \text{ m} + 38.1 \text{ m} + 56.4 \text{ m})/6$$
$$= 79 \text{ m}$$

**Net sand thickness**

Net sand thickness at the planned well site ($NST_{Virksomhedsvej}$) is estimated from the Børglum-1, Vedsted-1 and Haldager-1 wells. An evaluation of *NST* in the Flyvbjerg-1 well is not possible due to an incomplete log suite. To fill in the data gap at Flyvbjerg-1, $NST_{Flyvbjerg-1}$ is "borrowed" from $NST_{Børglum-1}$ and weighted one. $NST_{Børglum-1}$ is weighted double compared to $NST_{Flyvbjerg-1}$, $NST_{Vedsted-1}$ and $NST_{Haldager-1}$:

$$NST_{Virksomhedsvej} = (2xNST_{Børglum-1} + NST_{Flyvbjerg-1} + NST_{Vedsted-1} + NST_{Haldager-1})/5$$
$$= (2x22.4 \text{ m} + 22.4 + 8.5 \text{ m} + 43.6 \text{ m})/5$$
$$= 24 \text{ m}$$

**Net to gross ratio**

The net to gross ratio at the planned well site ($N/G_{Virksomhedsvej}$) is estimated from the Børglum-1, Vedsted-1 and Haldager-1 wells. An evaluation of *N/G* in the Flyvbjerg-1 well ($N/G_{Flyvbjerg-1}$) is not possible due to an incomplete log suite. To fill in the data gap, $N/G_{Flyvbjerg-1}$ is "borrowed" from Børglum-1 ($N/G_{Børglum-1}$) and weighted one. $N/G_{Børglum-1}$ is weighted double compared to $N/G_{Flyvbjerg-1}$, $N/G_{Vedsted-1}$ and $N/G_{Haldager-1}$:

$$N/G_{Virksomhedsvej} = (2xN/G_{Børglum-1} + N/G_{Flyvbjerg-1} + N/G_{Vedsted-1} + N/G_{Haldager-1})/5$$
$$= (2x0.10 + 0.10 + 0.04 + 0.18)/5$$
$$= 0.10$$

**Porosity**

Porosity at the planned well site ($\varphi_{Virksomhedsvej}$) is estimated from the Børglum-1, Vedsted-1 and Haldager-1 wells. An evaluation of $\varphi$ in the Flyvbjerg-1 well ($\varphi_{Flyvbjerg-1}$) is not possible due to an incomplete log suite. To fill in the data gap at Flyvbjerg-1, $\varphi_{Flyvbjerg-1}$ is "borrowed" from Børglum-1 ($\varphi_{Børglum-1}$) and weighted one. Børglum-1 is weighted double compared to $\varphi_{Flyvbjerg-1}$, $\varphi_{Vedsted-1}$ and $\varphi_{Haldager-1}$:

$$\varphi_{Virksomhedsvej} = (2x\varphi_{Børglum-1} + \varphi_{Flyvbjerg-1} + \varphi_{Vedsted-1} + \varphi_{Haldager-1})/5$$
$$= (2x19\% + 19\% + 16\% + 34\%)/5$$
$$= 21\%$$

**Estimated gas permeability**

Estimated gas permeability at the planned well site ($k_{Virksomhedsvej,\ gas}$) is estimated from the Børglum-1, Vedsted-1 and Haldager-1 wells. An evaluation of $k$ in the Flyvbjerg-1 well ($k_{Flyvbjerg-1}$) is not possible due to an incomplete log suite. To fill in the data gap, $k_{\text{Flyvbjerg-1}}$ is "borrowed" from Børglum-1 ($k_{\text{Børglum-1}}$) and weighted one. Børglum-1 is weighted double compared to $k_{\text{Flyvbjerg-1}}$, $k_{\text{Vedsted-1}}$ and $k_{\text{Haldager-1}}$:

$$
\begin{aligned}
k_{\text{Virksomhedsvej, gas}} &= (2\text{x}k_{\text{Børglum-1}} + k_{\text{Flyvbjerg-1}} + k_{\text{Vedsted-1}} + k_{\text{Haldager-1}})/5 \\
&= (2\text{x}160 \text{ mD} + 160 \text{ mD} + 65 \text{ mD} + 1800 \text{ mD})/5 \\
&= 469 \text{ mD}
\end{aligned}
$$

**Estimated reservoir permeability**

Estimated reservoir permeability at the planned well site ($k_{\text{Virksomhedsvej, res.}}$) is estimated by multiplying $k$ with an upscaling factor of 1.25 developed by GEUS:

$$
\begin{aligned}
k_{\text{Virksomhedsvej, res.}} &= k_{\text{Virksomhedsvej, gas}} \text{ x } 1.25 \\
&= 469 \text{ mD x } 1.25 \\
&= 586 \text{ mD}
\end{aligned}
$$

**Estimated transmissivity**

Transmissivity at the planned well site ($T_{\text{Virksomhedsvej}}$) is estimated by multiplying $k_{\text{Virksomhedsvej, res.}}$ with $NST_{\text{Virksomhedsvej}}$:

$$
\begin{aligned}
T_{\text{Virksomhedsvej}} &= (k_{\text{Virksomhedsvej, res.}} \text{ x } NST_{\text{Virksomhedsvej, min.}}) / 1000 \\
&= (586 \text{ mD x } 24 \text{ m}) / 1000 \\
&= 14 \text{ Dm}
\end{aligned}
$$

## 6.2 The Haldager Sand Formation

Sæby-1 is situated on the Skagerrak-Kattegat Platform and is considered irrelevant for assessing the reservoir parameters of the Haldager Sand Formation at the planned well site and will not be further considered in relation to this formation.

**Formation thickness**

Formation thickness at the planned well site ($FT_{\text{Virksomhedsvej}}$) is difficult to estimate from the seismic line DNJ-100 as the expected thickness is close to seismic resolution. Thus, $FT_{\text{Virksomhedsvej}}$ is estimated from formation thicknesses of the Børglum-1 ($FT_{\text{Børglum-1}}$), Flyvbjerg-1 ($FT_{\text{Flyvbjerg-1}}$), Vedsted-1 ($FT_{\text{Vedsted-1}}$) and Haldager-1 ($FT_{\text{Haldager-1}}$) wells. $FT_{\text{Børglum-1}}$ and $FT_{\text{Flyvbjerg-1}}$ are weighted double compared to $FT_{\text{Vedsted-1}}$ and $FT_{\text{Haldager-1}}$:

$$
\begin{aligned}
FT_{\text{Virksomhedsvej}} &= (2\text{x}FT_{\text{Børglum-1}} + 2\text{x}FT_{\text{Flyvbjerg-1}} + FT_{\text{Vedsted-1}} + FT_{\text{Haldager-1}})/6 \\
&= (2\text{x}29 \text{ m} + 2\text{x}54 \text{ m} + 75 \text{ m} + 155 \text{ m})/6 \\
&= 66 \text{ m}
\end{aligned}
$$

**Formation interval**

Formation depth at the planned well site ($FD_{\mathrm{Virksomhedsvej}}$) is estimated to be c. 1052 m from the seismic line DNJ-100 (**Table 1**) and formation thickness ($FT_{\mathrm{Virksomhedsvej}}$) is estimated to be 66 m. The formation interval ($FI_{\mathrm{Virksomhedsvej}}$) then is 1052–1118 m.

**Gross sand thickness**

Gross sand thickness at the planned well site ($GST_{\mathrm{Virksomhedsvej}}$) is estimated from gross sand thicknesses of the Børglum-1($GST_{\mathrm{Børglum\text{-}1}}$), Flyvbjerg-1 ($GST_{\mathrm{Flyvbjerg\text{-}1}}$), Vedsted-1 ($GST_{\mathrm{Vedsted\text{-}1}}$) and Haldager-1 ($GST_{\mathrm{Haldager\text{-}1}}$) wells. $GST_{\mathrm{Børglum\text{-}1}}$ and $GST_{\mathrm{Flyvbjerg\text{-}1}}$ are weighted double compared to $GST_{\mathrm{Vedsted\text{-}1}}$ and $GST_{\mathrm{Haldager\text{-}1}}$:

$$
\begin{aligned}
GST_{\mathrm{Virksomhedsvej}} &= (2\mathrm{x}GST_{\mathrm{Børglum\text{-}1}} + 2\mathrm{x}GST_{\mathrm{Flyvbjerg\text{-}1}} + GST_{\mathrm{Vedsted\text{-}1}} + GST_{\mathrm{Haldager\text{-}1}})/6 \\
&= (2\mathrm{x}15.6\ \mathrm{m} + 2\mathrm{x}45.8\ \mathrm{m} + 64.6\ \mathrm{m} + 126.3\ \mathrm{m})/6 \\
&= 52\ \mathrm{m}
\end{aligned}
$$

**Net sand thickness**

Net sand thickness at the planned well site ($NST_{\mathrm{Virksomhedsvej}}$) is estimated from the Børglum-1, Vedsted-1 and Haldager-1 wells. In the Flyvbjerg-1 well an evaluation of net sand thickness ($NST_{\mathrm{Flyvbjerg\text{-}1}}$) is not possible due to an incomplete log suite. To fill in the data gap, $NST_{\mathrm{Flyvbjerg\text{-}1}}$ is "borrowed" from Børglum-1 ($NST_{\mathrm{Børglum\text{-}1}}$) and weighted one. Børglum-1 is weighted double compared to $NST_{\mathrm{Flyvbjerg\text{-}1}}$, $NST_{\mathrm{Vedsted\text{-}1}}$ and $NST_{\mathrm{Haldager\text{-}1}}$:

$$
\begin{aligned}
NST_{\mathrm{Virksomhedsvej}} &= (2\mathrm{x}NST_{\mathrm{Børglum\text{-}1}} + NST_{\mathrm{Flyvbjerg\text{-}1}} + NST_{\mathrm{Vedsted\text{-}1}} + NST_{\mathrm{Haldager\text{-}1}})/5 \\
&= (2\mathrm{x}13.9\ \mathrm{m} + 13.9 + 64.0\ \mathrm{m} + 115.6\ \mathrm{m})/5 \\
&= 44\ \mathrm{m}
\end{aligned}
$$

**Net to gross ratio**

The net to gross ratio at the planned well site ($N/G_{\mathrm{Virksomhedsvej}}$) is estimated from the Børglum-1, Vedsted-1 and Haldager-1 wells. In the Flyvbjerg-1 well an evaluation of the net to gross ratio ($N/G_{\mathrm{Flyvbjerg\text{-}1}}$) is not possible due to an incomplete log suite. To fill in the data gap, $N/G_{\mathrm{Flyvbjerg\text{-}1}}$ is "borrowed" from Børglum-1 ($N/G_{\mathrm{Børglum\text{-}1}}$) and weighted one. $N/G_{\mathrm{Børglum\text{-}1}}$ is weighted double compared to $N/G_{\mathrm{Flyvbjerg\text{-}1}}$, $N/G_{\mathrm{Vedsted\text{-}1}}$ and $N/G_{\mathrm{Haldager\text{-}1}}$:

$$
\begin{aligned}
N/G_{\mathrm{Virksomhedsvej}} &= (2\mathrm{x}N/G_{\mathrm{Børglum\text{-}1}} + N/G_{\mathrm{Flyvbjerg\text{-}1}} + N/G_{\mathrm{Vedsted\text{-}1}} + N/G_{\mathrm{Haldager\text{-}1}})/5 \\
&= (2\mathrm{x}0.48 + 0.48 + 0.85 + 0.75)/5 \\
&= 0.61
\end{aligned}
$$

**Porosity**

Porosity at the planned well site ($\varphi_{Virksomhedsvej}$) is estimated from the Børglum-1, Vedsted-1 and Haldager-1 wells. An evaluation of the porosity in the Flyvbjerg-1 well ($\varphi_{Flyvbjerg\text{-}1}$) is not possible due to an incomplete log suite. To fill in the data gap, $\varphi_{Flyvbjerg\text{-}1}$ is "borrowed" from Børglum-1 and weighted one. ($\varphi_{Børglum\text{-}1}$) is weighted double compared to $\varphi_{Flyvbjerg\text{-}1}$, $\varphi_{Vedsted\text{-}1}$ and $\varphi_{Haldager\text{-}1}$:

$$\varphi_{Virksomhedsvej} = (2x\varphi_{Børglum\text{-}1} + \varphi_{Flyvbjerg\text{-}1} + \varphi_{Vedsted\text{-}1} + \varphi_{Haldager\text{-}1})/5$$
$$= (2x23\% + 23\% + 29\% + 27\%)/5$$
$$= 25\%$$

**Estimated gas permeability**

Estimated gas permeability at the planned well site ($k_{Virksomhedsvej}$) is estimated from the Børglum-1, Vedsted-1 and Haldager-1 wells. An evaluation of $k$ in the Flyvbjerg-1 well ($k_{Flyvbjerg\text{-}1}$) is not possible due to an incomplete log suite. To fill in the data gap, $k_{Flyvbjerg\text{-}1}$ is "borrowed" from Børglum-1 ($k_{Børglum\text{-}1}$) and weighted one. Børglum-1 is weighted double compared to $k_{Flyvbjerg\text{-}1}$, $k_{Vedsted\text{-}1}$ and $k_{Haldager\text{-}1}$:

$$k_{Virksomhedsvej} = (2xk_{Børglum\text{-}1} + k_{Flyvbjerg\text{-}1} + k_{Vedsted\text{-}1} + k_{Haldager\text{-}1})/5$$
$$= (2x660 \text{ mD} + 260 \text{ mD} + 960 \text{ mD} + 800 \text{ mD})/5$$
$$= 748 \text{ mD}$$

**Estimated reservoir permeability**

Estimated reservoir permeability at the planned well site ($k_{Virksomhedsvej,\ res.}$) is estimated by multiplying $k$ with an upscaling factor of 1.25 developed by GEUS:

$$k_{Virksomhedsvej,\ res.} = k \text{ x } 1.25$$
$$= 748 \text{ mD x } 1.25$$
$$= 935 \text{ mD}$$

**Estimated transmissivity**

Transmissivity at the planned well site ($T_{Virksomhedsvej}$) is estimated by multiplying $k_{Virksomhedsvej,\ res.}$ with $NST_{Virksomhedsvej}$:

$$T_{Virksomhedsvej} = (k_{Virksomhedsvej,\ res.} \text{ x } NST_{Virksomhedsvej,\ min.}) / 1000$$
$$= (935 \text{ mD x } 44 \text{ m}) / 1000$$
$$= 41 \text{ Dm}$$

## 6.3 The Gassum Formation

Several assumptions have been made in order to assess reservoir parameters of the Gassum Formation at the planned well site. This is due to an incomplete log suite in Flyvbjerg-1, the fact that the Gassum Formation is only partly penetrated in Børglum-1, the fact that Vedsted-1 and Haldager-1 are far away and the fact that Haldager-1 does not reach the Gassum Formation. Sæby-1 is situated on the Skagerrak-Kattegat Platform and is considered irrelevant for assessing reservoir parameters.

**Formation thickness**

Estimation of formation depth ($FD_{\text{Virksomhedsvej}}$) and thickness ($FT_{\text{Virksomhedsvej}}$) at the planned well site is based on the seismic line DNJ-100 where the seismic horizons representing near Top Gassum Fm. ($FD_{\text{Top Gassum}}$ = 1337 m) and near Base Gassum Fm. ($FD_{\text{Base Gassum}}$ = 1455 m) are identified. $FT_{\text{Virksomhedsvej}}$ then becomes:

$$\begin{aligned} FT_{\text{Virksomhedsvej}} &= FD_{\text{Base Gassum}} - FD_{\text{Top Gassum}} \\ &= 1455\text{ m} - 1337\text{ m} \\ &= 118\text{ m} \end{aligned}$$

Alternatively, $FT_{\text{Virksomhedsvej}}$ may be estimated from well data which, however, is limited. The Haldager-1 well does not reach the Gassum Formation, and Børglum-1 does not penetrate the entire Gassum Formation and thus formation depth for this well (147 m) is a minimum value (see **Table 15**–**Table 18**). Flyvbjerg-1, on the other hand, does penetrate the entire Gassum Formation and estimated from the seismic line DNJ-200 the Gassum Formation thicknesses of Børglum-1 and Flyvbjerg-1 are nearly identical (**Figure 3**). The formation thickness of Børglum-1 ($FT_{\text{Børglum-1}}$) is thus assigned the formation thickness of Flyvbjerg-1 ($FT_{\text{Flyvbjerg-1}}$, 178 m). $FT_{\text{Flyvbjerg-1}}$ is weighted double compared to $FT_{\text{Børglum-1}}$ and $FT_{\text{Vedsted-1}}$:

$$\begin{aligned} FT_{\text{Virksomhedsvej}} &= (1\text{x}FT_{\text{Børglum-1}} + 2\text{x}FT_{\text{Flyvbjerg-1}} + FT_{\text{Vedsted-1}})/4 \\ &= (1\text{x}178\text{ m} + 2\text{x}178\text{ m} + 194)/4 \\ &= 182\text{ m} \end{aligned}$$

The $FT_{\text{Virksomhedsvej}}$ value estimated from the seismic line DNJ-100 (118 m) has been evaluated to be more correct compared to the weighted well average (182 m). The consideration behind this choice is based on the formation thickening from the planned well site towards Flyvbjerg-1 (see **Figure 3**) and is discussed in detail in **Section 4.1**.

**Formation interval**

From the seismic line DNJ-100 the depth to formation top and base at the planned well site is estimated to be c. 1337 m and c. 1455 m (**Table 1**). The formation interval ($FI_{\text{Virksomhedsvej}}$) then is c. 1337–1455 m.

**Gross sand thickness**

The gross sand thickness at the planned well site ($GST_{Virksomhedsvej}$) is estimated from the Flyvbjerg-1 and Vedsted-1 wells. The Haldager-1 well does not reach the Gassum Formation, and Børglum-1 does not penetrate the entire Gassum Formation and thus gross sand thickness for this well ($GST_{Børglum\text{-}1}$ = 86 m) is a minimum value (see **Table 15**–**Table 18**). Assuming comparable reservoir characteristics between Børglum-1 and Flyvbjerg-1, $GST_{Børglum\text{-}1}$ is assigned the $GST_{Flyvbjerg\text{-}1}$ (122 m). $GST_{Flyvbjerg\text{-}1}$ is weighted double compared to $GST_{Børglum\text{-}1}$ and $GST_{Vedsted\text{-}1}$:

$$GST_{Well\ derived} = (1\mathrm{x}GST_{Børglum\text{-}1} + 2\mathrm{x}GST_{Flyvbjerg\text{-}1} + GST_{Vedsted\text{-}1})/4$$
$$= (1\mathrm{x}122\ \mathrm{m} + 2\mathrm{x}122\ \mathrm{m} + 109\ \mathrm{m})/4$$
$$= 119\ \mathrm{m}$$

$GST_{Well\ derived}$, however, is calculated from the formation thickness based on the weighted well average (182 m) which was discarded. In order to adjust gross sand thickness to the accepted seismics-derived formation thickness of 118 m the relative difference between the two formation thicknesses ($FT_{Seismics}$ / $FT_{Well\ average}$) must be included in the calculation:

$$GST_{Virksomhedsvej} = (FT_{Seismics} / FT_{Well\ average})\ \mathrm{x}\ GST_{Well\ derived}$$
$$= (118\ \mathrm{m} / 182\ \mathrm{m})\ \mathrm{x}\ 119\ \mathrm{m}$$
$$= 77\ \mathrm{m}$$

**Net sand thickness**

A well based net sand thickness at the planned well site ($NST_{Virksomhedsvej}$) is estimated by comparing data from the Børglum-1, Flyvbjerg-1 and Vedsted-1 wells. The Haldager-1 well does not reach the Gassum Formation. Børglum-1 does not penetrate the entire Gassum Formation and no estimation of net sand thickness is possible in Flyvbjerg-1 due to an incomplete log suite. It is, however, assumed that Børglum-1 and Flyvbjerg-1 share the same reservoir characteristics and net sand thickness for these wells ($NST_{Børglum\text{-}1}$ and $NST_{Flyvbjerg\text{-}1}$) is estimated from the minimum formation thickness and minimum net sand thickness listed for Børglum-1 and the formation thickness listed for Flyvbjerg-1 (see **Table 15**–**Table 18**). *NST* for Børglum-1 and Flyvbjerg-1 is estimated the following way:

$$NST_{Børglum\text{-}1} = NST_{Flyvbjerg\text{-}1} = (FT_{Flyvbjerg\text{-}1} / FT_{Børglum\text{-}1})\ \mathrm{x}\ NST_{Børglum\text{-}1}$$
$$= (178\ \mathrm{m} / 147\ \mathrm{m})\ \mathrm{x}\ 82\ \mathrm{m}$$
$$= 99\ \mathrm{m}$$

$NST_{Børglum\text{-}1}$ and $NST_{Flyvbjerg\text{-}1}$ are not log-derived values and thus considered to be less certain compared to the log-derived $NST_{Vedsted\text{-}1}$, but as Vedsted-1 is situated at a greater distance from the planned well site compared to Børglum-1 and Flyvbjerg-1 the importance of the three wells is weighted equal:

$$NST_{\text{Well derived}} = (NST_{\text{Børglum-1}} + NST_{\text{Flyvbjerg-1}} + NST_{\text{Vedsted-1}})/3$$
$$= (99\text{ m} + 99\text{ m} + 46\text{ m})/3$$
$$= 82\text{ m}$$

$NST_{\text{Well derived}}$, however, is calculated from the formation thickness based on the weighted well average (169 m) which was discarded. In order to adjust $NST_{Well\ derived}$ to the accepted seismics-derived formation thickness of 118 m the relative difference between the two formation thicknesses must be included in the calculation:

$$NST_{\text{Virksomhedsvej}} = (FT_{\text{Seismics}} / FT_{\text{Well average}}) \text{ x } NST_{\text{Well derived}}$$
$$= (118\text{ m} / 182\text{ m}) \text{ x } 82\text{ m}$$
$$= 53\text{ m}$$

**Net to gross ratio**

The net to gross ratio at the planned well site ($N/G_{\text{Virksomhedsvej}}$) is calculated using the estimated formation thickness ($FT_{\text{Virksomhedsvej}}$) and net sand thickness ($NST_{\text{Virksomhedsvej}}$) at the planned well site:

$$N/G_{\text{Virksomhedsvej}} = NST_{\text{Virksomhedsvej}} / FT_{\text{Virksomhedsvej}}$$
$$= 53 / 118\text{ m}$$
$$= 0.45$$

**Porosity**

Porosity at the planned well site ($\varphi_{\text{Virksomhedsvej}}$) is estimated for the centre of the reservoir ($FD_{\text{Centre Gassum}}$). $FD_{\text{Centre Gassum}}$ is calculated as follows:

$$FD_{\text{Centre Gassum}} = FD_{\text{Top Gassum}} + (FD_{\text{Base Gassum}} - FD_{\text{Top Gassum}})/2$$
$$= 1337 + (1455\text{ m} - 1337\text{ m})/2$$
$$= 1396\text{ m}$$

$\varphi_{\text{Virksomhedsvej}}$ is calculated by using the expression for the regional depth-porosity trend described in **Section 5.6.2** and shown in **Figure 18**. $\varphi_{\text{Virksomhedsvej}}$ is calculated as follows:

$$\varphi_{\text{Virksomhedsvej}} = -0.0033\text{x}FD_{\text{Centre Gassum}} + 28.474$$
$$= -0.0033\text{x}1396 + 28.474$$
$$= 24\%$$

Alternatively, $\varphi_{\text{Virksomhedsvej}}$ can be calculated from $\varphi_{\text{Børglum-1}}$ and $\varphi_{\text{Vedsted-1}}$. An evaluation of the porosity in the Flyvbjerg-1 well ($\varphi_{\text{Flyvbjerg-1}}$) is not possible due to an incomplete log suite and a very limited amount of core analysis data. It is, however, assumed that Børglum-1 and Flyvbjerg-1 share the same reservoir characteristics, and thus $\varphi_{\text{Flyvbjerg-1}}$ is “borrowed” from Børglum-1. $\varphi_{\text{Børglum-1}}$ is weighted double compared to $\varphi_{\text{Flyvbjerg-1}}$ and $\varphi_{\text{Vedsted-1}}$ when calculating $\varphi_{\text{Virksomhedsvej}}$:

$$\begin{aligned}\varphi_{\text{Virksomhedsvej}} &= (2 \text{ x } \varphi_{\text{Børglum-1}} + \varphi_{\text{Flyvbjerg-1}} + \varphi_{\text{Vedsted-1}})/4 \\ &= (2 \text{ x } 29\% + 29\% + 18\%)/4 \\ &= 26\%\end{aligned}$$

$\varphi_{\text{Børglum-1}}$ seems overestimated and $\varphi_{\text{Vedsted-1}}$ seem underestimated which is supported by the regional depth-porosity trend (**Figure 18**) where also $\varphi_{\text{Sæby-1}}$ seems underestimated.

**Estimated gas permeability**

Estimated gas permeability at the planned well site ($k_{\text{Virksomhedsvej}}$) is based on estimated permeabilities from the Børglum-1 ($k_{\text{Børglum-1}}$) and Vedsted-1 wells ($k_{\text{Vedsted-1}}$). An evaluation of $k$ in the Flyvbjerg-1 well ($k_{\text{Flyvbjerg-1}}$) is not possible due to an incomplete log suite and a very limited amount of core analysis data. It is, however, assumed that Børglum-1 and Flyvbjerg-1 share the same reservoir characteristics and thus $k_{\text{Flyvbjerg-1}}$ is “borrowed” from Børglum-1. $k_{\text{Børglum-1}}$ is weighted double compared to $k_{\text{Flyvbjerg-1}}$ and $k_{\text{Vedsted-1}}$ when calculating $k_{\text{Virksomhedsvej}}$:

$$\begin{aligned}k_{\text{Virksomhedsvej}} &= (2 \text{ x } k_{\text{Børglum-1}} + k_{\text{Flyvbjerg-1}} + k_{\text{Vedsted-1}})/4 \\ &= (2 \text{ x } 1200 \text{ mD} + 1200 \text{ mD} + 110 \text{ mD})/4 \\ &= 928 \text{ mD}\end{aligned}$$

$k_{\text{Virksomhedsvej}}$, however, is calculated as a linear average and overestimates the actual permeability due to the fact that $k_{\text{Børglum-1}}$ and $k_{\text{Vedsted-1}}$ are calculated from an expression derived for a regression line describing the scatter of porosity-permeability data points in a single logarithmic plot. To correct this error $k_{\text{Børglum-1}}$ and $k_{\text{Vedsted-1}}$ must be $\log_{10}$ converted before computing their average value to which the antilogarithm is taken:

$$\begin{aligned}k_{\text{Virksomhedsvej}} &= \text{Antilog } ((2 \text{ x } \log_{10}(k_{\text{Børglum-1}}) + \log_{10}(k_{\text{Flyvbjerg-1}}) + \log_{10}(k_{\text{Vedsted-1}}))/4) \\ &= \text{Antilog } ((2 \text{ x } \log_{10}(1200 \text{ mD}) + \log_{10}(1200 \text{ mD}) + \log_{10}(110 \text{ mD}))/4) \\ &= 660 \text{ mD}\end{aligned}$$

This $k_{\text{Virksomhedsvej}}$ is calculated from permeabilities ($k_{\text{Børglum-1}}$ and $k_{\text{Vedsted-1}}$) which are based on log-derived porosities. The log-derived porosities ($\varphi_{\text{Børglum-1}} = 29\%$ and $\varphi_{\text{Vedsted-1}} = 18\%$) were considered uncertain and discarded together with the derived $\varphi_{\text{Virksomhedsvej}} = 26\%$. The estimated porosity based on the regional depth-porosity relation $\varphi_{\text{Virksomhedsvej}} = 24\%$ is considered a more qualified estimate. Thus, a porosity correction must be applied to $k_{\text{Virksomhedsvej}}$:

$k_{\text{Virksomhedsvej}}$ = (24% / 26%) x 660 mD

= 609 mD

**Estimated reservoir permeability**

Estimated reservoir permeability at the planned well site ($k_{\text{Reservoir}}$) is estimated by multiplying $k_{\text{Virksomhedsvej}}$ with an upscaling factor of 1.25 developed by GEUS. $k_{\text{Reservoir}}$ then becomes:

$k_{\text{Reservoir}}$ = $k_{\text{Virksomhedsvej}}$ x 1.25

= 609 mD x 1.25

= 762 mD

**Estimated transmissivity**

Transmissivity at the planned well site ($T_{\text{Virksomhedsvej}}$) is estimated by multiplying $k_{\text{Virksomhedsvej, res.}}$ with $NST_{\text{Virksomhedsvej}}$:

$T_{\text{Virksomhedsvej}}$ = ($k_{\text{Virksomhedsvej, res.}}$ x $NST_{\text{Virksomhedsvej, min.}}$) / 1000

= (762 mD x 53 m) / 1000

= 40 Dm

## 6.4 The Skagerrak Formation

The wells in the Fjerritslev Trough either do not reach the Skagerrak Formation (Børglum-1, Haldager-1) or only penetrate the uppermost part of the formation (Flyvbjerg-1, Vedsted-1). The most complete source of information about the Skagerrak Formation is the Sæby-1 well situated on the Skagerrak-Kattegat Platform (**Figure 1**), i.e. north of the Fjerritslev Fault in a very different geological setting compared to the Fjerritslev Trough. From the seismic line DNJ-300 (**Figure 4**), it is clearly evident that the Skagerrak Formation is vastly thicker in the Fjerritslev Trough with a depth interval ranging from c. 1400 m to more than 3400 m. The existing seismic data show that the Skagerrak Formation at the eastern part of the Skagerrak-Kattegat Platform has a generally continuous and constant thickness of more than c. 700 m, but thins towards the Sæby-1 well (538 m; **Figure 5**).

In the Sæby-1 well, the upper part of the Skagerrak Formation (1111–1444 m MD) is here regarded as mainly non-reservoir with low net-to-gross ratio. However, thin intervals with reasonable reservoir quality potential exist. The lower part of the Skagerrak Formation (1444–1639 m MD) contains fairly large accumulated thickness of sandstones with geothermal potential, however, as discussed in **Section 5.10.3**, core material shows a high degree of heterogeneity over short vertical intervals with very poor sorting, presence of silt and cementation which reduce the porosity and permeability. In addition, transferring the prospective lower part of the Skagerrak Formation from the Skagerrak-Kattegat Platform and into the

Fjerritslev Trough would situate this part of the formation at c. 2700–3500 m depth at the planned well site. Assumedly, the geothermal potential at this depth would be low.

A more realistic assessment of the geothermal potential of the Skagerrak Formation may be presented by the Flyvbjerg-1 and Vedsted-1 wells even though they only penetrated the upper 194 m (Flyvbjerg-1) and 36 m (Vedsted-1) of the formation (see **Section 5.10** and **Figure 2–Figure 4**). Nielsen (2003) identified fluvial sandstone units in Flyvbjerg-1 and Vedsted-1 based on core description (Vedsted-1) and log motifs (Flyvbjerg-1 and Vedsted-1). He correlated the sandstone units suggesting fluvial facies to be present in the area between the two wells which includes the Brønderslev area. The dynamics of a fluvial deposition environment often leads to formation of more mature sandstones with good reservoir qualities; this is supported by core analysis data from Vedsted-1 indicating good reservoir qualities with high porosities (23–29%) and high gas permeabilities (341–3112 mD) (Olsen & Jørgensen 2008).

Based on data derived from well logs, core analyses and core inspections of the Sæby-1, Flyvbjerg-1 and Vedsted-1 wells it is assessed that the upper part of the Skagerrak Formation offers the most favourable conditions with respect to production of geothermal energy at the planned well site. The Sæby-1 well is situated 30 km away in a very different geological setting and despite offering good reservoir properties in the lower part of the Skagerrak Formation the depth analogue at the planned well site probably is too deeply buried to be of geothermal value. The Flyvbjerg-1 and Vedsted-1 wells are situated closer to the planned well site in a similar geological setting and display sandstone units in the upper part of the Skagerrak Formation with good reservoir properties. Acknowledging that well log and core data are available only at the uppermost c. 200 m of the formation (Flyvbjerg-1) these two wells provide the basis for assessing the reservoir properties in a depth range limited to *the upper 200 m of the Skagerrak Formation*.

**Formation interval**

From the seismic line DNJ-100 the depth to formation top ($FD_{\text{Top Skagerrak}}$ = 1455 m) and base ($FD_{\text{Base Skagerrak}}$ = 3425 m) at the planned well site is estimated to be c. 1455 m and c. 3425 m (**Table 1**). The formation interval ($FI_{\text{Virksomhedsvej}}$) then is c. 1455–3425 m. As mentioned the lowermost 425 m of the formation is situated below the geothermal depth window of 800–3000 m and is discarded.

As mentioned above only the upper 200 m of the formation is evaluated based on data from the Flyvbjerg-1 and Vedsted-1 wells. The considered formation interval thus is a minimum value:

$FI_{\text{Virksomhedsvej}}$ = c. 1455–1655 m.

**Formation thickness**

At the planned well site the formation thickness ($FT_{\text{Virksomhedsvej}}$) can be calculated from $FD_{\text{Top Skagerrak}}$ and $FD_{\text{Base Skagerrak}}$:

$FT_{Virksomhedsvej}$ = $FD_{Base\ Skagerrak} - FD_{Top\ Skagerrak}$
= 3425 m – 1455 m
= 1970 m

The lowermost 425 m of the formation is situated below the geothermal depth window of 800–3000 m. They are thus not included in the geothermal relevant formation thickness. The $FT_{Virksomhedsvej}$ is corrected to:

$FT_{Virksomhedsvej}$ = $3000 - FD_{Top\ Skagerrak}$
= 3000 m – 1455 m
= 1545 m

As mentioned above only the upper 200 m of the formation is evaluated based on data from the Flyvbjerg-1 and Vedsted-1 wells. The considered formation thickness ($FT_{Virksomhedsvej}$) thus is a minimum value:

$FT_{Virksomhedsvej}$ = c. 200 m.

**Gross sand thickness**

At the planned well site the gross sand thickness ($GST_{Virksomhedsvej}$) of the upper 200 m of the Skagerrak Formation is assumed identical to the known minimum gross sand thickness at the Flyvbjerg-1 well ($GST_{Flyvbjerg\text{-}1}$):

$GST_{Virksomhedsvej}$ = $GST_{Flyvbjerg\text{-}1}$
= 61 m

**Net to gross ratio**

The net to gross ratio at the planned well site is assumed identical to the net to gross ratio in the Vedsted-1 well ($N/G_{Vedsted\text{-}1}$) as no net to gross ratio is available from the Flyvbjerg-1 well:

$N/G_{Virksomhedsvej}$ = $N/G_{Vedsted\text{-}1}$ = 0.42

**Net sand thickness**

The net sand thickness at the planned well site ($NST_{Virksomhedsvej}$) is calculated as the gross sand thickness at the Flyvbjerg-1 well ($GST_{Flyvbjerg\text{-}1}$) multiplied with the net to gross ratio in the Vedsted-1 well ($N/G_{Vedsted\text{-}1}$):

$NST_{Virksomhedsvej}$ = $GST_{Flyvbjerg\text{-}1}$ x $N/G_{Vedsted\text{-}1}$
= 61 m x 0.42
= 26 m

This is a minimum value as only the upper 200 m of the formation is evaluated; more sandstones of fluvial origin is expected from GEUS´ general geological models to be present also at deeper levels.

**Porosity**

The porosity at the planned well site ($\varphi_{Virksomhedsvej}$) is assumed identical to porosity in the Vedsted-1 well ($\varphi_{Vedsted-1}$):

$$\varphi_{Virksomhedsvej} = \varphi_{Vedsted-1} = 25\%$$

This porosity value, however, should be adjusted due to the differing burial depth of the Skagerrak Formation in the Vedsted-1 well and at the planned well site. The vertical midpoint of the penetrated part of the Skagerrak Formation in Vedsted-1 is 2055 m; at the planned well site it is 1555 m. The porosity increase can be estimated using the depth-porosity relation presented in **Section 5.6.2** and shown in **Figure 18**:

$$\varphi_{increase} = (–0.0033 \times 2055) + 28.474) – (–0.0033 \times 1555 + 28.474)$$
$$= 1.7\%$$

Thus the corrected porosity for the planned well site is:

$$\varphi_{Virksomhedsvej} = 25\% + 1.7\% = \sim 26.7\%$$

Though this relation was developed for the Gassum Formation, is thought to be generally applicable to sandstone units.

**Estimated gas permeability**

The estimated gas permeability at the planned well site ($k_{Virksomhedsvej,\ gas}$) is, as a starting point, assumed identical to the estimated gas permeability in the Vedsted-1 well ($k_{Vedsted-1,\ gas}$):

$$k_{Virksomhedsvej,\ gas} = k_{Vedsted-1,\ gas} = 300 \text{ mD}$$

However, the expected higher porosity at the planned well site (26.7%) compared to Vedsted-1 (25%) will cause a gas permeability increase:

$$k_{Increase\ factor} = (0.00002 \times 26.7^{4.9859}) / (0.00002 \times 25^{4.9859})$$
$$= 1.3$$

The estimated gas permeability at a porosity of 26.7% is calculated as:

$$k_{\text{Virksomhedsvej, gas}} = 300 \text{ mD} \times 1.3$$
$$= 390 \text{ mD}$$

**Estimated reservoir permeability**

Reservoir permeability at the planned well site ($k_{\text{Virksomhedsvej, res.}}$) is estimated by multiplying $k_{\text{Virksomhedsvej, gas}}$ with an upscaling factor of 1.25 developed by GEUS:

$$k_{\text{Virksomhedsvej, res.}} = k_{\text{Virksomhedsvej, gas}} \times 1.25$$
$$= 390 \text{ mD} \times 1.25$$
$$= 488 \text{ mD}$$

**Estimated transmissivity**

Transmissivity at the planned well site ($T_{\text{Virksomhedsvej}}$) is estimated by multiplying $k_{\text{Virksomhedsvej, res.}}$ with $NST_{\text{Virksomhedsvej}}$:

$$T_{\text{Virksomhedsvej, min.}} = (k_{\text{Virksomhedsvej, res.}} \times NST_{\text{Virksomhedsvej, min.}}) / 1000$$
$$= (488 \text{ mD} \times 26 \text{ m}) / 1000$$
$$= \sim 13 \text{ Dm}$$

The transmissivity of c. 13 Dm is only representable for the upper c. 200 m of the Skagerrak Fm. This interval is assumed to exhibit good reservoir properties.

# 7 Temperature assessment

Generally, the existing Danish onshore subsurface temperature database is limited and contains values from wells measured at different depths and at different times, resulting in uncertain geothermal gradients. Generally, the gradient varies from 28 °C/km to less than 20 °C/km, in the Danish onshore area.

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.

A depth-temperature relation has been developed based on relatively few available temperature measurements performed on wells in the Northern Jutland are (Poulsen et al. in prep.). The equation describing this relation (0.027 x depth + 8) has been used for assessing the temperature at the centre of potential geothermal formations (**Table 24**). All temperatures are estimated at the formation centre with an uncertainty of ± 10%.

As described in **Section 6.4** the evaluation of reservoir properties is performed on the uppermost 200 m of the Skagerrak Formation at the planned well site.

**Table 24:** Assessed temperature ± 10% of potential geothermal reservoirs.

| **Formation** | **Formation interval** (m MD) | **Depth of temperature assessment** (m) | **Temperature** (°C) |
|---|---|---|---|
| Frederikshavn | 778–989 | 884 | 32 |
| Haldager Sand | 1052–1118 | 1085 | 37 |
| Gassum | 1337–1455 | 1396 | 46 |
| Skagerrak | 1455–1655 | 1555 | 50 |

# 8 Conclusions

The objective of this report is to assess the geothermal potential in the Brønderslev area with focus on one well site, Virksomhedsvej, selected by Brønderslev Varme A/S. The assessment of the geothermal potential is based on the evaluation and interpretation of the available seismic data, well data from the Børglum-1, Flyvbjerg-1, Vedsted-1, Haldager-1 and Sæby-1 wells and core analysis data. The following conclusions can be made:

1. **Potential reservoirs.** Based on well log interpretation, core analysis data and cuttings descriptions four formations with geothermal potential have been identified: the Frederikshavn Formation, the Haldager Sand Formation, the Gassum Formation and the Skagerrak Formation.

2. **Seismic horizons.** Seven seismic horizons have been identified in order to assess the presence of faults and to provide depth maps. The seismic horizons include the near top of the Frederikshavn, Haldager Sand, Gassum and Skagerrak formations (= near base of the Gassum Formation). It has not been possible to map single reservoir sections within the Gassum Formation due the relatively low resolution of the seismic data. The seismic line DNJ-100 passes relatively close to the planned well site (c. 1.5 km) and provides the basis for depth estimations of potential reservoirs.

3. **Faults.** Three major faults or fault zones have been identified. The Børglum and Haldager faults are situated c. 10 km NE and 20 km SW of Brønderslev town, respectively, and assumable have no impact on continuity of potential reservoirs. The Brønderslev Fault is situated c. 3 km SW of Brønderslev town and possibly does not influence the reservoir continuity. Minor faults may exist but remain unidentified due to the poor to moderate quality of the seismic data.

4. **Depth structure maps.** New depth structure maps have been prepared based on the new seismic interpretation. These include the Base Upper Cretaceous (BUC), Mid-Cimmerian Unconformity (MCU), near Top Gassum Formation and near Top Skagerrak Formation (= near Base Gassum Formation).

5. **Burial depth.** At the planned well site approximate depths to formation tops are estimated from the seismic line DNJ-100: Frederikshavn Formation: 778 m; Haldager Sand Formation: 1052 m; Gassum Formation: 1337 m; Skagerrak Formation: 1455 m. C. 5 km to the SW of the planned well site the burial depth of the Gassum Formation may be in the range of c. 400–700 m corresponding to a temperature increase in the range of c. 11–19 °C.

6. **Net sand thickness.** At the planned well site the net sand thickness has been assessed based on well data from the Børglum-1, Flyvbjerg-1, Vedsted-1 and Haldager-1 wells: Frederikshavn Formation: 24 m; Haldager Sand Formation: 44 m; Gassum Formation: 53 m; Skagerrak Formation: 26 m. The net sand thickness of the Skagerrak Formation is provided for the "known" upper 200 m and probably is higher as the formation is more than 1.5 km thick.

7. **The regional porosity-permeability trend.** Core analysis data in terms of porosity and permeability from the Sæby-1 and Vedsted-1 wells seem to follow a high and a low permeability trend which fit poorly with the regional distribution of Skagerrak Formation data points. The equation of the regional trend has thus been adjusted to better represent the porosity-permeability relation in the Brønderslev area.

8. **Porosity.** At the planned well site the porosity for the Frederikshavn, Haldager Sand and Skagerrak formations are based on log-derived porosities of the Børglum-1, Vedsted-1 and Haldager-1 wells: Frederikshavn Formation: 21%; Haldager Sand Formation: 25%; Skagerrak Formation: 25%. For the Gassum Formation the porosity is calculated from a newly developed depth-porosity relationship including only one average porosity value for each Danish onshore well containing the Gassum Formation: Gassum Formation: 24%.

9. **Permeability.** At the planned well site the permeabilities for the four formations with geothermal potential are based on the log-derived gas permeability of the Børglum-1, Vedsted-1 and Haldager-1 wells multiplied with an upscaling factor: Frederikshavn Formation: 586 mD; Haldager Sand Formation: 935 mD; Gassum Formation: 762 mD; Skagerrak Formation: 488 mD.

10. **Transmissivity.** At the planned well site transmissivities are obtained as a multiple of net sand thickness and upscaled permeability: Frederikshavn Formation: 14 Dm; Haldager Sand Formation: 41 Dm; Gassum Formation: 40 Dm; Skagerrak Formation: 13 Dm. The transmissivity of the Skagerrak Formation is provided for the “known” upper 200 m and probably is higher as the formation is more than 1.5 km thick.

11. **Reservoir temperature.** At the planned well site the assessed temperatures for the four formations with geothermal potential are: Frederikshavn Formation: 32 °C; Haldager Sand Formation: 37 °C; Gassum Formation: 46 °C; Skagerrak Formation: 50 °C.

# 9 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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# 11 Figures

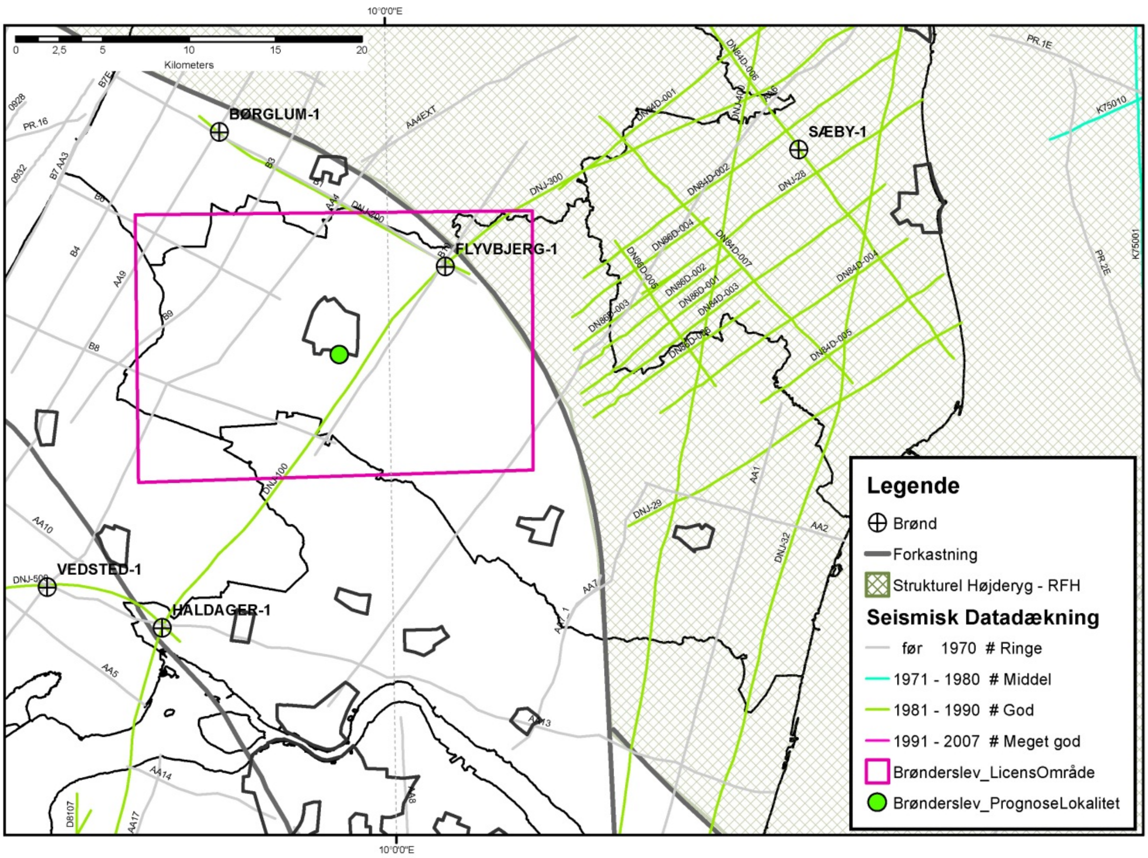



**Figure 1:** Map of the greater Brønderslev area showing seismic data coverage, well locations, licence area and planned well site. The quality estimation of the seismic lines is based on age; the actual quality of single lines may deviate. The grey line passing close by the Børglum-1 and Flyvbjerg-1 wells represents the Børglum Fault zone that separates the Fjerritslev Trough to the south from the Skagerrak-Kattegat Platform to the north.

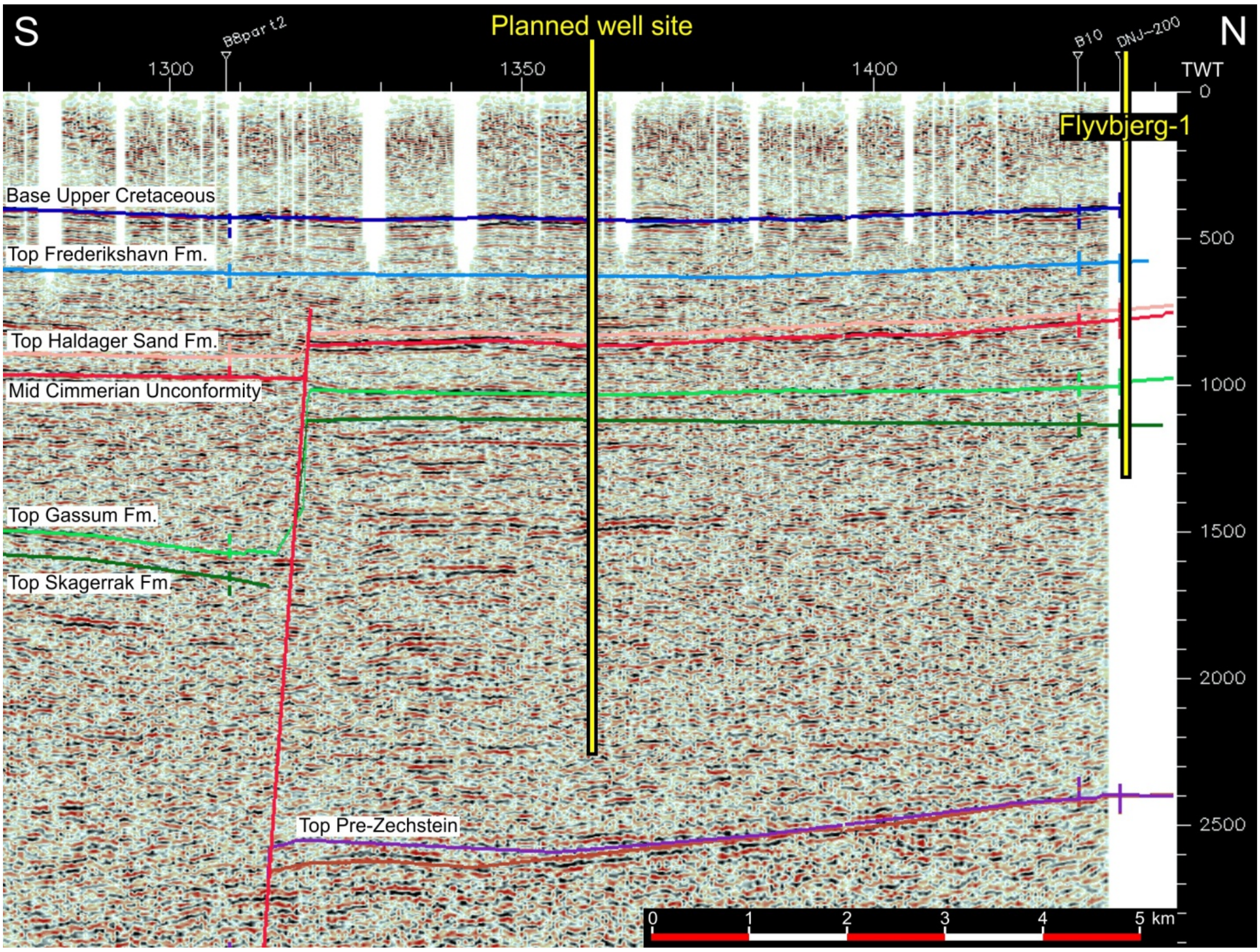



**Figure 2:** Northern section of the seismic line DNJ-100 with depth measured in Time [msec] showing the Flyvbjerg-1 well and the planned well site projected into the line (shot point 1360, c. 1.5 km away). Note the significant Haldager Fault c. 3 km south of the planned well site.

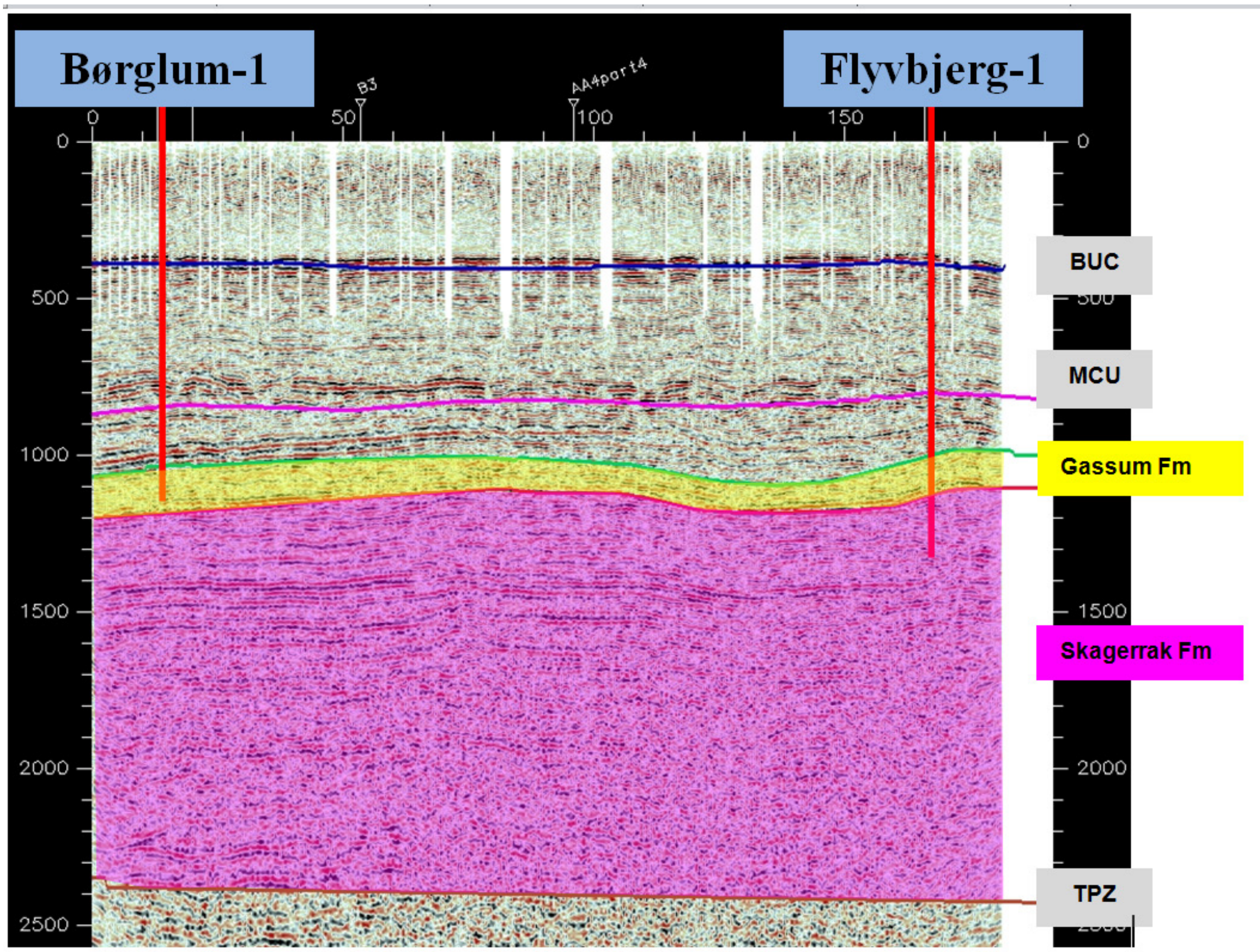



**Figure 3:** Section of the seismic line DNJ-200 with depth measured in Time [msec] showing the subsurface in the area between the Børglum-1 and Flyvbjerg-1 wells. Notice the relative constant thickness of the Gassum Formation (yellow area) and the expected Skagerrak Formation (pink area). Note also that Børglum-1 well did not reach the base of the Gassum Formation.

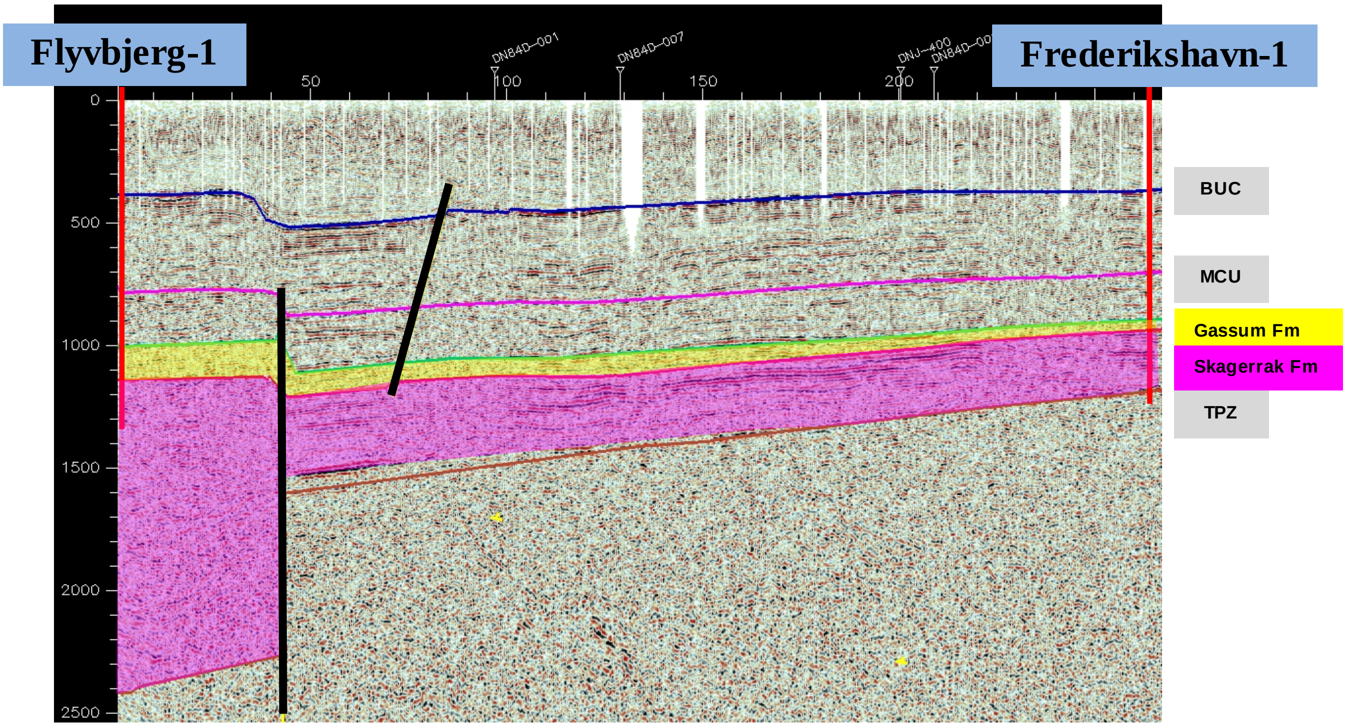



**Figure 4:** Section of the seismic line DNJ-300 with depth measured in Time [msec] showing the subsurface in the area northeast of the Flyvbjerg-1 well. Notice the presence of the fault zones (black lines) northeast of the Flyvbjerg-1 well location and the thinning of the Gassum Formation (yellow area) towards northeast; the thickness of the Skagerrak Formation on the Skagerrak-Kattegat Platform is expected to be more constant with a weak thinning towards the northeast (pink area). Notice that the marked Børglum Fault closely northeast of the Flyvbjerg-1 well is a normal fault that later was inverted.

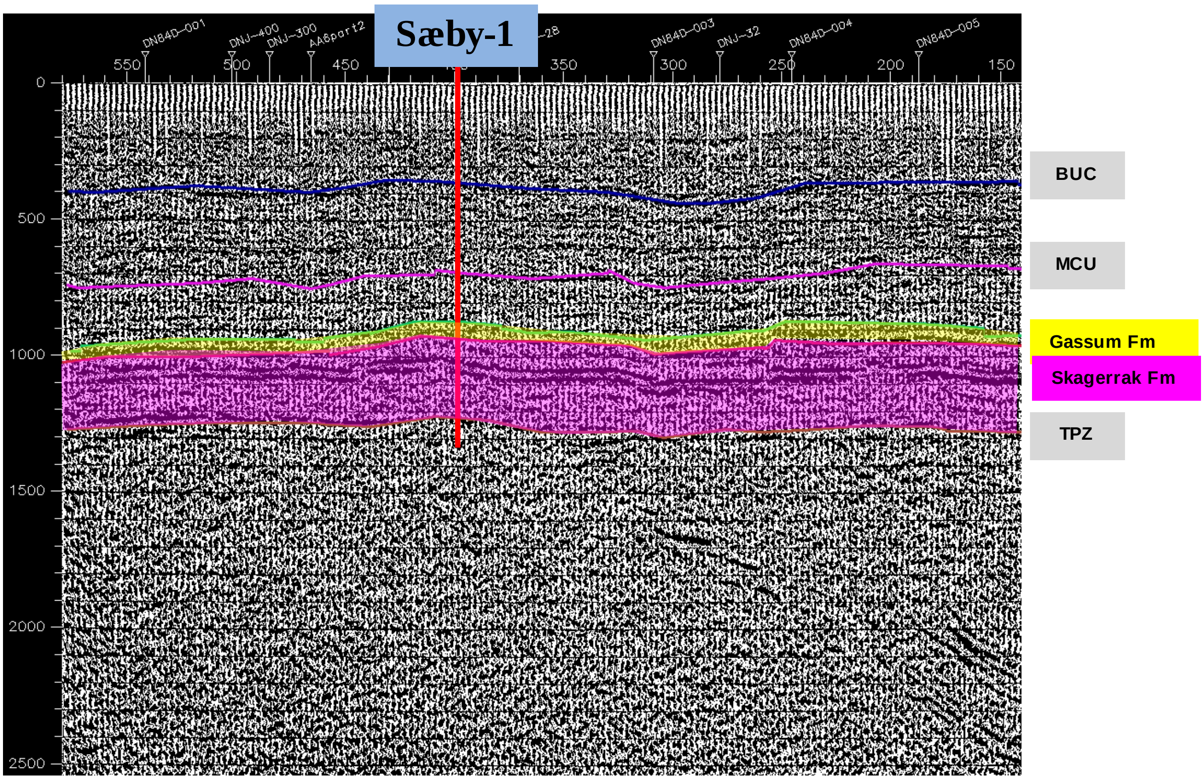



**Figure 5:** Part of the seismic line DN84D-006 with depth measured in Time [msec] showing the subsurface in the area around the Sæby-1 well. Notice the relative constant thickness of the Gassum Formation (yellow area) and the expected thickness of the Skagerrak Formation (pink area). (BUC: Base Upper Cretaceous; MCU: Mid Cimmerian Unconformity; TPZ: Top Pre-Zechstein).

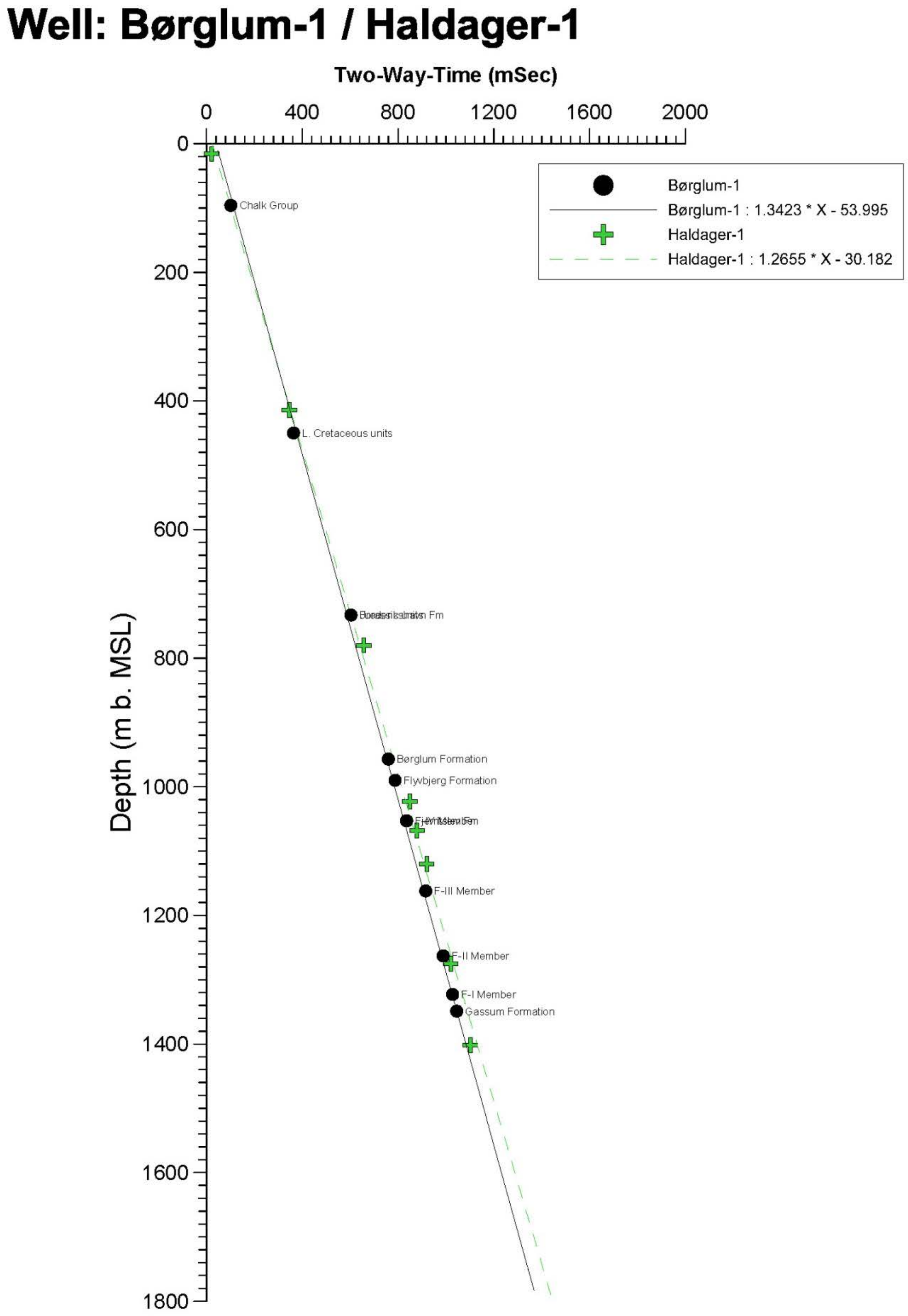



**Figure 6:** Time-depth relation for the Børglum-1 and Haldager-1 wells.

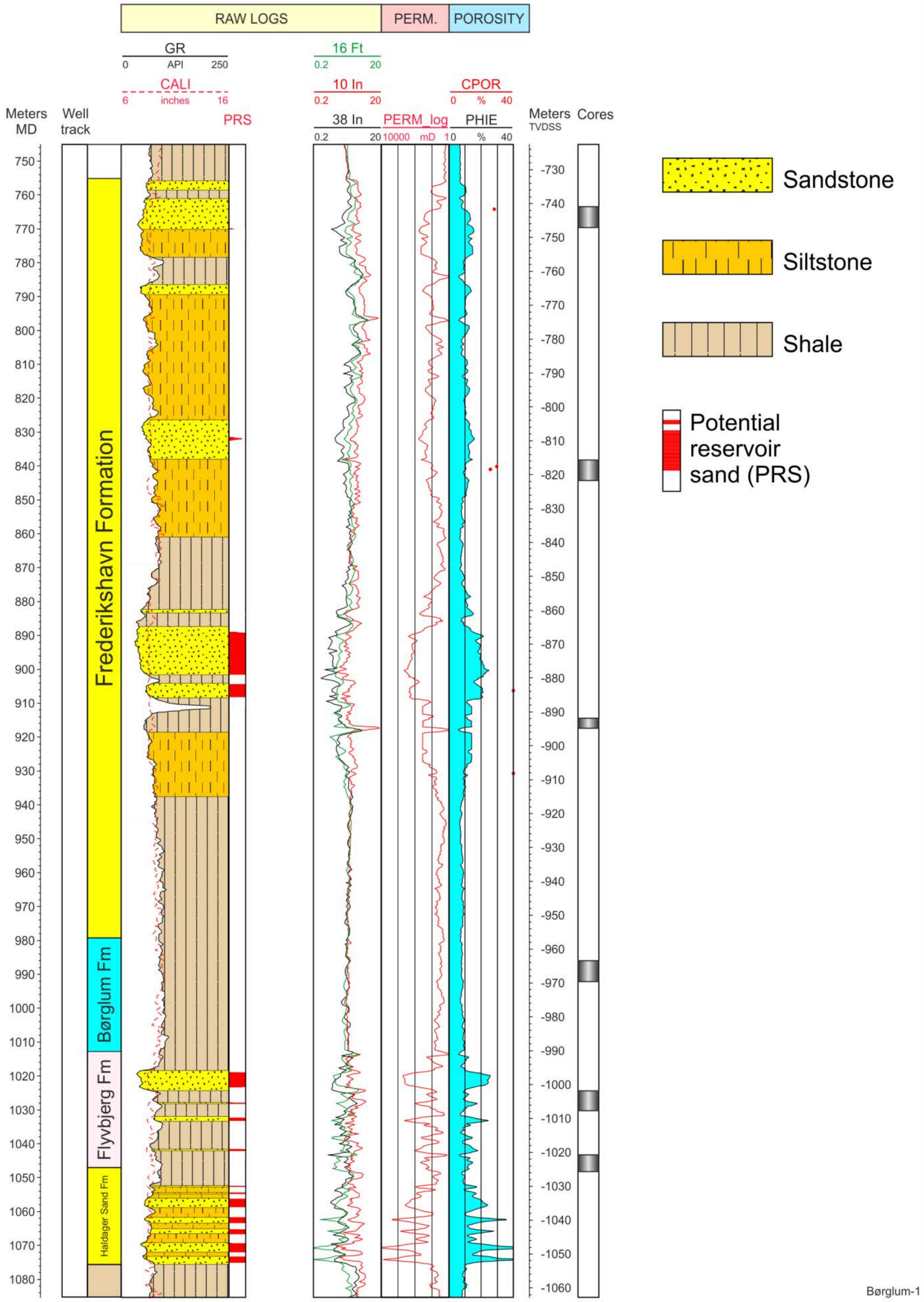



**Figure 7:** Petrophysical evaluation of the Frederikshavn and Haldager Sand formations in the **Børglum-1 well**, including a lithological interpretation. The lithology column and the gamma-ray log are shown to the left. Resistivity logs are shown in the middle. The estimated porosity (PHIE) is highlighted by blue colour fill, and the permeability estimate (PERM_log) is plotted in red left of the porosity curve. Core porosity data are shown by red dots Cored intervals are indicated by black bars. Core porosity data are shown by red dots. For log abbreviations, see **Table 4**.

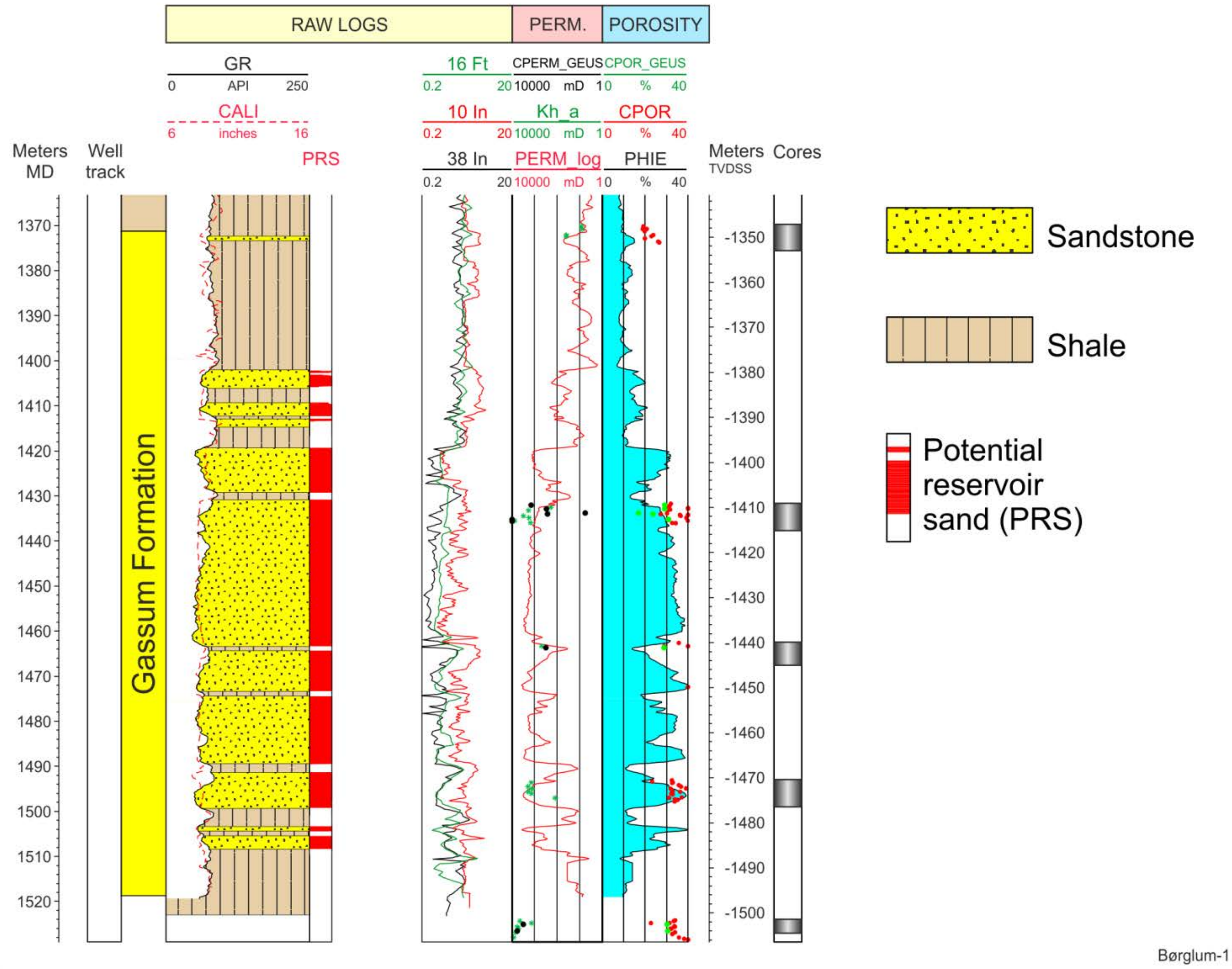



**Figure 8:** Petrophysical evaluation of the Gassum Formation in the **Børglum-1 well**, including a lithological interpretation. The lithology column and the gamma-ray log are shown to the left. Resistivity logs are shown in the middle. The estimated porosity (PHIE) is highlighted by blue colour fill, and the permeability estimate (PERM_log) is plotted in red left of the porosity curve. Core porosity data are shown by red and green dots; core permeability data are shown by green and black dots. Cored intervals are indicated by black bars. For log abbreviations, see **Table 4**.

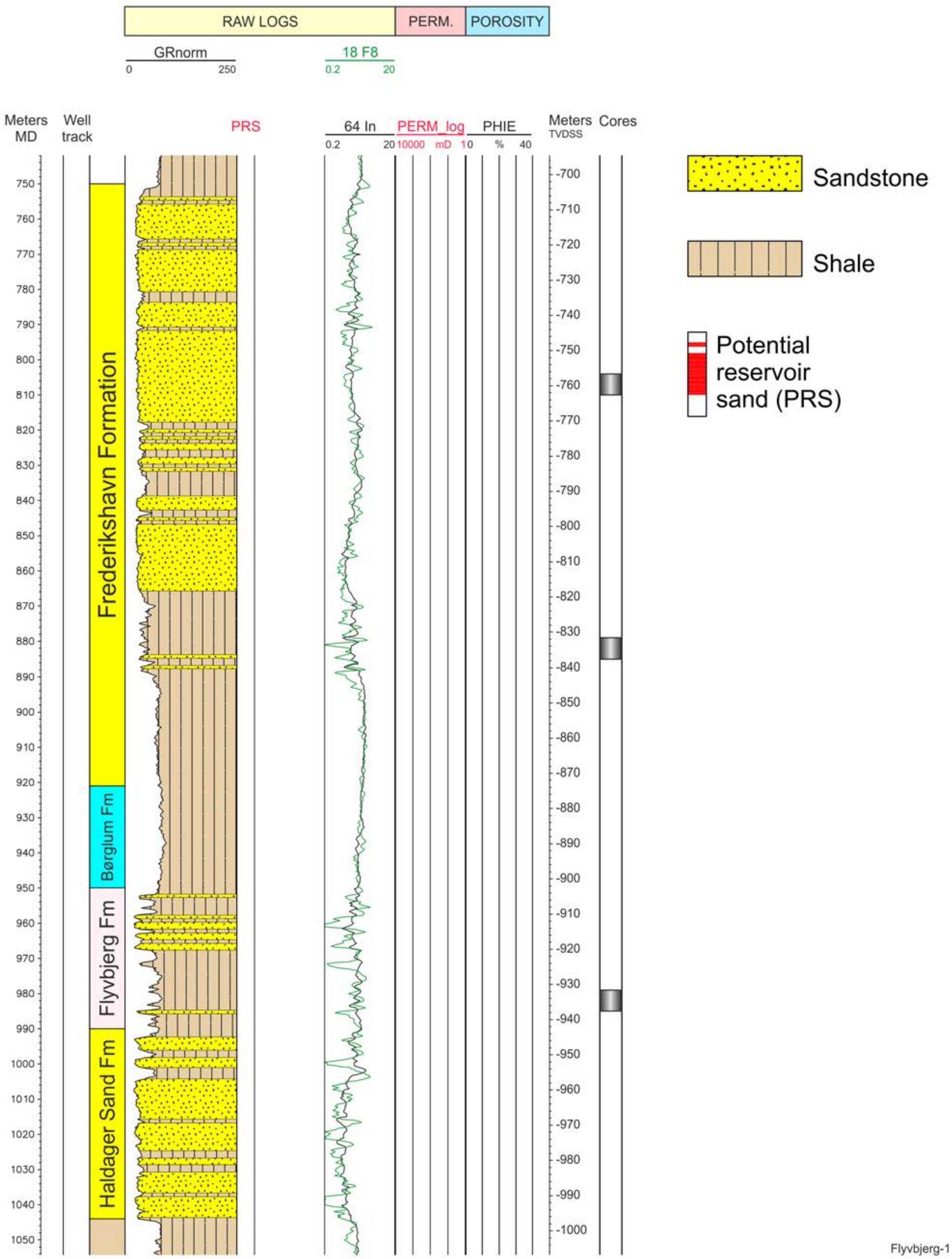



**Figure 9:** Petrophysical evaluation of the Frederikshavn and Haldager Sand formations in the **Flyvbjerg-1 well**, including a lithological interpretation. The lithology column and the gamma-ray log are shown to the left. Resistivity logs are shown in the middle. No Neutron-log (NPHI) and density-log (RHOB) were recorded, thus estimation of porosity (PHIE) and permeability (PERM_log) is not possible. Cored intervals are indicated by black bars. For log abbreviations, see **Table 4**.

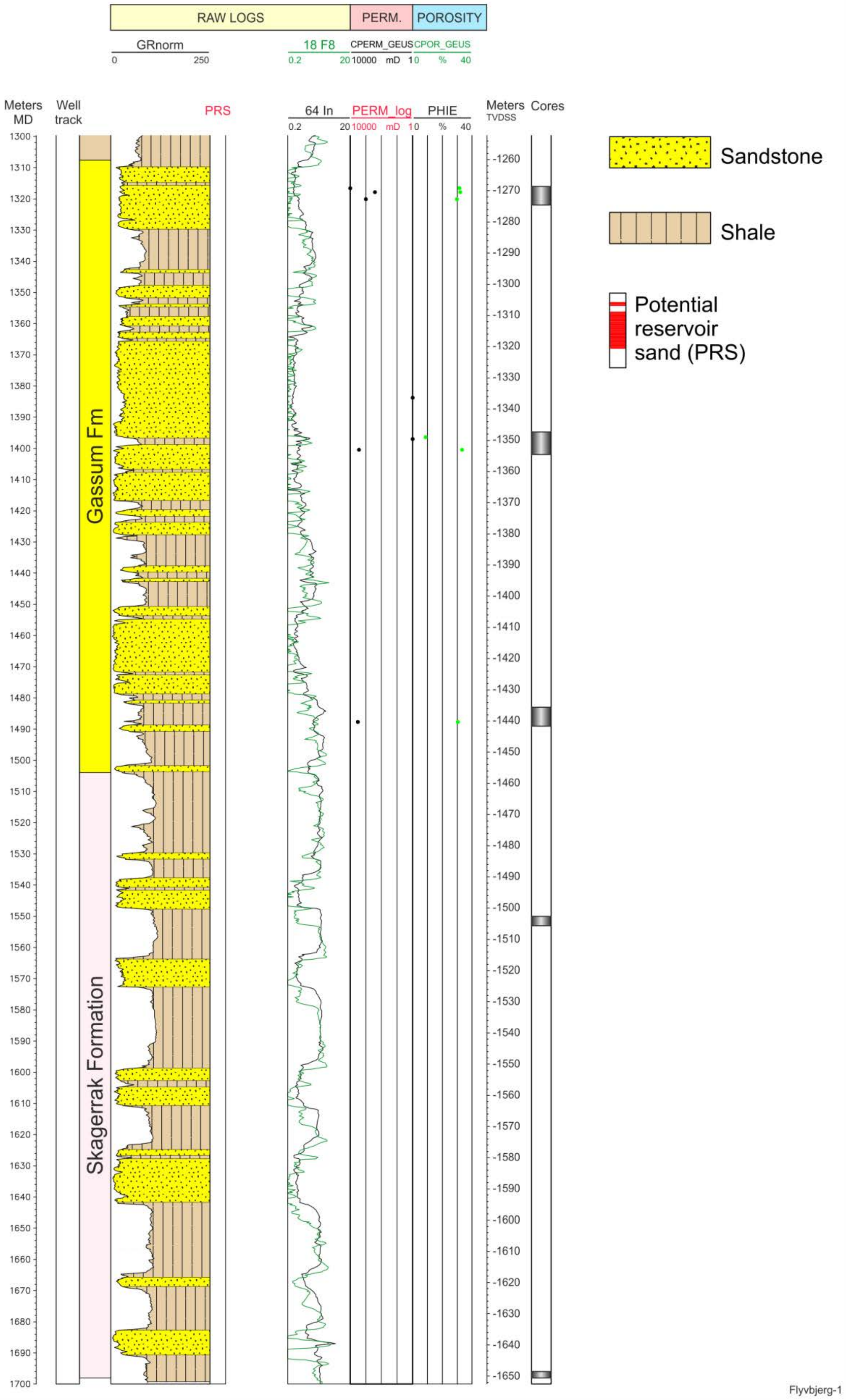



**Figure 10:** Petrophysical evaluation of the Gassum and Skagerrak formations in the **Flyvbjerg-1 well**, including a lithological interpretation. The lithology column and the gamma-ray log are shown to the left. Resistivity logs are shown in the middle. No Neutron-log (NPHI) and density-log (RHOB) were recorded, thus estimation of porosity (PHIE) and permeability (PERM_log) is not possible. Core porosity data are shown by green dots; core permeability data are shown by black dots. Cored intervals are indicated by black bars. For log abbreviations, see **Table 4**.

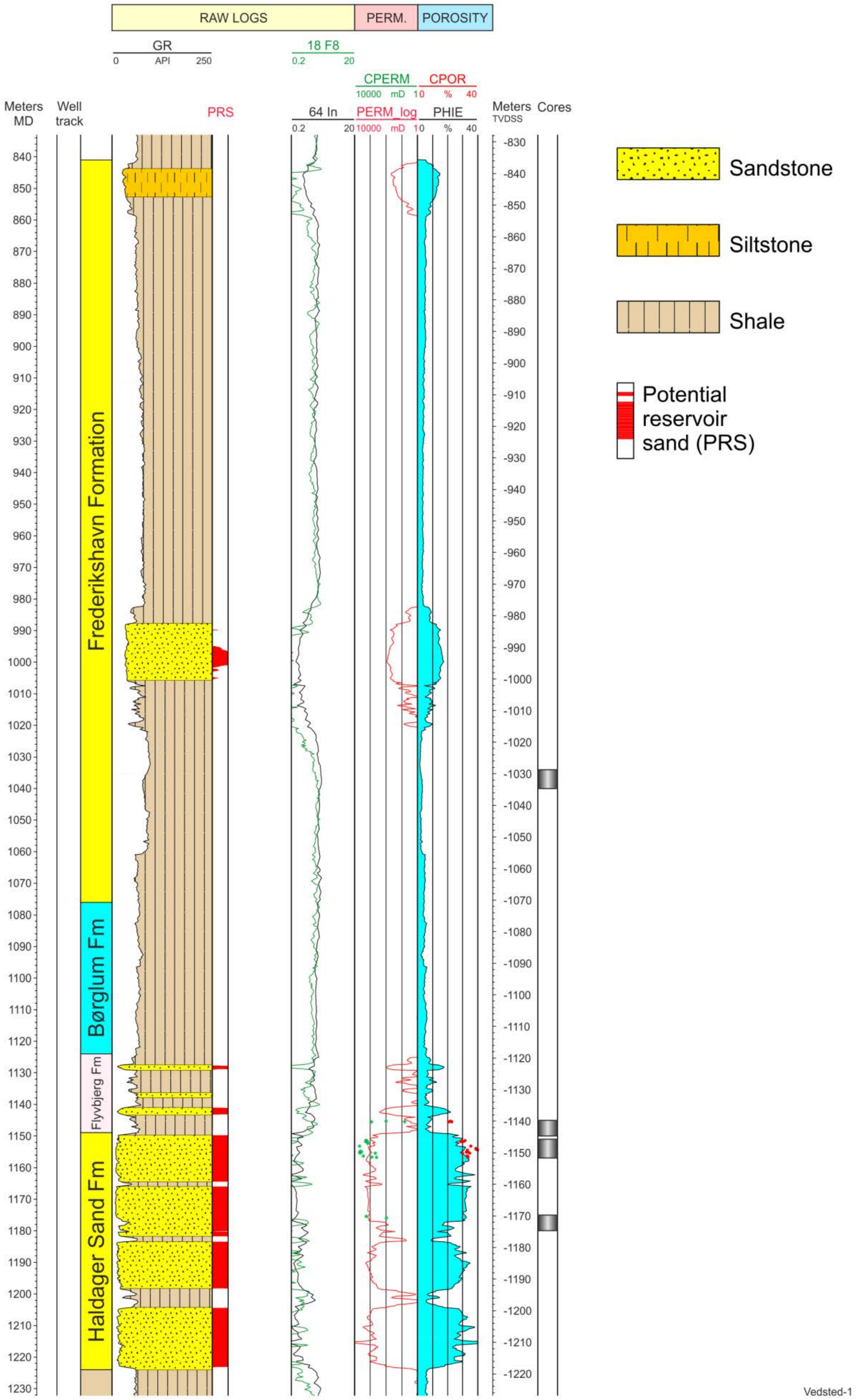



**Figure 11:** Petrophysical evaluation of the Frederikshavn and Haldager Sand formations in the **Vedsted-1 well**, including a lithological interpretation. The lithology column and the gamma-ray log are shown to the left. Resistivity logs are shown in the middle. The estimated porosity (PHIE) is highlighted by blue colour fill, and the permeability estimate (PERM_log) is plotted in red left of the porosity curve. Core porosity data are shown by red dots; core permeability data are shown by green dots. Cored intervals are indicated by black bars. Core porosity data are shown by red dots. For log abbreviations, see **Table 4**.

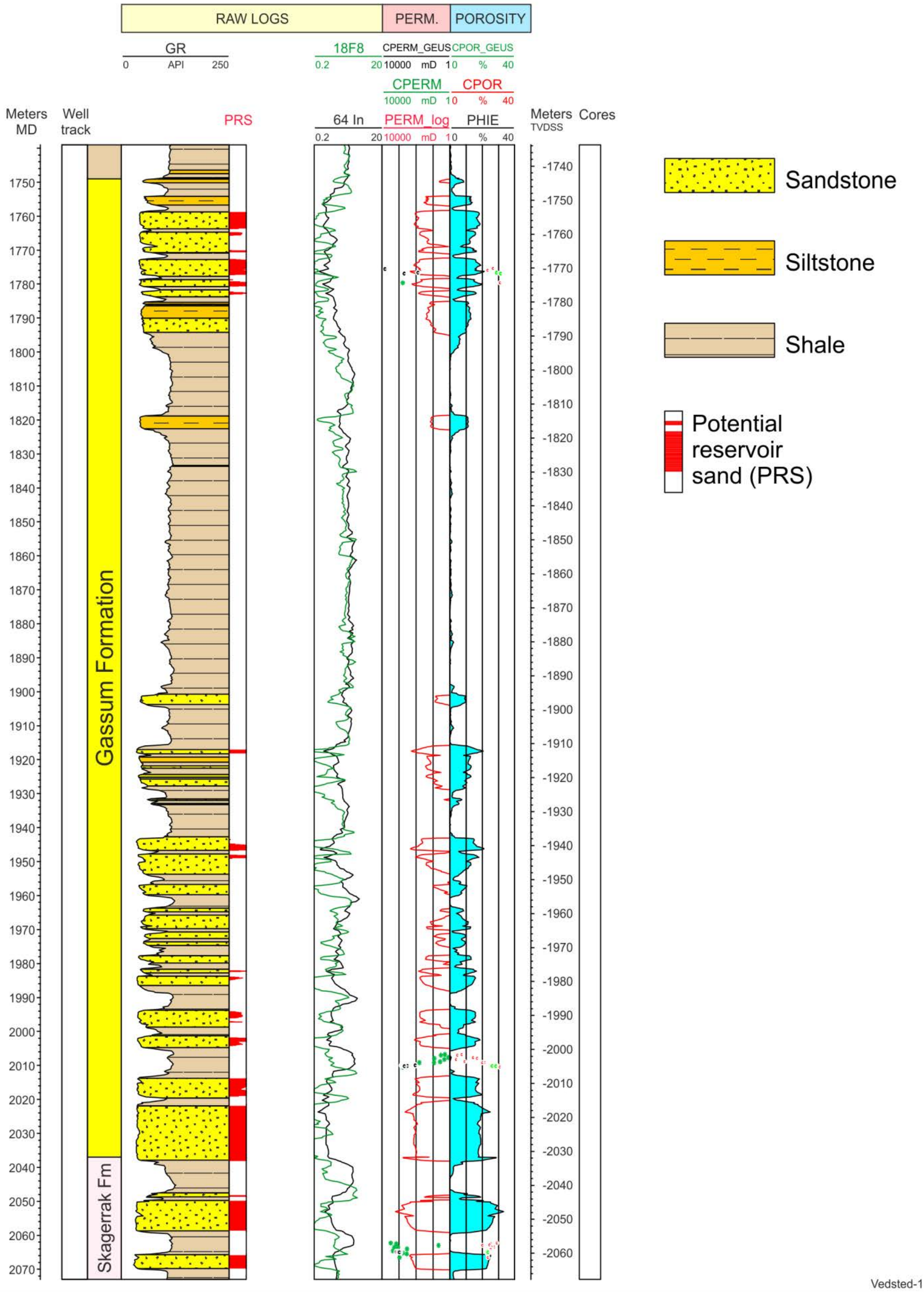



**Figure 12:** Petrophysical evaluation of the Gassum and Skagerrak formations in the **Vedsted-1 well**, including a lithological interpretation. The lithology column and the gamma-ray log are shown to the left. Resistivity logs are shown in the middle. The estimated porosity (PHIE) is highlighted by blue colour fill, and the permeability estimate (PERM_log) is plotted in red left of the porosity curve. Core porosity data are shown by red and green dots; core permeability data are shown by green and black dots. For log abbreviations, see **Table 4**.

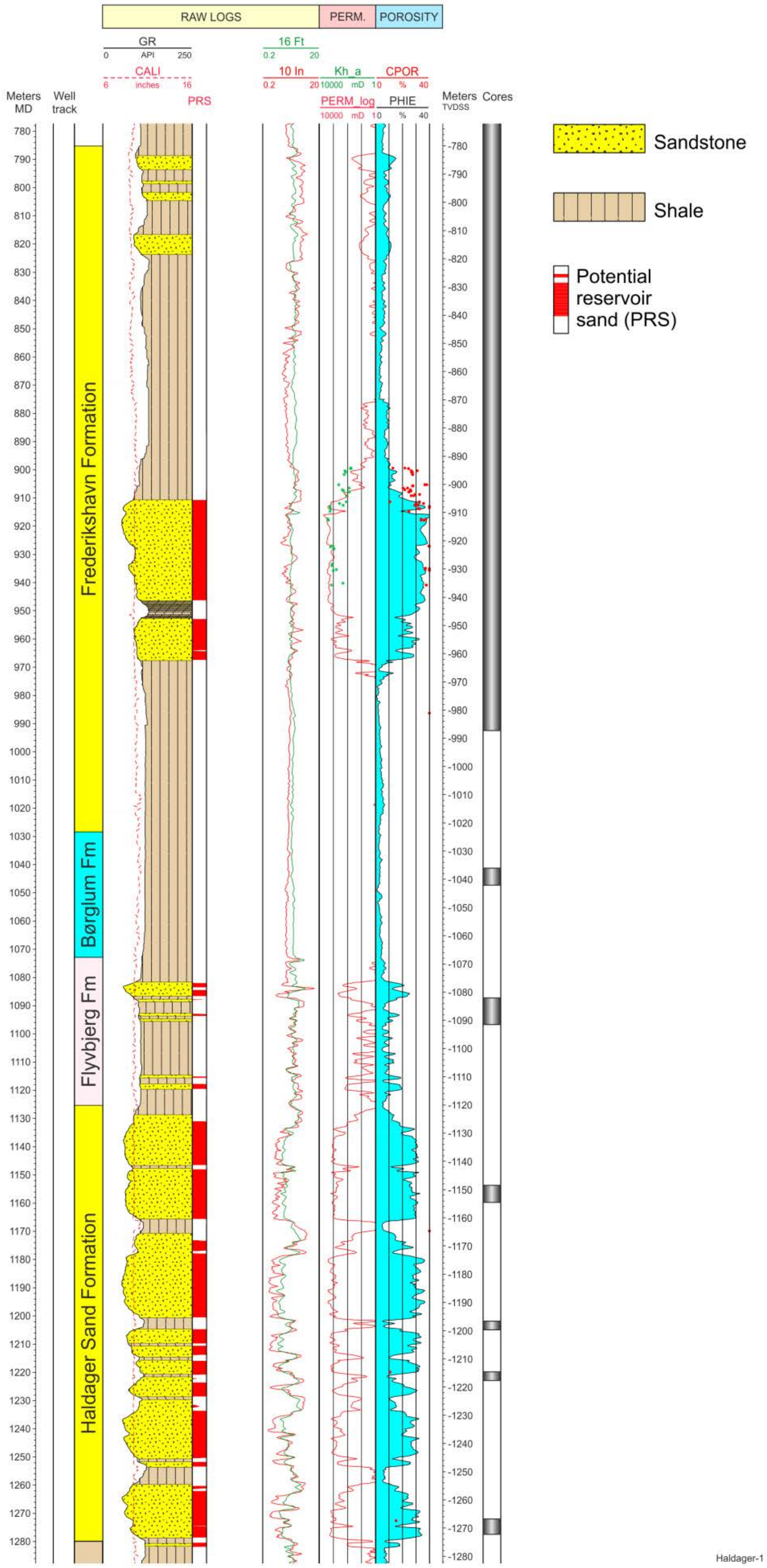



**Figure 13:** Petrophysical evaluation of the Frederikshavn and Haldager Sand formations in the **Haldager-1 well**, including a lithological interpretation. The lithology column and the gamma-ray log are shown to the left. Resistivity logs are shown in the middle. The estimated porosity (PHIE) is highlighted by blue colour fill, and the permeability estimate (PERM_log) is plotted in red left of the porosity curve. Core porosity data are shown by red dots; core permeability data are shown by green dots. Cored intervals are indicated by black bars. Core porosity data are shown by red dots. For log abbreviations, see **Table 4**.

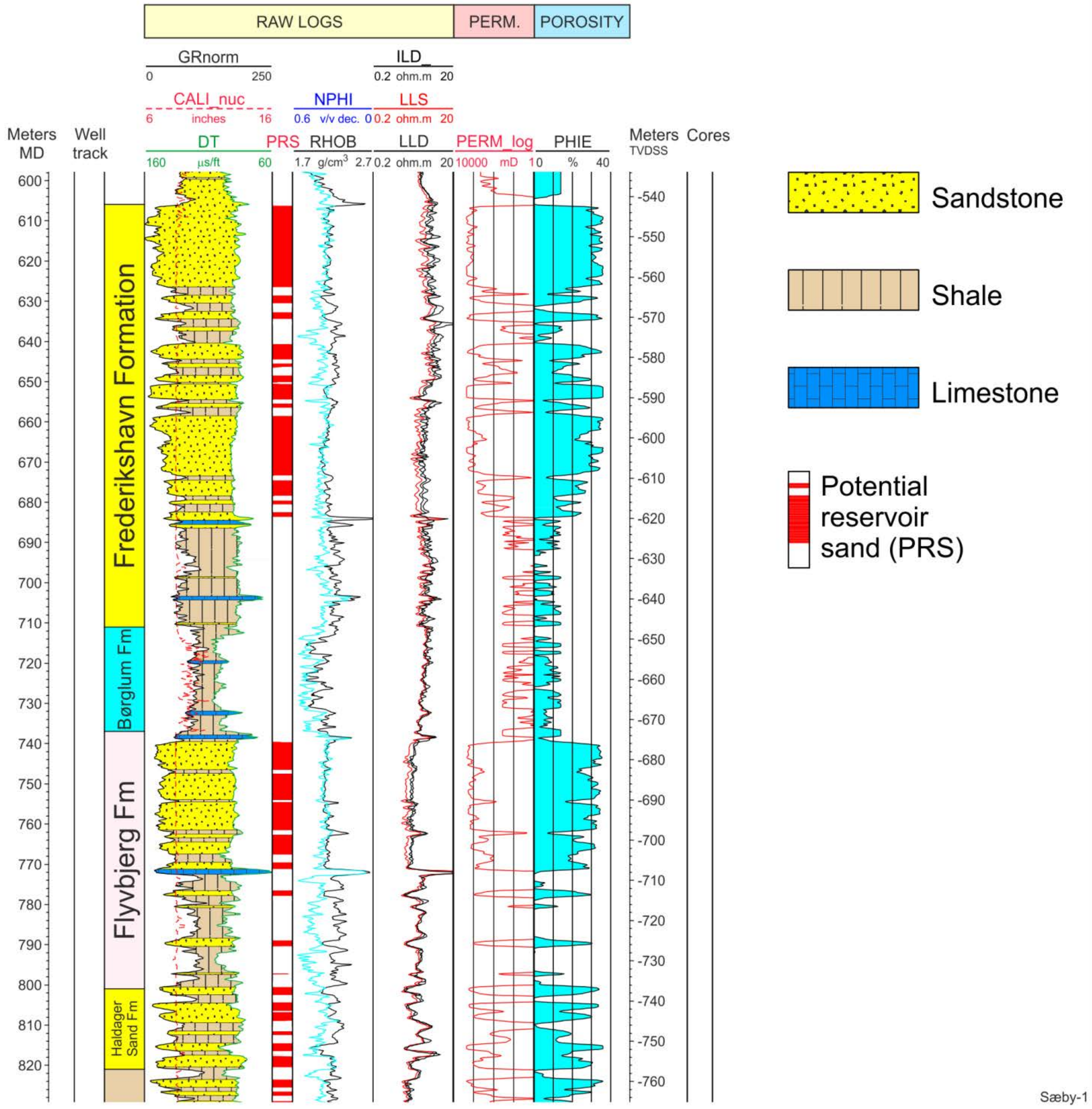



**Figure 14:** Petrophysical evaluation of the Frederikshavn and Haldager Sand formations in the **Sæby-1 well**, including a lithological interpretation. The lithology column (left) is bounded by the gamma-ray (GR) and sonic (DT) logs. The Neutron-log (NPHI) and the density-log (RHOB) are plotted to the right of the lithological interpretation. Resistivity logs are shown in the middle. The porosity determination (PHIE) is highlighted in blue colour fill, and the permeability estimate (PERM_log) is plotted in red left of the porosity curve. For log abbreviations, see **Table 4**.

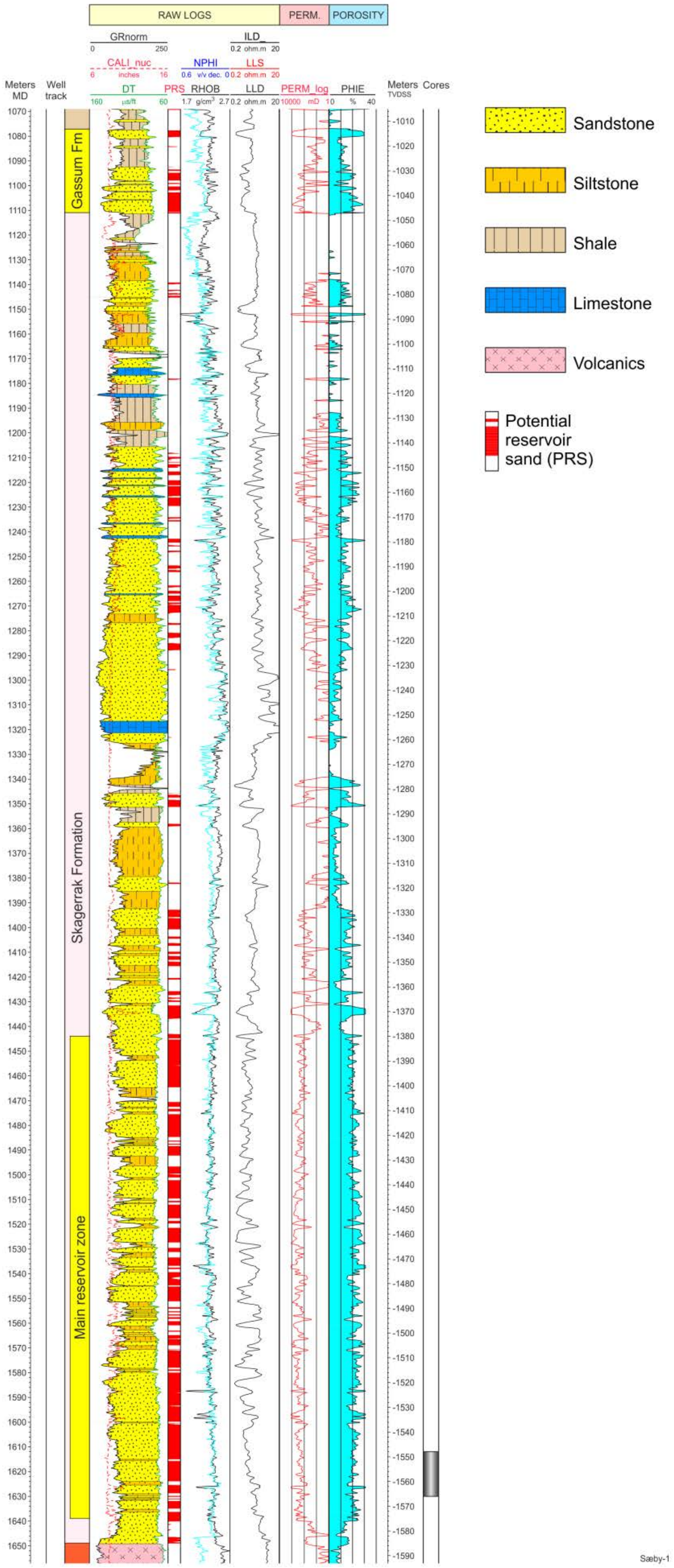



**Figure 15:** Petrophysical evaluation of the Gassum and Skagerrak formations in the **Sæby-1 well**, including a lithological interpretation. The lithology column (left) is bounded by the gamma-ray (GR) and sonic (DT) logs. Resistivity logs are shown in the middle. The Neutron-log (NPHI) and the density-log (RHOB) are plotted to the right of the lithological interpretation. The porosity determination (PHIE) is highlighted in blue colour fill, and the permeability estimate (PERM_log) is plotted in red left of the porosity curve. Cored intervals are indicated by black bars. For log abbreviations, see **Table 4**.

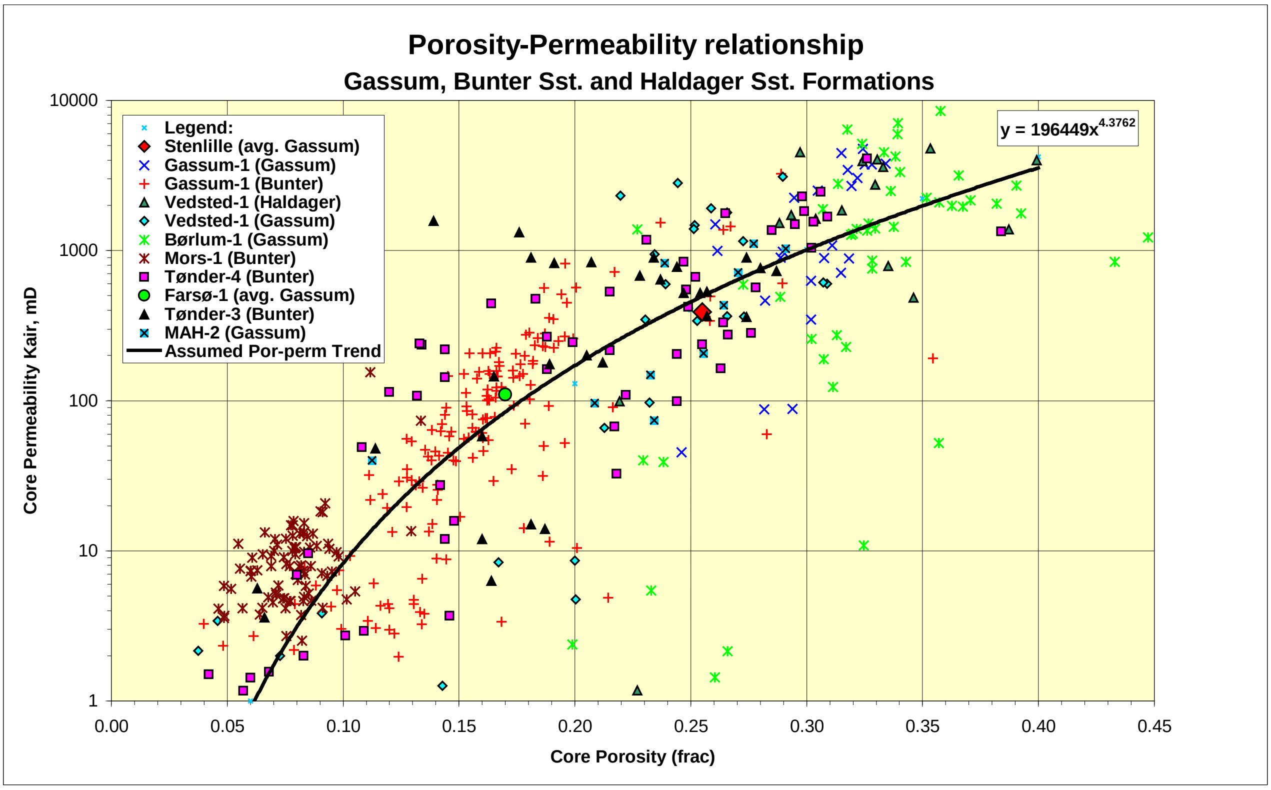



**Figure 16:** Generalised relation between porosity and permeability for sandstones based on conventional core analysis data from selected Danish onshore wells in the Danish Basin. The underlying database includes core data from the Bunter Sandstone, Gassum and Haldager Sand formations. Note that the core permeability data are gas/air permeabilities.

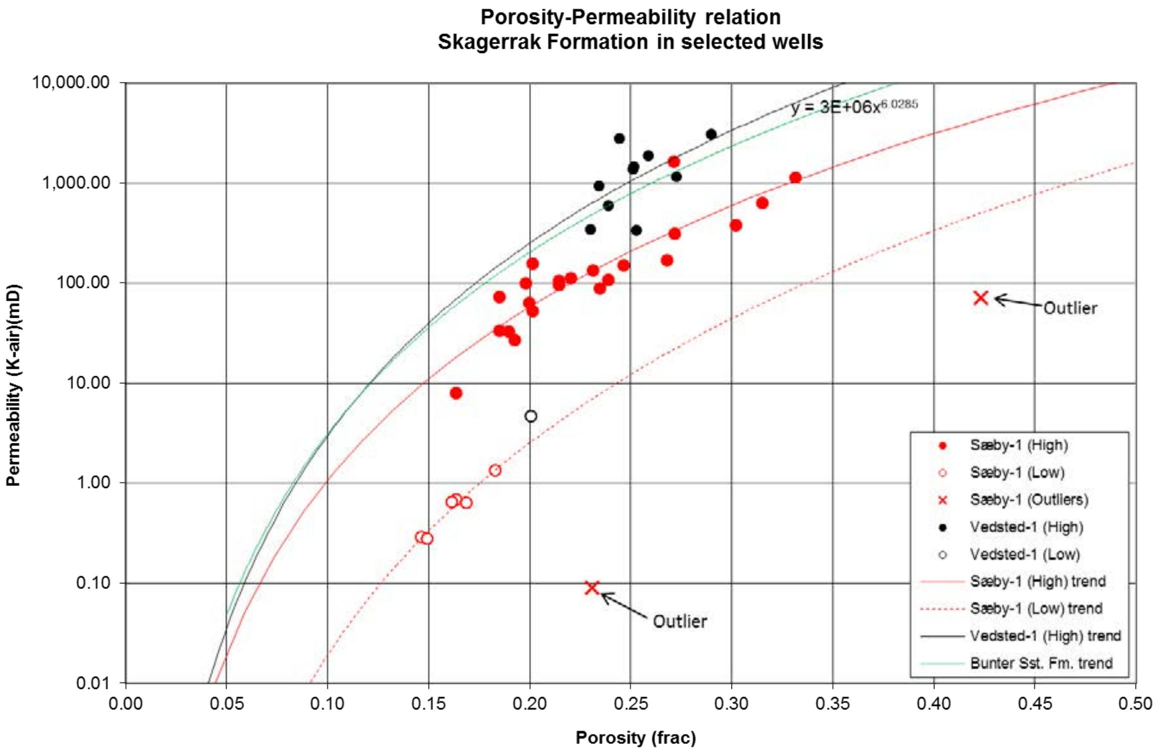



**Figure 17:** Porosity-permeability relation for Skagerrak Formation sandstones based on conventional core analysis data from the Vedsted-1 and Sæby-1 wells. Note that Sæby-1 data plot along a high and a low trend lines. Vedsted-1 data follow a similar distribution; the high permeability trend corresponds well with the regional trend of the Bunter Sandstone Formation for Danish onshore wells. The core permeability data are gas/air permeabilities.

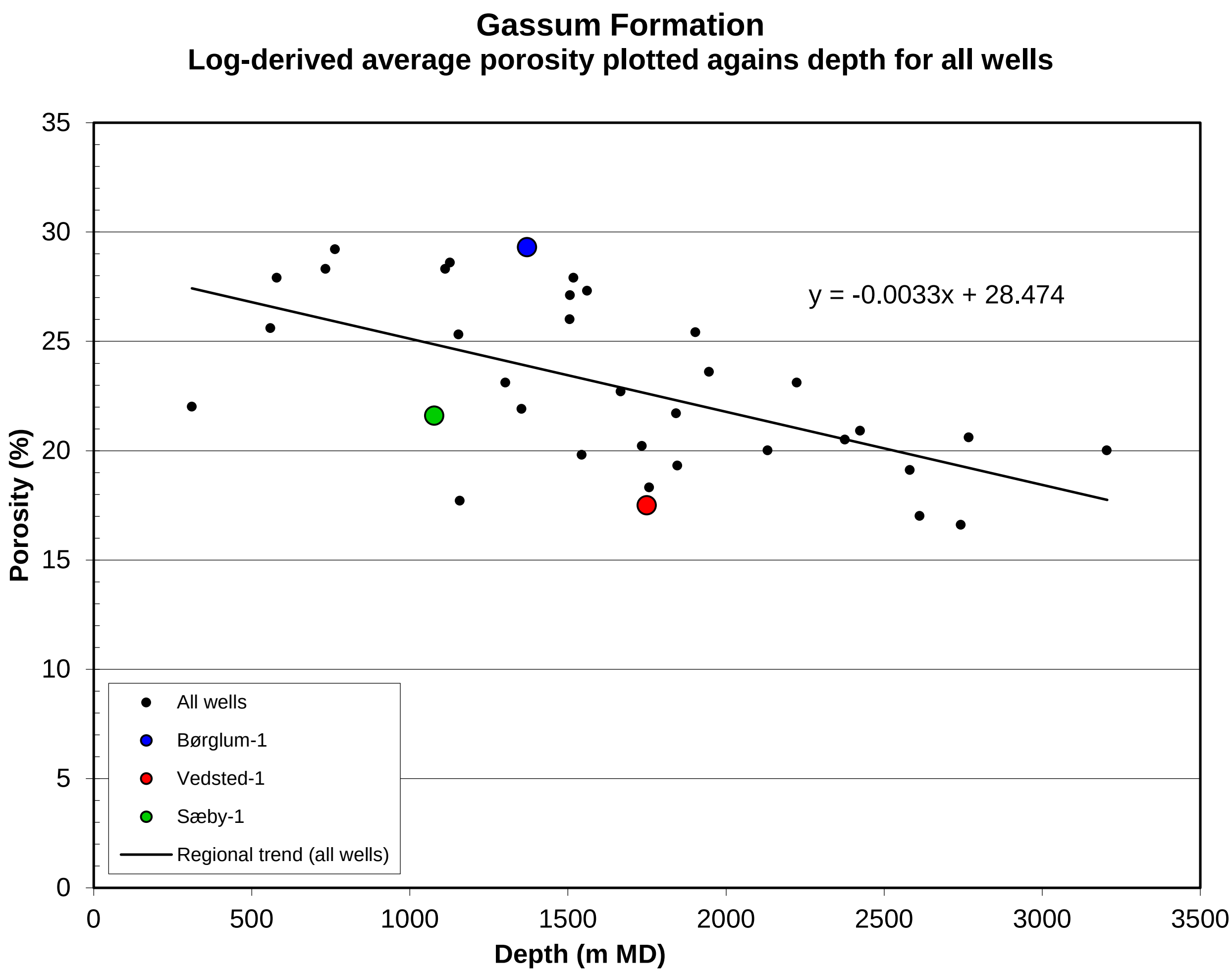



**Figure 18:** Depth-porosity relation for the Gassum Formation based on well log data from 35 onshore wells. Each data point represents the depth to the top of the Gassum Formation plotted against average effective porosity of net sand for *one* well. The depth-porosity trend is used to estimate porosity of Gassum Formation samples at a given depth. Though the relation has been developed for Gassum Formation sandstones it is assumed to be general and applicable to sandstones of other formations.

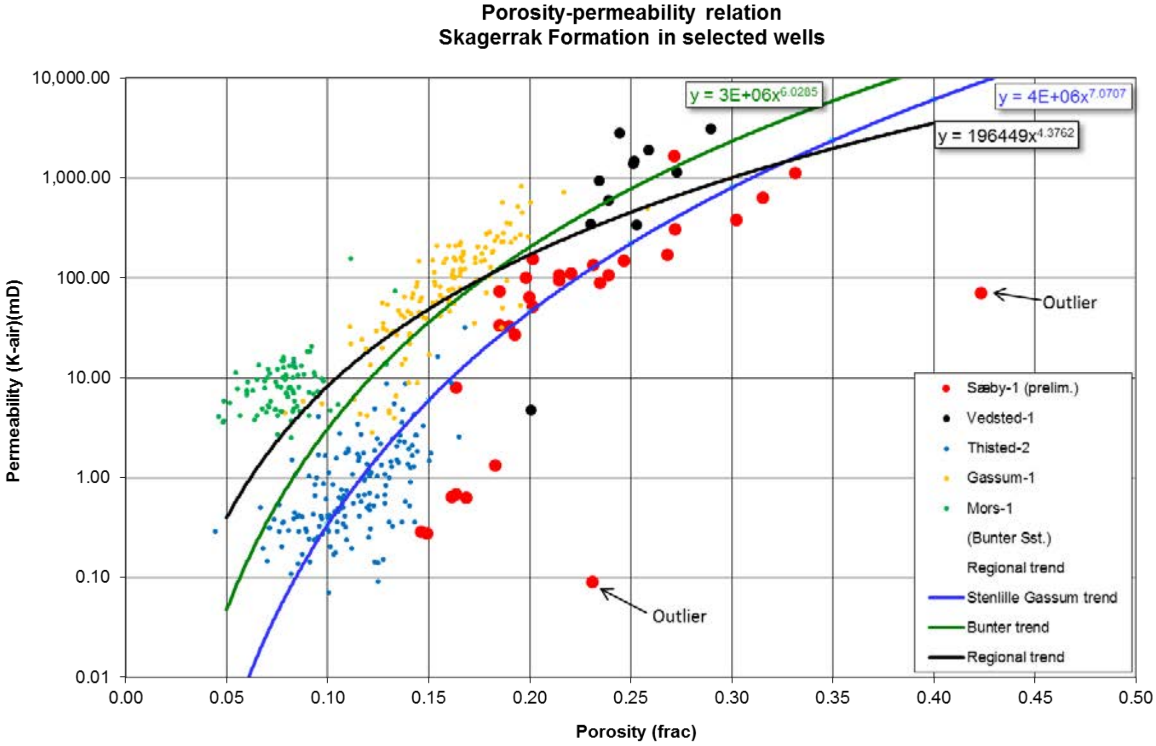



**Figure 19:** Regional porosity-permeability relation for the Skagerrak Formation based on data from Sæby-1 and Vedsted-1 and the wells Thisted-1, Gassum-1, Mors-1 situated relatively close to the Brønderslev area. The regional relation (black trend line) as well as the Bunter Sandstone Formation trend (green line) fits the distribution of Skagerrak Formation data points poorly and is replaced by an adjusted relation (blue trend line).

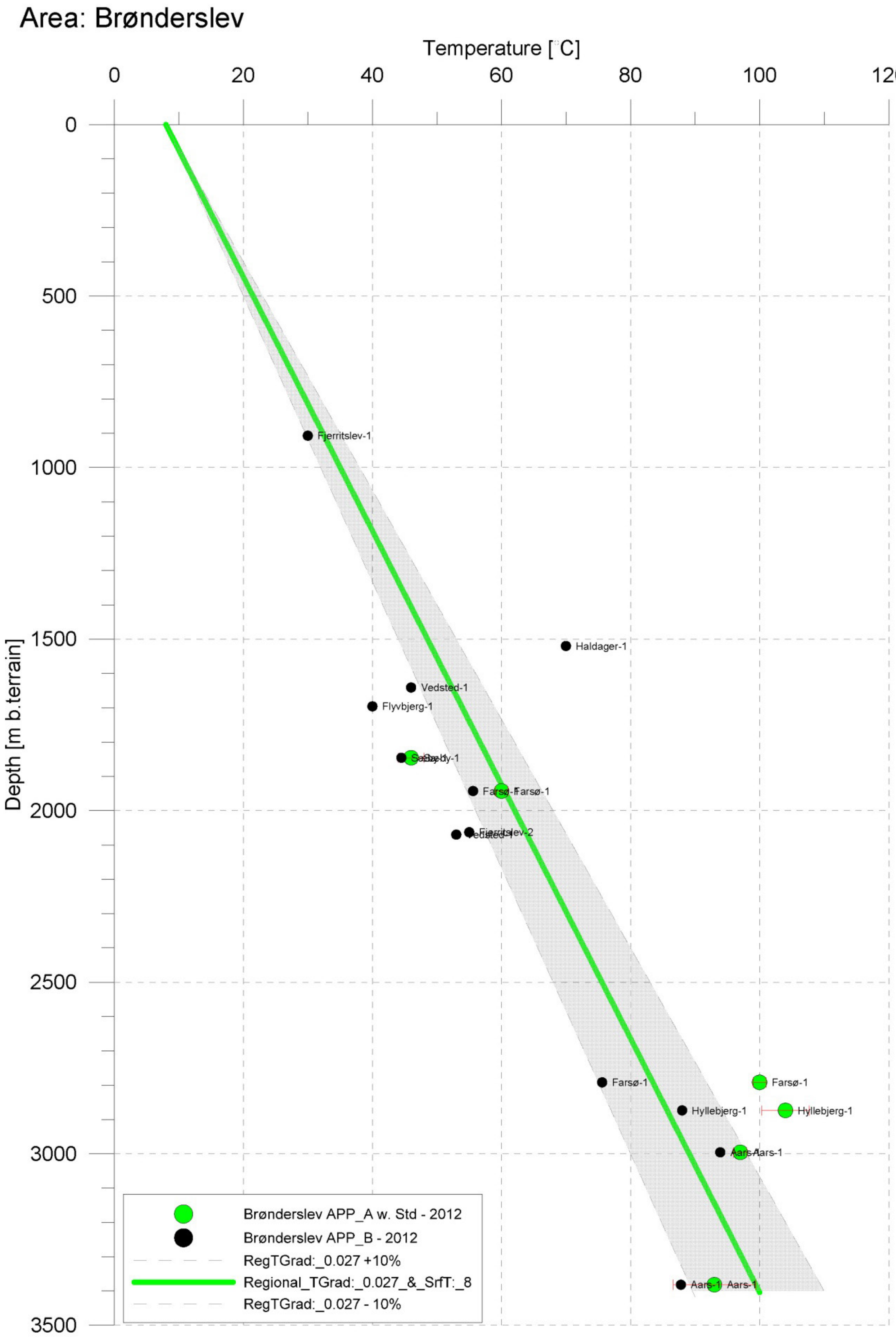



**Figure 20:** Temperature prognosis for the Brønderslev area based on available temperature data from Northern Jutland. The grey area represents a ± 10% uncertainty range. Green dots represent measurements of higher quality including standard deviation; the black dots represent measurements of lower quality and do not include standard deviation.

# 12 Enclosures

**Enclosure 1:** *Base Upper Cretaceous (BCU) depth structure map, contour intervals 200 m.*

**Enclosure 2:** *Mid-Cimmerian Unconformity (MCU) depth structure map, contour intervals 200 m.*

**Enclosure 3:** *Near Top Gassum Formation depth structure map, contour intervals 200 m.*

**Enclosure 4:** *Near Top Skagerrak Formation depth structure map, contour intervals 200 m.*

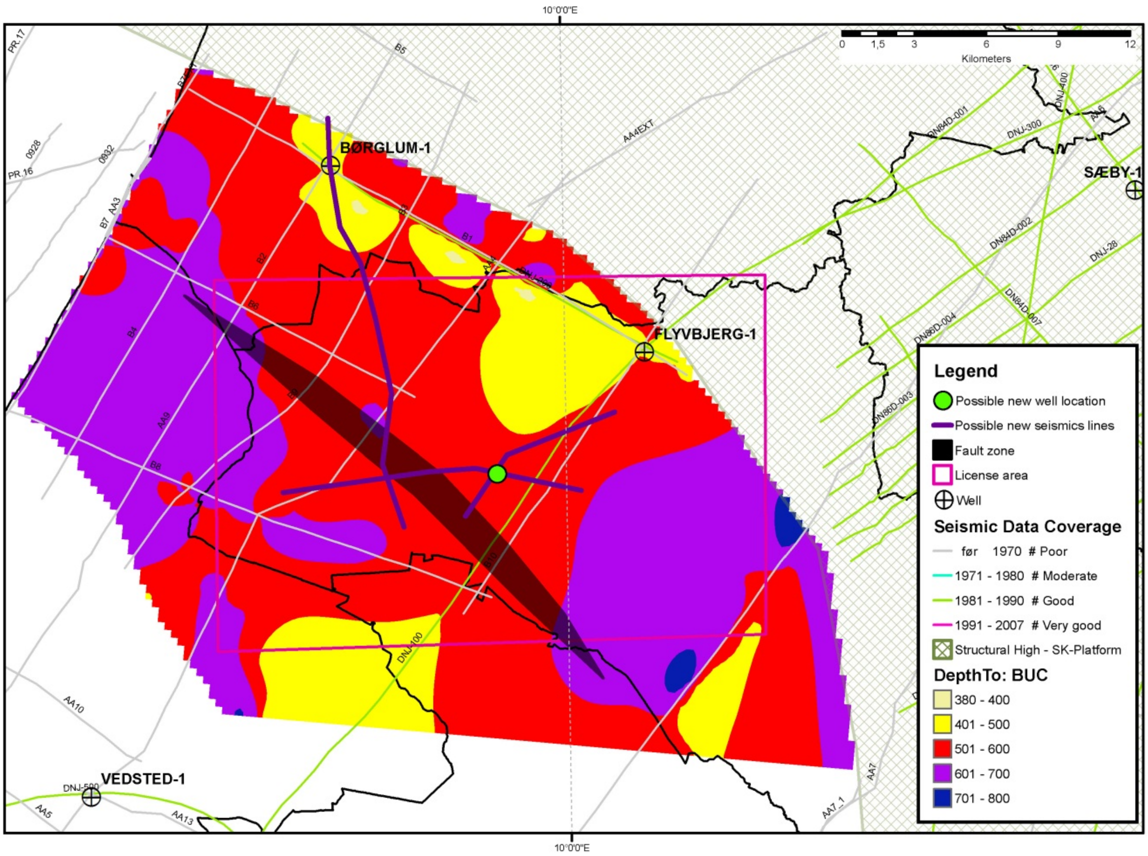
**Enclosure 5:** *Lithology of formations containing possible reservoirs in the Børglum-1 well.*

**Enclosure 6:** *Lithology of formations containing possible reservoirs in the Flyvbjerg -1 well.*

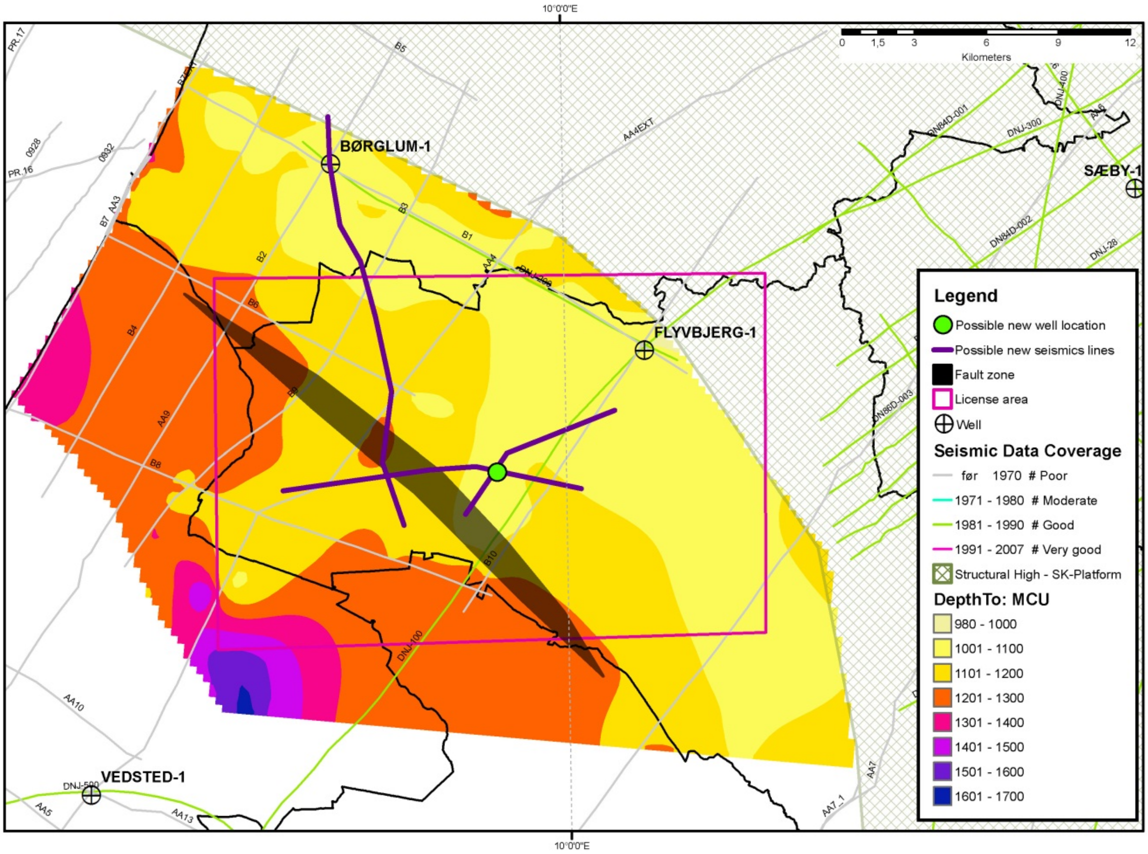
**Enclosure 7:** *Lithology of formations containing possible reservoirs in the Vedsted-1 well.*

**Enclosure 8:** *Lithology of formations containing possible reservoirs in the Haldager-1 well.*

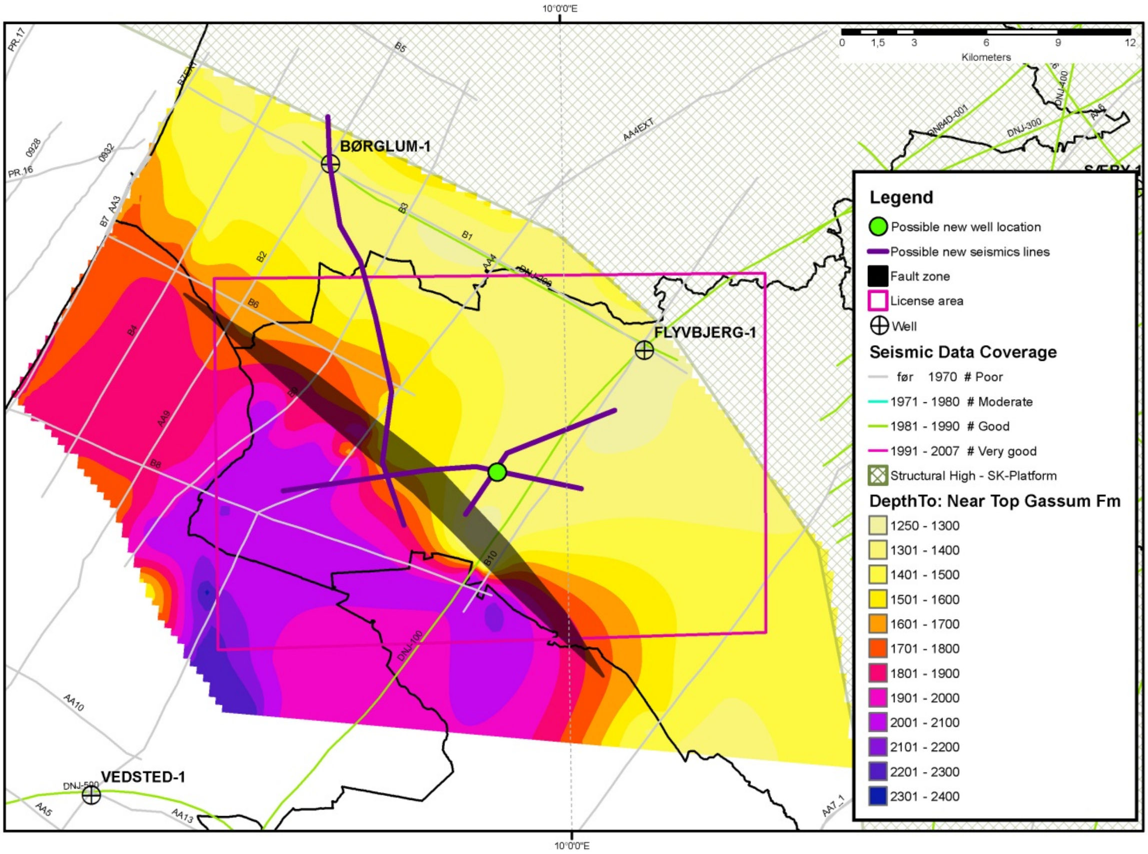
**Enclosure 9:** *Lithology of formations containing possible reservoirs in the Sæby-1 well.*



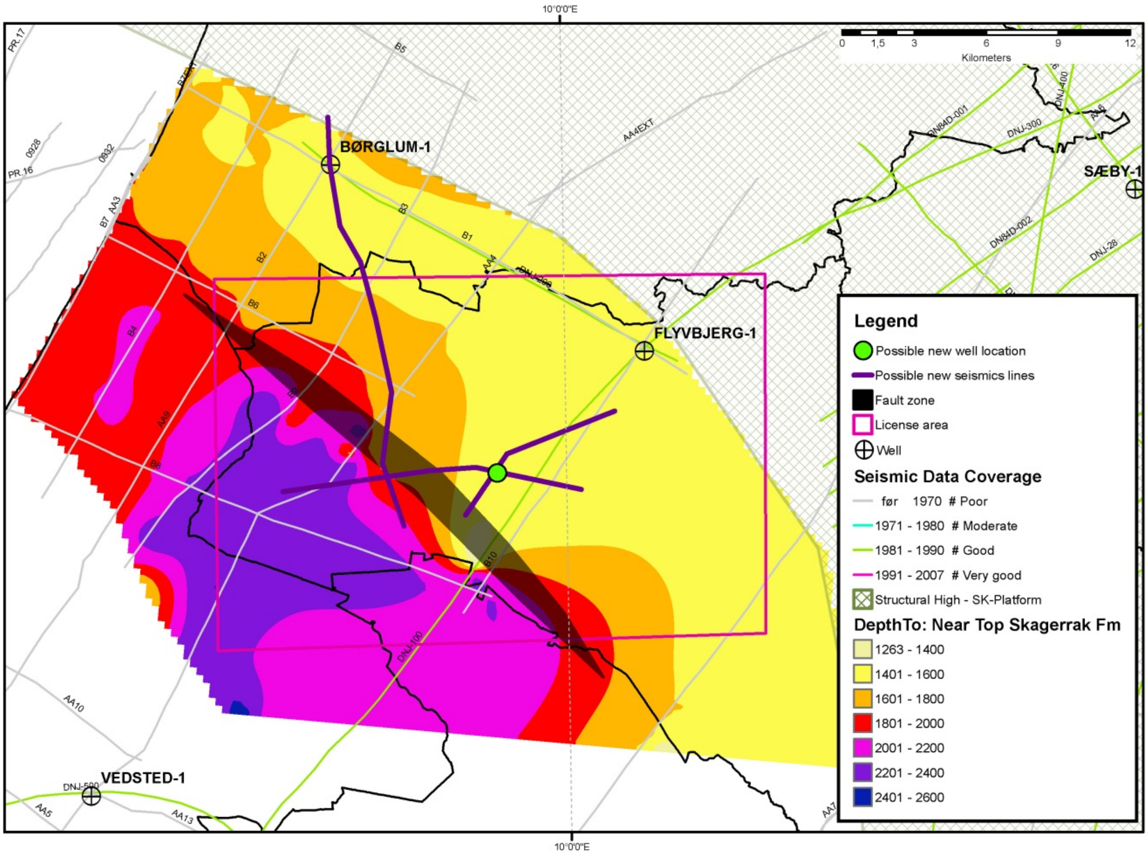

**Enclosure 1:** *Base Upper Cretaceous (BUC) depth structure map, contour intervals 200 m. Well locations, planned well site, coast line and positions of seismic lines are included.*




**Enclosure 2:** *Mid-Cimmerian Unconformity (MCU)/Base Middle Jurassic depth structure map, contour intervals 200 m. Well locations, planned well site, coast line and positions of seismic lines are included.*




**Enclosure 3:** *Near Top Gassum Formation depth structure map, contour intervals 200 m. Well locations, planned well site, coast line and positions of seismic lines are included.*




**Enclosure 4:** *Depth structure map for near Top Skagerrak Formation corresponding to near Base Gassum Formation, contour intervals 200 m. Well locations, planned well site, coast line and positions of seismic lines are included.*

**Enclosure 5:** *Lithology of formations containing possible reservoirs in the Børglum-1 well. Grain size, grain shape, sorting and cementation refer to sand/sandstone sections. The lithology data is extracted from cuttings and core descriptions in the completion report of the Børglum-1well (DAPCO & DGU 1951).*

| Age | Formation | Formation depth interval (m MD) | Formation thickness (m) | Lithology (within formation/unit) | Res. depth interval (m MD) | Grain size | Grain shape | Sorting | Consolidation / cementation |
|---|---|---|---|---|---|---|---|---|---|
| Cretaceous | Frederikshavn | 755–979 | 224 | Sand | 759.0–763.5 | Very fine | | | Calcareous |
| | | | | Sand/sandstone | 763.5–769.6 | Very fine | | | Calcareous |
| | | | | Silty sand | 778.8–797.1 | Very fine | | | |
| | | | | Silt and sandstone | 797.1–821.4 | Very fine to fine | | | Calcareous |
| | | | | Silty sand | 830.6–838.2 | Fine | | | Partly calcareous |
| | | | | Siltstone/Very fine grained sandstone | 838.2–850.4 | Very fine | | | Non-calcareous |
| | | | | Silty sand and clay | 880.9–887.0 | Very fine to medium | | | Calcareous |
| | | | | Sand | 897.6–905.3 | Coarse | Angular | | Non-calcareous |
| | | | | Siltstone/Very fine grained sandstone | 914.4–917.4 | Very fine | | | |
| Jurassic | Haldager Sand | 1047–1076 | 29 | No significant sand/sandstone observations | – | – | – | – | – |
| Triassic | Gassum | 1371–1518 | 147 | Sandstone | 1375.6–1397.5 | Very fine | | | Non-calcareous |
| | | | | Sandstone and shale | 1402.1–1412.7 | Very fine | | | Calcareous |
| | | | | Sandstone | 1420.4–1453.0 | Varies betw. very fine and very coarse | | | Non-calcareous |
| | | | | Sandstone | 1453.0–1462.4 | Medium to coarse | | | Non-calcareous |
| | | | | Sandstone | 1462.4–1467.6 | Very fine to medium | | | Mainly non-calcareous |
| | | | | Sandstone | 1467.6–1479.8 | Fine to medium | | | Mainly non-calcareous |
| | | | | Sandstone | 1479.8–1492.9 | Coarse | | | Non-calcareous |
| | | | | Sandstone | 1492.9–1499.0 | Very fine to fine | | | Non-calcareous |
| | | | | Sandstone | 1501.1–1510 | Fine to medium, medium to coarse | | | Slightly calcareous |

**Enclosure 6:** *Lithology of formations containing possible reservoirs in the Flyvbjerg -1 well. Grain size, grain shape, sorting and cementation refer to sand/sandstone sections. The lithology data is extracted from cuttings and core descriptions in the completion report of the Flyvbjerg-1 well (DAPCO 1958a).*

| Age | Formation | Formation depth interval (m MD) | Formation thickness (m) | Lithology (within formation/unit) | Res. depth interval (m MD) | Grain size | Grain shape | Sorting | Consolidation / cementation |
|---|---|---|---|---|---|---|---|---|---|
| Cretaceous | Frederikshavn | 750–921 | 171 | Loose sand | 770–804 | Fine to medium, occ. coarse | | Good | |
| | | | | Sand | 804–810 | Fine | | | |
| | | | | Sand with mudstone | 810–835 | Fine | | Good | |
| | | | | Sand and mudstone | 845–879 | Fine to medium, occ. coarse | | | |
| | | | | Sandstone and mudstone | 879–885 | Very fine | | | |
| | | | | Sand and mudstone | 885–895 | Fine to medium, occ. coarse | | | |
| Jurassic | Haldager Sand | 990–1044 | 54 | Loose sand | 1030–1044 | Fine to medium, occ. coarse | | | |
| Triassic | Gassum | 1308–1504 | 196 | Sand and shale | 1310–1316 | Medium, occ. coarse | | Good | |
| | | | | Sand with thin interbeds of shale | 1316–1622 | Fine to medium, occ. coarse | | | None |
| | | | | Sand | 1342–1347 | Medium to coarse | | | |
| | | | | Sand and shale | 1357–1362 | Medium to coarse | | | |
| | | | | Sand and shale | 1384–1389 | Medium to coarse | | | |
| | | | | Sandstone | 1412–1417 | Medium | | | |
| | Skagerrak | 1504–1698 | >194 | Sandstone with shale | 1573–1578 | Medium | | | |
| | | | | Sandstone | 1628–1643 | Medium, occ. coarse | Rounded | Fairly good | |
| | | | | Sandstone and shale | 1683–1688 | Medium to coarse | | | |

**Enclosure 7:** *Lithology of formations containing possible reservoirs in the Vedsted-1 well. Grain size, grain shape, sorting and cementation refer to sand/sandstone sections. The lithology data is extracted from cuttings and core descriptions in the completion report of the Vedsted-1 well (DAPCO 1958b).*

| **Age** | **Formation** | **Formation depth interval** (m MD) | **Formation thickness** (m) | **Lithology** (within formation/unit) | **Res. depth interval** (m MD) | **Grain size** | **Grain shape** | **Sorting** | **Consolidation / cementation** |
|---|---|---|---|---|---|---|---|---|---|
| Cretaceous | Frederikshavn | 841–1076 | 235 | No significant sand/sandstone observations | – | – | – | – | – |
| Jurassic | Haldager Sand | 1149–1224 | 75 | Sandstone | 1151–1157 | Fine | | | |
| | | | | Loose sand | 1222–1227 | Coarse to very coarse | | | Unconsolidated |
| Triassic | Gassum | 1749–2037 | 288 | Sandstone and shale | 1775–1780 | Medium to coarse | Subangular to angular | | Clay-cemented |
| | | | | Shale with sandstone | 1885–1915 | Fine to medium | | | |
| | | | | Shale with sandstone | 1955–2005 | Fine | | | |
| | | | | Sandstone, siltstone and shale | 2006–2012 | Medium, occ. coarse | | | |
| | | | | Shale and interbedded sandstone | 2012–2035 | Fine to medium, occ. coarse | | | |
| | Skagerrak | 2037–2073 | >36 | Conglomerate, shale and sandstone | 2062–2068 | Coarse to granule (congl.), fine to medium (sst.) | | | |

**Enclosure 8:** *Lithology of formations containing possible reservoirs in the Haldager-1 well. Grain size, grain shape, sorting and cementation refer to sand/sandstone sections. The lithology data is extracted from cuttings and core descriptions in the completion report of the Haldager-1 well (DAPCO & DGU 1950).*

| Age | Formation | Formation depth interval (m MD) | Formation thickness (m) | Lithology (within formation/unit) | Res. depth interval (m MD) | Grain size | Grain shape | Sorting | Consolidation / cementation |
|---|---|---|---|---|---|---|---|---|---|
| Cretaceous | Frederikshavn | 785–1028 | 243 | No significant sand/sandstone observations | – | – | – | – | – |
| Jurassic | Haldager Sand | 1125–1280 | 155 | Sand | 1153.7–1159.7 | Fine | | | |
| | | | | Shale and sand | 1162.8–1181.1 | Fine to medium | | | |
| | | | | Sandy clay and sand | 1188.7–1194.8 | Fine to medium | | | |
| | | | | Sand | 1197.9–1204.9 | Coarse | | | |
| | | | | Sand with some clay | 1211.6–1216.2 | Coarse | | | |
| | | | | Sand | 1216.2–1222.9 | Coarse | | | |
| | | | | Sand with some clay | 1229.9–1237.5 | Medium to coarse | | | |
| | | | | Sand with some clay | 1240.5–1248.2 | Fine to medium | | | Non-calcareous |
| | | | | Sand with some silty clay | 1252.7–1257.3 | | | | |

**Enclosure 9:** *Lithology of formations containing possible reservoirs in the Sæby-1 well. Grain size, grain shape, sorting and cementation refer to sand/sandstone sections. The lithology data is extracted from cuttings and core descriptions in the completion report of the Sæby-1 well (Dansk Olie og Gas Produktion A/S 1985).*

| Age | Formation | Formation depth interval (m MD) | Formation thickness (m) | Potential reservoir sections (within formation/unit) | Res. depth interval (m MD) | Grain size | Grain shape | Sorting | Consolidation / cementation |
|---|---|---|---|---|---|---|---|---|---|
| Cretaceous | Frederikshavn | 606–711 | 105 | Sand and clay | 600–724 | Medium to coarse and fine to medium | Subrounded to subangular | Moderate to good | |
| Jurassic | Haldager Sand | 801–821 | 20 | Sand and clay | 804–830 | Fine to medium, medium to coarse (locally) | Subangular to subrounded | Moderate to good | |
| Triassic | Gassum | 1077–1111 | 34 | Clay and sand | 1020–1090 | Fine to coarse | Rounded to subangular | Moderate | Calcite |
| | | | | Sand and clay | 1090–1110 | Medium to very coarse | Rounded to subangular | Poor | |
| | Skagerrak | 1111–1649 | 538 | Clay and sand | 1110–1198 | Medium to coarse and fine to medium | Subangular to subrounded | Moderate | |
| | | | | Sand/sandstone and limestone | 1198–1236 | Fine to medium, medium to coarse | Subangular | Moderate to poor | Calcite |
| | | | | Sand/sandstone and limestone | 1236–1344 | Fine to medium | Subangular to subrounded | Moderate to good | Calcite |
| | | | | Sand/sandstone | 1344–1472 | Medium to coarse | Subangular to subrounded | Moderate to good | Calcite and silica |
| | | | | Sand | 1472–1607 | Medium to coarse | Subangular to subrounded | Moderate to good | Calcite and silica |
| | | | | Sandstone and siltstone | 1607–1647 | Medium to very coarse, conglomeratic | Subangular to well rounded | Poor | |