DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2014/59

Assessment of the geothermal potential of the upper sandstone unit in the Bunter Sandstone Formation in the Tønder area

Contribution to an evaluation of the geothermal potential

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GEUS

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G E U S

Preface

On Thursday, 15 of May 2014, a meeting was held at Ross Engineering, Frederiksberg, with participation of Tønder Fjernvarme A.m.b.a., Dansk Fjernvarmes Projektselskab, Erdwerk, Ross Engineering and GEUS. The main subject of the meeting was identification of options which may lead to an increase of the geothermal potential at the Tønder-6 site. The possibility of including the upper sandstone unit (hereafter called upper Bunter reservoir) of the Bunter Sandstone Formation together with the potential negative effect of halite cement and nitrogen gas present in this unit was discussed. It was subsequently agreed upon that GEUS should collect current knowledge of the upper Bunter reservoir and prepare the present report.

CONTENT

1 Dansk resumé

I forbindelse med etableringen af et geotermisk anlæg ved Tønder er målet for indvinding af varmt vand fra Bunter Sandsten Formationens øvre og nedre sandstensreservoirer. Grundet mulig forekomst af nitrogengas samt halitcement i det øvre Bunter-reservoir har de hidtidige undersøgelser koncentreret sig om det nedre Bunter-reservoir. Imidlertid viser simuleringer af dette reservoirs potentiale, at produktionsraterne er lave i forhold til det ønskede. Når produktionen samtidig er begrænset til ét enkelt reservoir, øges risikoen i forsikringsmæssig forstand, hvis reservoirets ydeevne skulle vise sig ikke at leve op til forventningerne. Med henblik på at forbedre det geotermiske potentiale, dvs. øge de forventede produktionsrater, samt styrke forsikringsmulighederne udgør det øvre Bunter-reservoir et oplagt tillægspotentiale, såfremt tilstrækkeligt gode reservoiregenskaber kan påvises for dette reservoir.

På et møde afholdt hos Ross Engineering, torsdag, d. 15. maj 2014, blev det aftalt, at GEUS skulle udfærdige en rapport, som sammenfatter den nuværende viden om det øvre Bunter-reservoir. Med udgangspunkt i de eksisterende GEUS-rapporter og -notater, tilgængelig relevant litteratur samt ny viden baseret på et Ph.D.-studium på GEUS kan reservoiregenskaberne for det øvre Bunter-reservoir sammenfattes som følger:

- Tønder-6-borepladsen er placeret et stykke nede af Tønder-strukturens sydlige flanke og det øvre Bunter-reservoir er her begravet ca. 190 m dybere end under toppen af strukturen
- På Tønder-6-borepladsen vurderes mængden af nitrogengas i det øvre Bunter-reservoir til at være ubetydelig
- På Tønder-6-borepladsen vurderes mængden af porøsitets- og permeabilitetsreducerende halitcement til at være ubetydelig; forekomsten af halitcement antages at være forbundet med nitrogenforekomsten
- På baggrund af flere reservoirsimuleringer vurderes det øvre Bunter-reservoir at bidrage med ca. 30 % af Bunter-reservoirernes totale produktivitet; forskellen tilskrives forskelle i reservoiregenskaber
- Aflejringsmiljøet formodes at være en kontrollerende faktor for reservoiregenskaberne i det øvre Bunter-reservoir; flodsystemer med periodisk udtørring dominerede, men lokale saltsøer, ligeledes med periodisk udtørring, forekom af og til. På baggrund af aflejringsmiljøets kompleksitet kan to scenarier visualiseres:
- Scenarie 1: Det øvre Bunter-reservoirs reservoiregenskaber ved Tønder-6 vurderes at være identisk med eller ringere end ved Tønder-5. Med dybdekorrektion medfører det en netsand-tykkelse på mindre end 16.4 m, en gennemsnitsporøsitet på mindre end 19 % og en estimeret reservoirpermeabilitet på mindre end 160 mD
- Scenarie 2: Det øvre Bunter-reservoirs reservoiregenskaber ved Tønder-6 er beregnet som et dybdekorrigeret gennemsnit af Tønder-3, -4 og -5-boringerne. Dette medfører en netsand-tykkelse på

21 m, en gennemsnitsporøsitet på 20.5 % og en estimeret gennemsnitlig, reservoirpermeabilitet på ca. 240 mD

- Af de to nævnte scenarier anser GEUS scenarie 2 for det mest sandsynlige, eftersom aflejringsmiljøet efter GEUS' opfattelse formodes at have været ensartet i hele Tønder-området, og blandt boringerne Tønder-3–5 er det kun Tønder-5, som udviser reducerede reservoiregenskaber
- Det øvre Bunter-reservoirs øgede begravelsesdybde ved Tønder-6 fører til en forventet reservoirtemperatur på ca. 60 °C, dvs. en stigning på ca. 4 °C sammenlignet med Tønder-4 på toppen af strukturen

2 Introduction

The planned geothermal plant at Tønder is situated in the southern part of Denmark. In geological terms the Tønder site is positioned in the northern part of the North German Basin closely south of the Ringkøbing-Fyn High in an area that have been extensively explored for hydrocarbons since the first well was drilled in 1952. Since that time, 15 more deep wells have been drilled for hydrocarbons providing petrophysical well-log data as well as conventional cores, sidewall cores and cuttings samples. In addition to the large number of wells, several seismic surveys, as well as gravimetric and magnetic surveys, cover the area. This vast database of geological and geophysical exploration data, which is kept and documented in GEUS´ archive and core store, is the fundament of the general assessment of the geothermal potential of the area.

2.1 Data coverage and previous work

The Tønder site is covered not only by the five Tønder wells drilled over the years from 1952–1983, but also 2D seismic lines of reasonably good quality as well as a high-quality 3D seismic survey acquired in 1995, are available for the detailed geothermal assessment at Tønder. This pool of integrated well and seismic data has been evaluated intensely for the geothermal project and is documented in a series of technical reports prepared for Tønder Fjernvarme (Nielsen 2011, 2012b, 2013; Laier 2013b; Mathiesen et al. 2013a, 2013b; Savvatis & Stoyke 2014).

The thorough evaluation of the integrated and comprehensive dataset has identified suitable geothermal reservoirs in the Lower Triassic Bunter Sandstone Formation, which forms a gentle structure over a Zechstein salt pillow beneath the Tønder area. The formation attains a thickness of 186–217 m in the five Tønder wells, showing only minor variations in thickness and composition between the wells. The Bunter Sandstone Formation consists of sandstones and mudstones distributed in four major units comprising the 40–50 m thick upper Bunter sandstone reservoir and the approx. 30 m thick lower Bunter sandstone reservoir separated by a thick mudstone-dominated succession. The upper reservoir unit is overlain by mudstones constituting the top part of the formation. Based on the numerous well-logs, the reservoir parameters including lateral continuity and transmissivity of the reservoir sandstones have been evaluated and used for input in a 3D digital reservoir model for simulations (Nielsen 2011, 2012b, 2013). Based on the results of the reservoir model, a vertical appraisal well, the Tønder-6 well, is planned.

2.2 Geological Risks

The geological risks have been thoroughly evaluated based on the extensive database and the documented drilling experiences from the five previously drilled Tønder wells.

The principal geological structures and stratigraphy in the area of interest is well documented by the available dataset. As the planned appraisal well is drilled within the area covered with high-quality 3D seismic data, the geological prognosis regarding stratigraphy and depths is very well constrained with only

+/- 5-10 % uncertainty on depths estimates. Similarly, the estimate of temperature is also quite certain with an uncertainty of less than +/- 10 %. The production forecast has been simulated by running low, medium and high cases for accommodating the uncertainties of the applied reservoir model and the input data. The model is considered as well-constrained and robust.

The challenge for occurrence of shallow gas has been evaluated, and no indication has been identified from seismic data or from the five previous Tønder wells. Thus, the risk is considered very low.

The main challenge is related to the production of salty formation water. The formation water is considered as being saturated with salt (NaCl) and cooling in particular, but also reduction of pressure related to the production is expected to cause some precipitation of salt. This risk may be mitigated by careful design of the production loop.

2.3 Purpose of this report

So far, focus has been on the lower Bunter reservoir as the upper Bunter reservoir was discarded in the initial assessments due to the risk of encountering nitrogen gas and halite cements. However, simulations of the geothermal potential (Nielsen 2013; Savvatis & Stoyke 2014) have yielded low production rates when producing geothermal water from only the lower Bunter reservoir. Further, from an insurance point of view, the current strategy of producing hot water from one single reservoir poses a risk in case the productivity should be lower than predicted; consequently, a reservoir backup is needed. Thus, in order to increase geothermal productivity and to strengthen the insurance case, a production setup comprising two reservoirs has been considered, and the reservoir properties of the upper Bunter reservoir have been prognosed for the Tønder-6 well site.

In order to assess the reservoir properties of the upper Bunter reservoir at the Tønder-6 well site relevant literature has been scrutinized and combined with information from existing GEUS reports and notes as well as new important knowledge from an ongoing Ph.D. study at GEUS.

3 Geological setting

The Bunter Sandstone Formation is a Lower Triassic red-brown fine-grained sandstone, grading to siltstone in the upper and lower parts, found in deep wells in the North German Basin (**Figure 1**) (Bertelsen 1980). In the Danish part of the North German Basin the Bunter Sandstone Formation correlates with the "Mittlerer Buntsandstein" in the German part of the North German Basin (Bertelsen 1980; Weibel & Friis 2004).

The depositional environment of the mudstone intervals is interpreted as sabkha (very shallow marine inland sea), playa lake, or lake (Clemmensen 1985). The sandstone intervals have been interpreted as fluvial, or a mixture of ephemeral streams and aeolian sand sheets (Clemmensen 1985). The climate was arid to semiarid, with a mega-monsoonal circulation, leading to strong seasonal rainfall (Weibel & Friis 2004).

The Late Triassic and Early Jurassic deposition continued with an unvarying rate of accumulation resulting in a steady burial of the Bunter Sandstone until the Middle Jurassic to Early Cretaceous thermal rifting in the Central North Sea that resulted in uplift of the Ringkøbing-Fyn High. Also, movement of the Zechstein salt into pillows and diapirs affected the burial history of the investigated Bunter Sandstone.

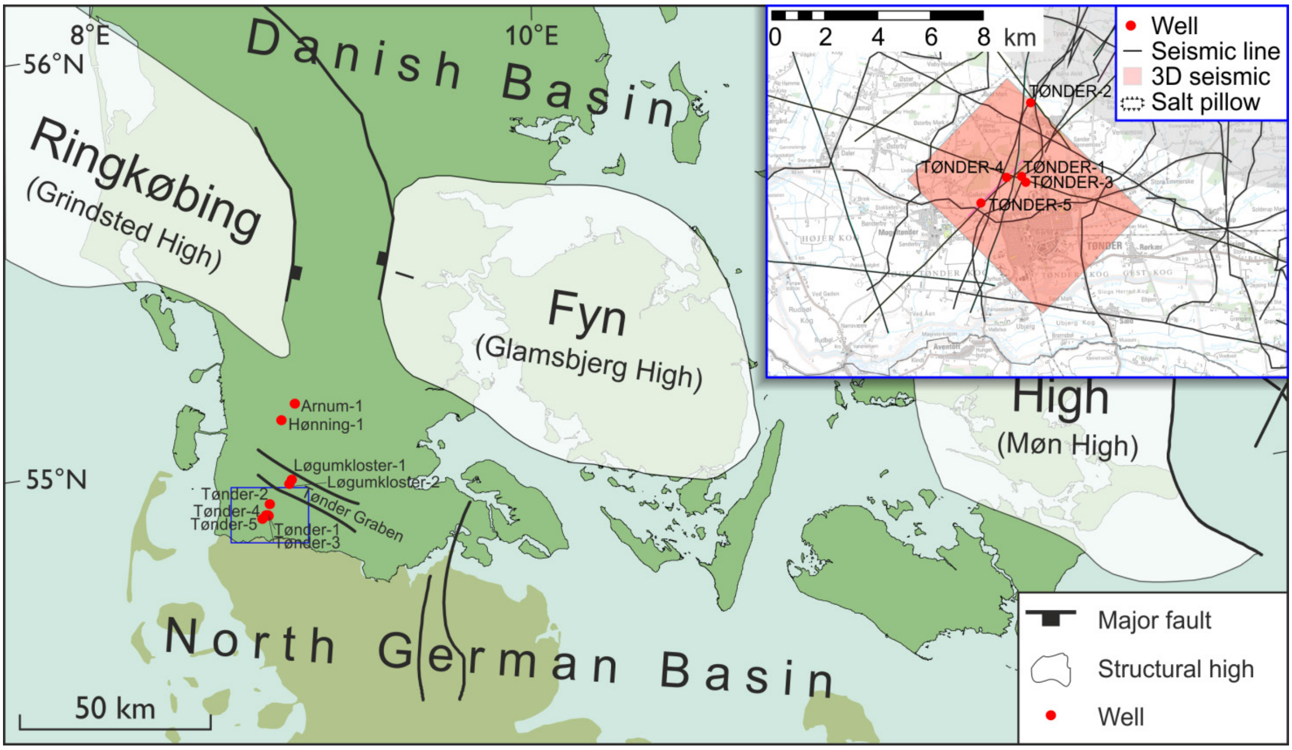

Figure 1: Structural map showing the North German Basin, the Ringkøbing-Fyn High, the Tønder Graben and relevant wells in the Tønder area. Close-up of Tønder area shows well and seismic data coverage.

4 The Bunter Sandstone Formation in the Tønder area

Data from wells Tønder-1–5 along with a 3D seismic survey and more scattered 2D seismic lines in the Tønder area (**Figure 1**) provides good data coverage and a solid foundation for describing the Bunter Sandstone Formation. The formation thickness varies between c. 186 and c. 210 m with lithologies varying from sandstone dominated sections with few thin mudstone beds to silt- and mudstone dominated sections with relatively few sandstone beds. Two major, informal sandstone units, the upper Bunter reservoir (c. 43–50 m thick) and the lower Bunter reservoir (c. 32–38 m thick), are clearly defined in Tønder-1–5 (**Figure 2**).

So far focus has been on the lower Bunter reservoir due to indications of a nitrogen gas accumulation in the upper Bunter reservoir within the crestal part of the Tønder salt structure (Mathiesen et al. 2010a) and to a lesser degree downflank of the structure. Further, the presence of cementing halite in the upper Bunter reservoir has been assumed to affect the reservoir quality (Mathiesen et al. 2010a; Laier & Nielsen 1989; Dansk Olie & Naturgas A/S 1983. However, at the planned location of the Tønder-6 well downflank of the structure (**Figure 3**) the content of nitrogen gas and cementing halite is expected to be lower as described in a later section.

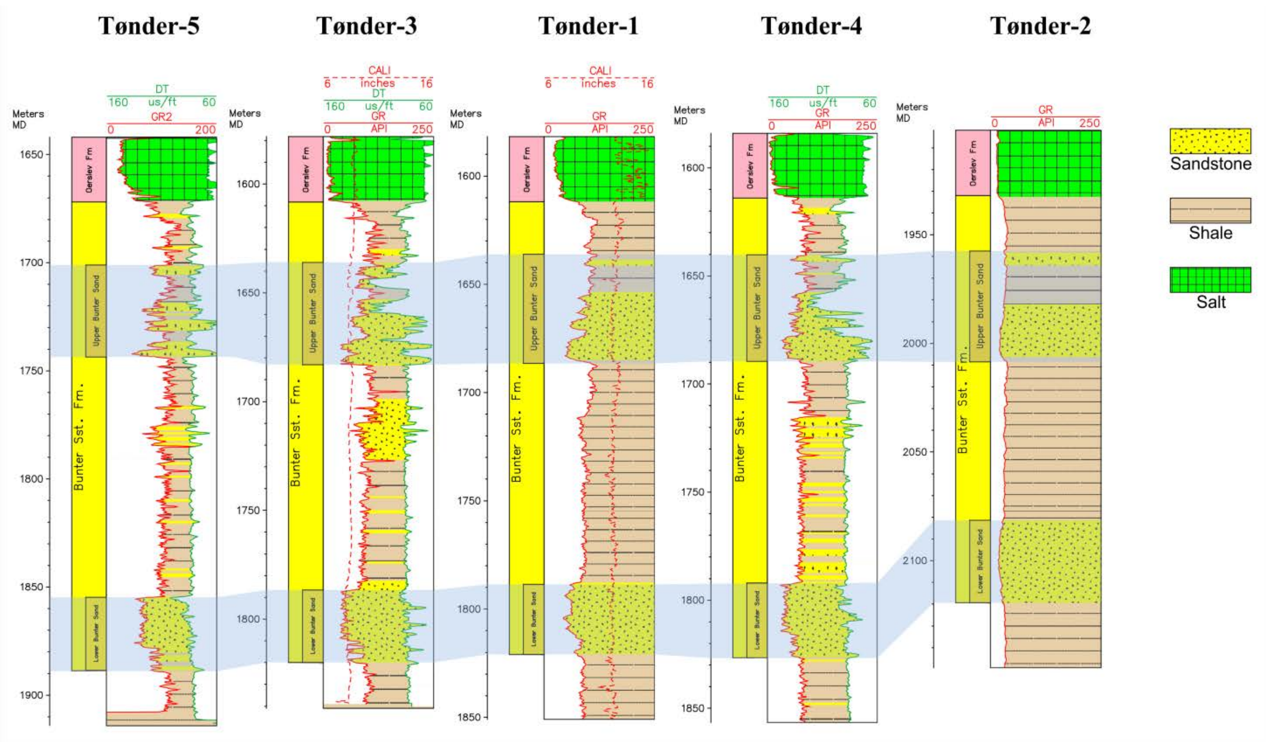

Figure 2: Log panels showing the lithological composition of the Bunter Sandstone Formation. The upper and lower Bunter reservoirs are indicated with light blue.

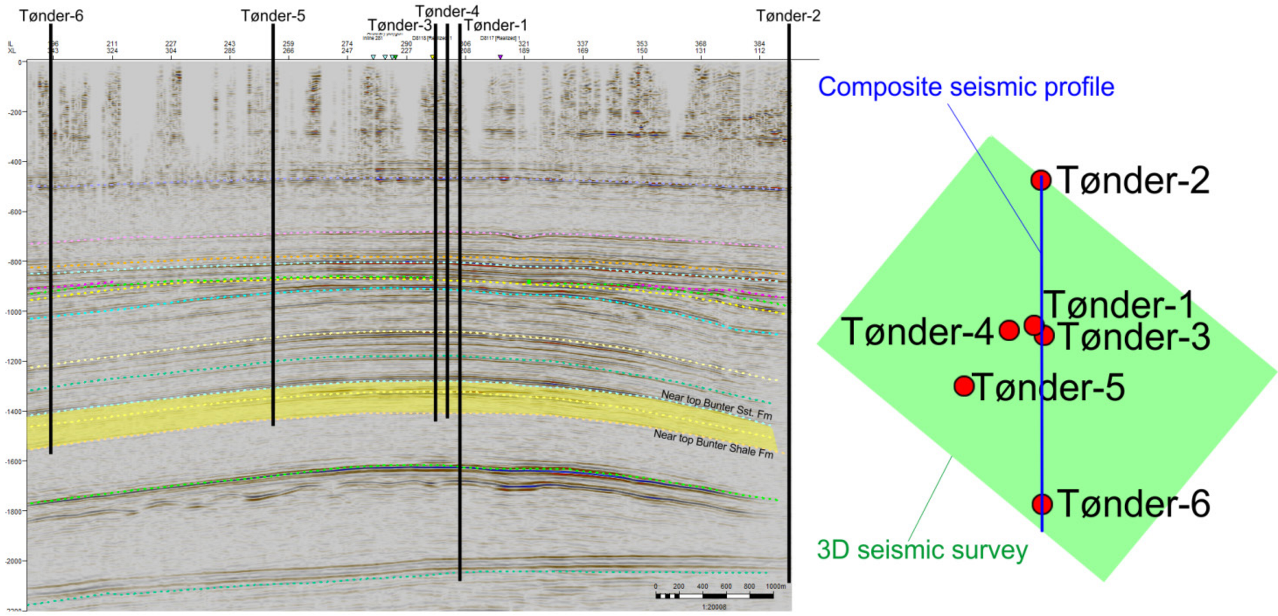

Figure 3: Composite seismic profile based on the 3D seismic survey and running between Tønder-2 and the planned Tønder-6 well; the wells Tønder-1, -4 and -5 are less than 1.5 km offset from the profile. The doming of the Tønder salt structure is clearly visible. The Bunter Sandstone Formation is indicated. Note that depth is measured in msec.

GEUS has in a number of reports and notes evaluated the geothermal properties of the upper and lower Bunter reservoirs (Mathiesen et al. 2010a, 2010b), including potential challenges regarding salt precipitation in installations (Laier 2010, 2013a, 2013b, 2013c), halite cementation in the formation (Mathiesen et al. 2010a; Laier & Nielsen 1989; Dansk Olie & Naturgas A/S 1983), presence of nitrogen (Mathiesen et al. 2010a; Dansk Olie & Naturgas A/S 1983; Nielsen 2012a), and formation pressure (Springer & Kristensen 2012). Further, lifespan and production capacity of a geothermal plant have been simulated (Nielsen 2011, 2012b, 2013).

5 The upper Bunter reservoir in the Tønder area

5.1 Depositional system

In order to assess the reservoir parameters of the c. 43–50 m thick upper Bunter reservoir at Tønder-6 well site it is important to understand the depositional systems responsible for forming the reservoir sandstones in the Tønder area and identify possible lateral facies changes. Based on core description of the Tønder-3–5 wells the upper Bunter reservoir has been subdivided into a c. 23–32 m thick lower unit and a somewhat thinner upper unit representing differing depositional systems (**Figure 4**) (Clemmensen 1985; Olsen 1987).

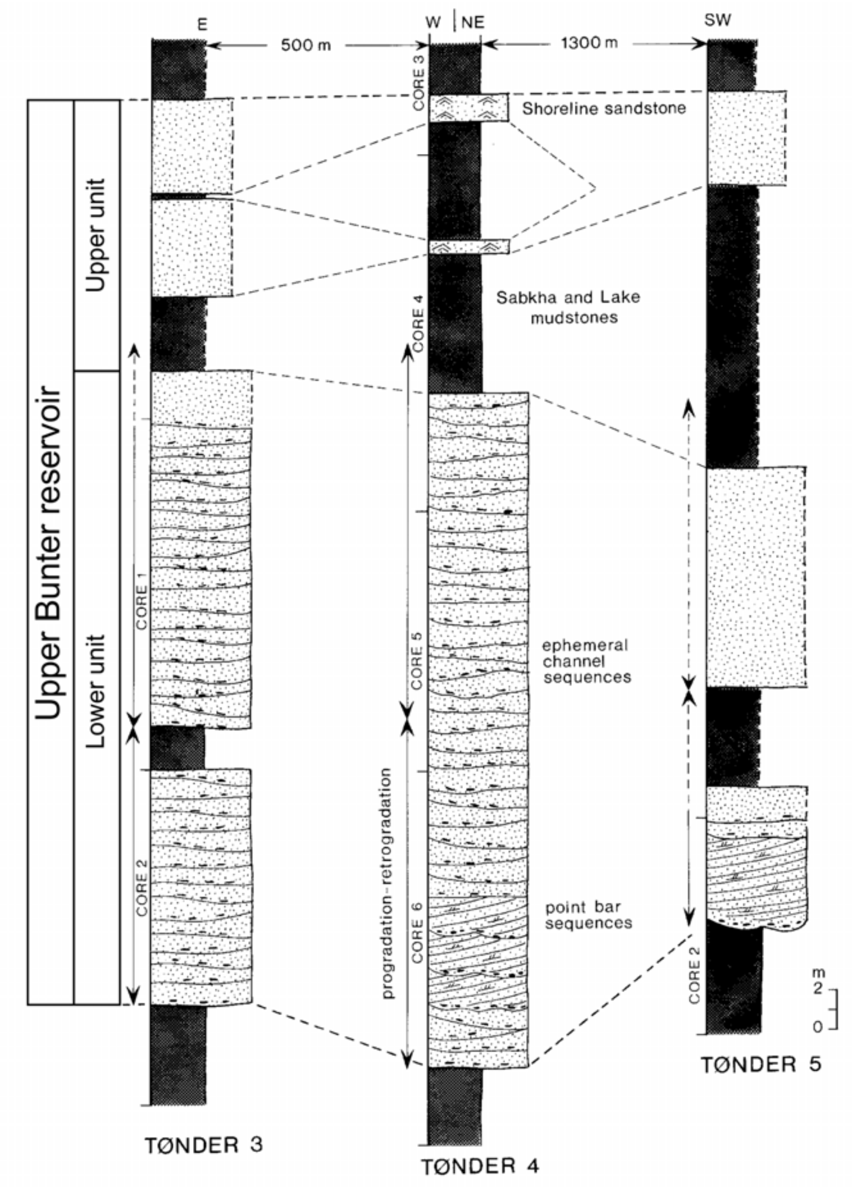

Figure 4: Facies associations of the upper Bunter reservoir in wells Tønder-3–5 showing the subdivision into a lower and an upper unit. Modified from Fig. 8 in Clemmensen (1985).

5.2 The lower unit of the upper Bunter reservoir

The lower unit has been interpreted as a southward flowing ephemeral stream complex grading into sabkha and shoreline systems (Clemmensen 1985; Olsen 1987) (**Figure 4**). In the Early Triassic parts of the Ringkøbing-Fyn High are assumed to have been exposed while other parts were covered with thin sediment layers. The main sediment source region was formerly believed to be the Fennoscandian Shield (Olsen 1987). According to this model the Tønder-3–5 wells are located in the transition zone between these depositional systems with Tønder-5 situated in a more distal position (as indicated in **Figure 5**) thus containing more fine-grained sediments (Clemmensen 1985).

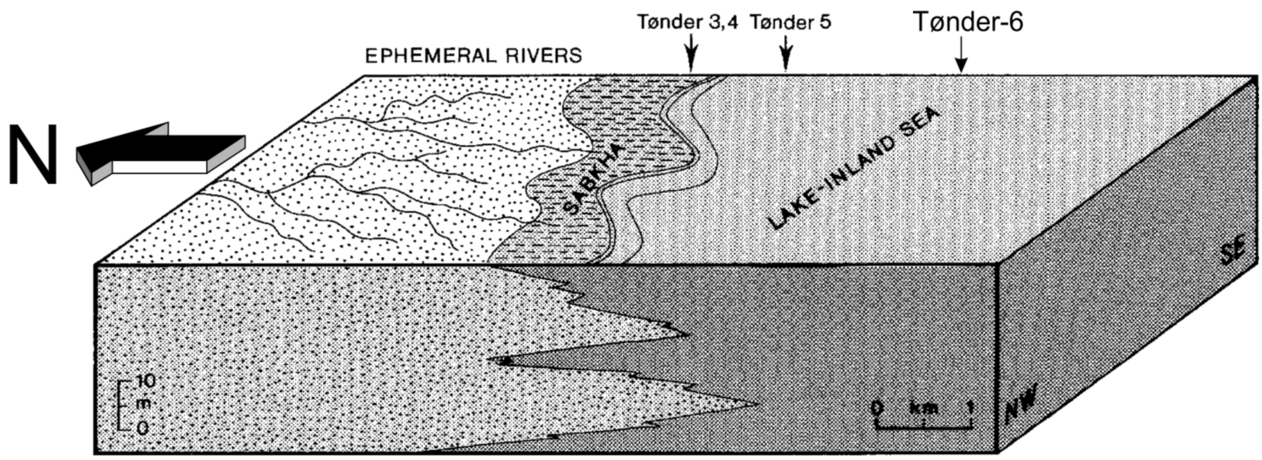

Figure 5: Depositional model for the upper Bunter reservoir. Note position of the Tønder-6 well according to this model. Modified from Fig. 10 in Clemmensen (1985).

New studies at GEUS show that the sediment load carried and deposited by the ephemeral river system was derived from a part of the Ringkøbing-Fyn High termed the Glamsbjerg High (see **Figure 1**) (Mette Olivarius pers. comm.). Accordingly, this part of the Ringkøbing-Fyn High may have been subaerially exposed to a larger extent with higher relief than suggested by Clemmensen (1985) and Olsen (1987) in order to provide the amounts of sediments contained in the upper Bunter reservoir. However, the nature of the deposited sediments suggests a second sediment source, possibly from the south; minor sediment contributions from the Fennoscandian Shield cannot be excluded. With the northern source area less than 100 km away alluvial fans at the foothills of the Glamsbjerg High possibly grading in to braided river systems should be expected north of the ephemeral river-sabkha-lake depositional systems described by Clemmensen (1985) and Olsen (1987). If present, the spatial extent of alluvial fan and braided river deposits should be controlled by topography and sediment production of the Glamsbjerg High as well as tectonic activities in Southern Jutland. So far alluvial fan and braided river sediments have not been observed, probably due to the lack of well data near the Glamsbjerg High (the nearest cored well is c. 30 km away) and/or due to syn- and post tectonic activity (Clemmensen 1985; Fine 1986; Dansk Olie og Naturgas A/S 1984a).

Figure 5 shows the general development of the depositional system of the upper Bunter reservoir: in the northeastern (left part of **Figure 5**) more proximal part of the depositional system fluvial sandy facies dominate; moving in a distal direction (southwest, right part of **Figure 5**) grain size is reduced and sabkha facies becomes increasingly frequent; in the most distal parts lake facies dominate. As mentioned, this depositional model is based on core descriptions of the Tønder-3–5 wells and in **Figure 5** the facies distribution is controlled by well position.

Figure 5 may be seen as a depiction of the depositional system on either a regional or local scale.

As a depiction of the depositional system on a regional scale the model has significant implications for the reservoir quality of the lower unit of the upper Bunter reservoir of the Tønder-6 well as the well is situated more distally in an environment dominated by fine-grained lake sediments and subordinate sand content.

As a depiction of the depositional system on a local scale the model may show how shifting ephemeral rivers develop into relatively short-lived sabkha-lake systems of limited extent. In this case the reservoir quality of the lower unit of the upper Bunter reservoir of the Tønder-6 well is difficult to predict.

The local scale depositional model is seen as the most probable for the following reasons:

a) As ephemeral river complexes usually stretch for decades of kilometres and may cover vast areas it is unlikely that the closely spaced Tønder-3–5 wells represent two different depositional systems. The facies variations between Tønder-3–4 and Tønder-5, as indicated in cores (Clemmensen 1985; Olsen 1987) and petrophysical logs (**Figure 6**) and described in (Mathiesen et al. 2010a) are thus interpreted as local depositional variations occurring in an overall ephemeral fluvial system. Thus, local facies variations may be explained by Tønder-3–4 penetrating channel sediments and Tønder-5 penetrating a mixture of channel, sabkha and lake sediments with the sabkha and lake sediments having been deposited between ephemeral channels.

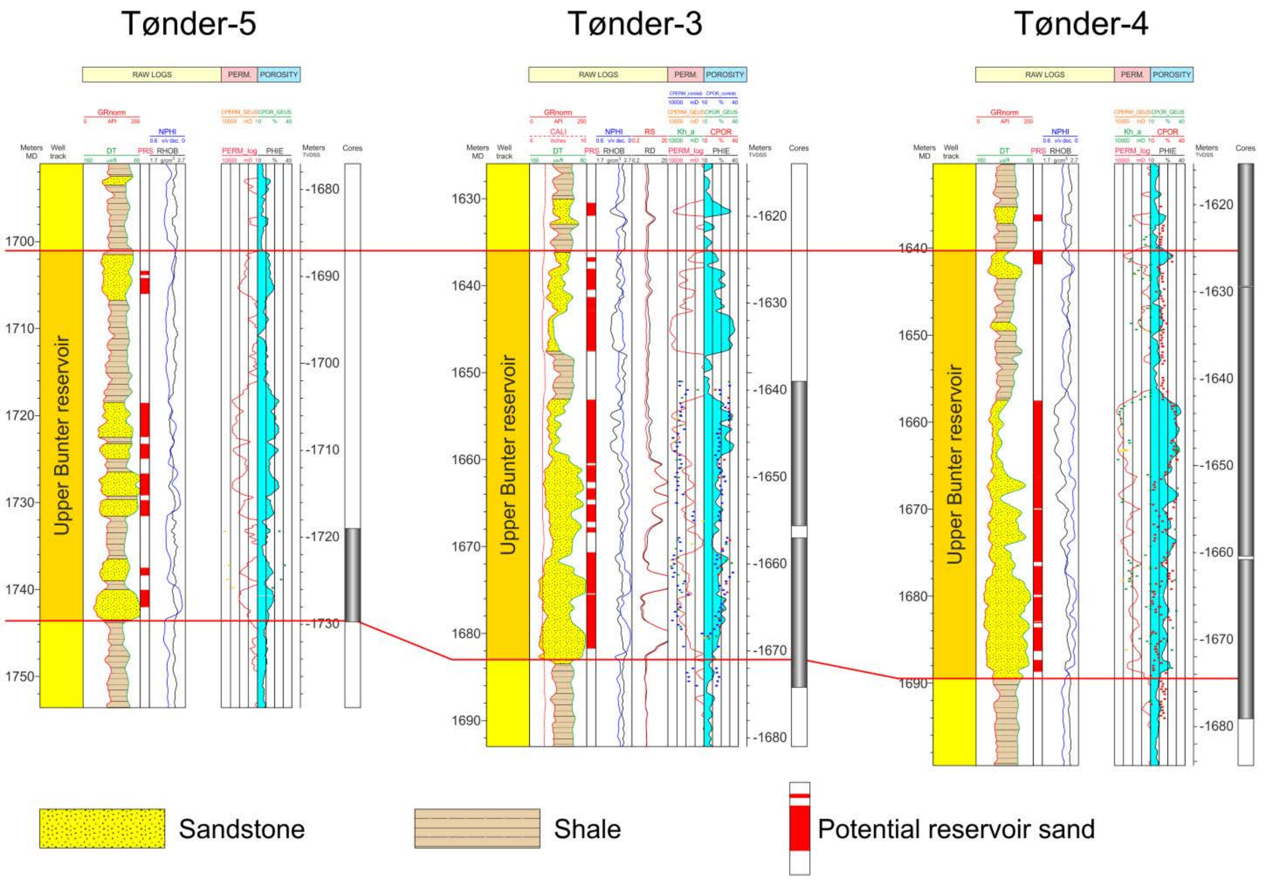

Figure 6: Petrophysical logs showing lithological variations between Tønder-3–4 and Tønder-5. The top of the upper Bunter reservoir is used as datum line.

b) The gamma ray log pattern of the Tønder-5 well strongly resembles the log pattern of the more proximal situated Løgumkloster-1–2/2A wells (**Figure 1**), both with respect to the entire Bunter Sand Formation and the upper Bunter reservoir (**Figure 7**). Thus, a succession of alternating channel, sabkha and lake sediments, as described from the upper Bunter reservoir of the Tønder-5 well, may have been deposited also in the Løgumkloster well site area. Unfortunately, this interpretation cannot be confirmed by core description as no cores exist for the Løgumkloster wells.

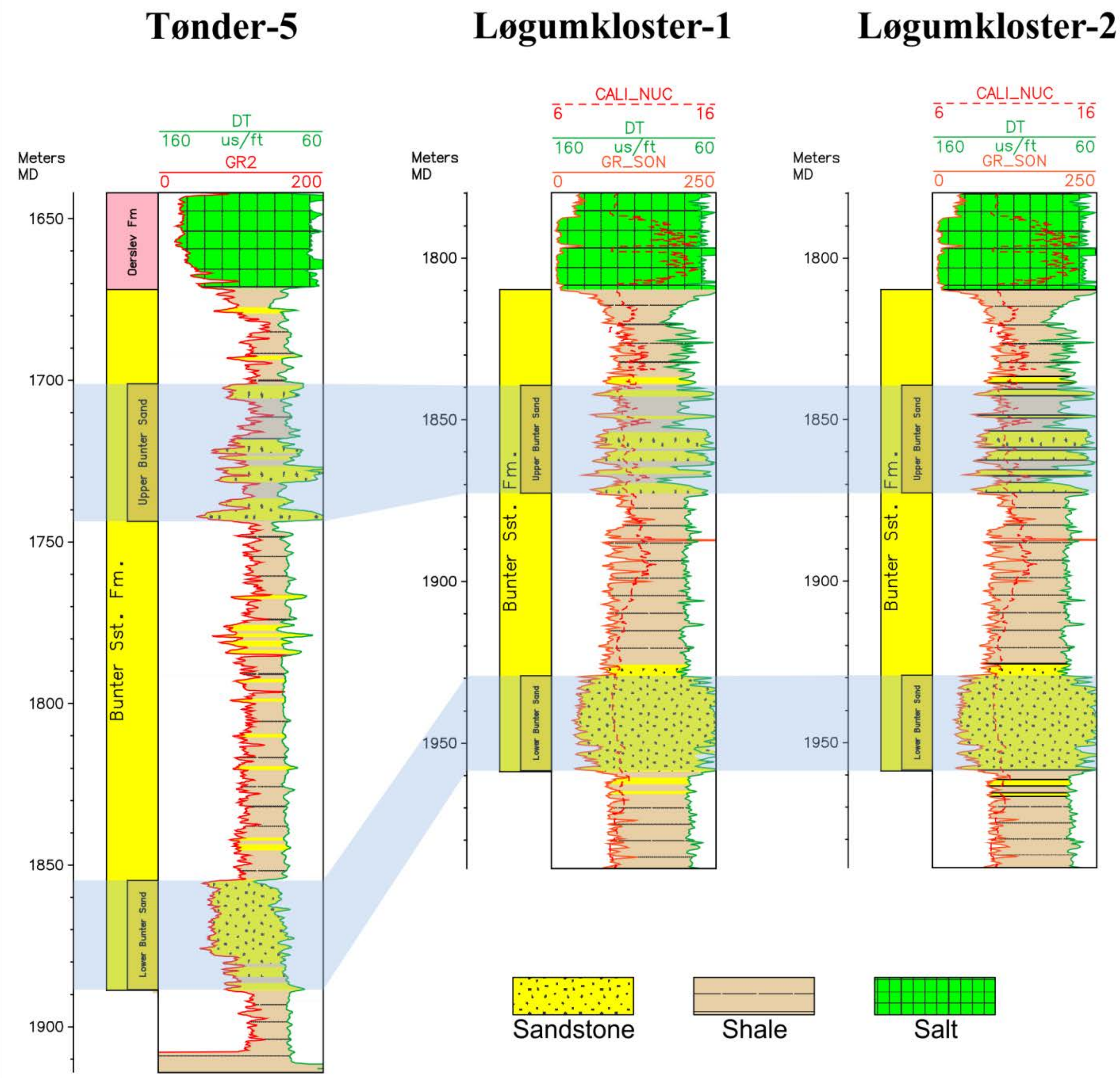

Figure 7: Log panels of the Bunter Sandstone Formation in the Tønder-5 and the more proximal Løgumkloster-1–2 wells. The gamma ray (GR) log motif of the Tønder-5 well corresponds very well with the log motifs of the Løgumkloster-1–2 wells, in particular the similar log motifs of the upper Bunter reservoir hints at similar depositional environments. The top of the upper Bunter reservoir is used as datum line.

Another factor of uncertainty is the effect of the Løgumkloster wells being located in the so-called Tønder Graben, an approximately NW-SE running fracture zone (**Figure 1**). However, as indicated by the similarity of logs (**Figure 7**) and by the seismic interpretation shown in **Figure 8** the salt movements of the Tønder salt structure and the faulting of the Tønder Graben occurred after deposition of the Bunter Sandstone Formation. Thus, assuming similar depositional conditions in the areas of the Tønder-5 and Løgumkloster wells is considered valid.

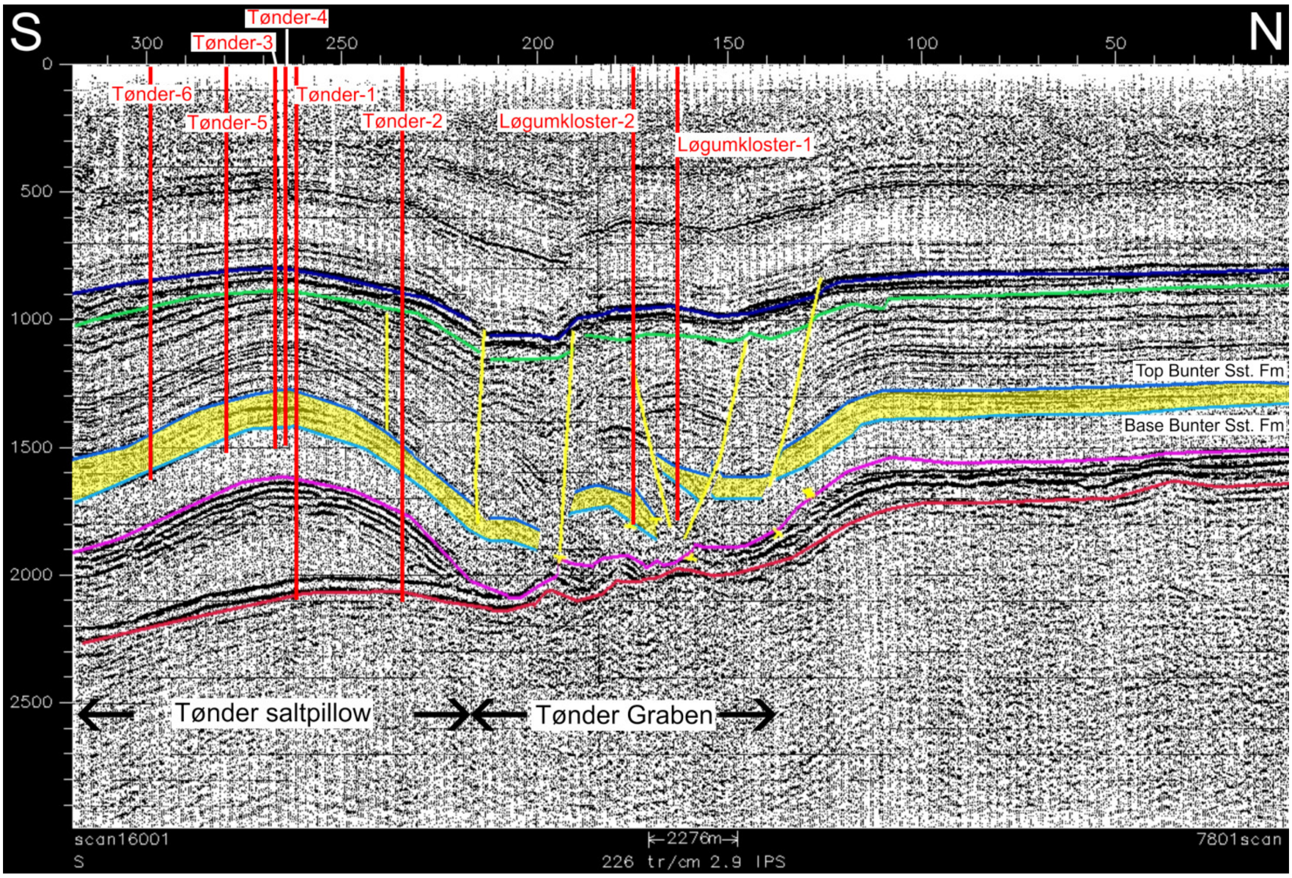

Figure 8: Section of the seismic line 7801 in time [msec] showing the subsurface from the Tønder-6 well in the south and northwards through the Tønder salt pillow and the fault zone (Tønder Graben). Note the distribution of the Bunter Sandstone Formation highlighted in yellow. Modified from Fig. 15 in Mathiesen et al. (2010a).

c) The Arnum-1 and Hønning-1 wells further to the north (see **Figure 1**) are separated only by few km but display completely different gamma ray log patterns and formation thicknesses indicating significant lateral variations of the depositional environment. Also, the log patterns of the Arnum-1 and Hønning-1 wells correlate poorly with the corresponding log patterns of the Tønder and Løgumkloster wells c. 20 km to the south. Preliminary observations of the few meters of core obtained from these wells suggest playa lake and ephemeral/deltaic facies in Arnum-1 and playa lake and lacustrine distributary channel facies in Hønning-1 (Rikke Weibel pers. comm.); i.e. facies associations corresponding to those described in the Tønder-3–5 wells. The Arnum-1 and Hønning-1 wells are together with the Tønder and Løgumkloster wells assumed to be part of the same regional depositional system, but with local facies variations.

5.3 The upper unit of the upper Bunter reservoir

In the Tønder area the uppermost part of the upper Bunter reservoir has, based on core descriptions of the Tønder-3–5 wells, been interpreted as sabkha and lake mudstones with some sandy intervals formed as shoreline deposits (**Figure 4**) (Clemmensen 1985). The significant variation in sand content between the wells suggests facies variations on a local scale (as described for the lower unit) and, thus, the presence of several metres of sand in the upper unit at the Tønder-6 well site cannot be ruled out.

5.4 Reservoir continuity of the upper Bunter reservoir

5.4.1 The lower unit

The productivity of sandstone reservoirs formed from ephemeral river systems depends on the hydraulic connectivity between individual sandstone bodies. Facies analysis based on the Tønder-3–5 wells indicates that the complex of ephemeral streams formed a fan system consisting of channel flow deposits and overbank flow deposits (Olsen 1987). The facies analysis has also demonstrated a higher preservation potential for the sandy channel deposits compared to the more fine-grained overbank deposits (**Figure 4**), which indicates good reservoir connectivity.

Further evidence of good reservoir connectivity is provided by a 7-day long term test conducted in the Tønder-4 well indicating good reservoir properties and good reservoir continuity in the lower unit (Dansk Olie og Naturgas A/S 1984b). However, as mentioned above, lithological variations exist between the Tønder-3, -4 and -5 wells and it is likely that the record of sandy sediments may vary from one area to another within a braided stream system with possible consequences for connectivity.

3D seismic data indicate channelizing at the crestal part of the Tønder structure (sandstone bodies seen as gas filled high porosity zones (bright spots)). However, when moving downflank towards Tønder-5 and -6 indications of sandstone layers or sandstone bodies become gradually weaker, most likely due to diminishing gas amounts to "highlight" high porosity sandstones; alternatively, due to a reduction in high porosity lithologies. The quality of the 3D seismic data may be good enough to reveal spatial distribution and connectivity of individual sandstone bodies, but this demands a thorough analysis of the 3D seismic data (Lars Ole Boldreel pers. comm.).

5.4.2 The upper unit

Based on core descriptions the number and thickness of sandy intervals of the Tønder-3, -4 and -5 wells vary significantly (Clemmensen 1985). In addition, fine-grained sediments including sabkha and lake mudstones are more frequent compared to the lower unit (**Figure 4**). The reservoir connectivity is expectedly low.

6 Reservoir parameters of the upper Bunter reservoir

The log data and the cuttings descriptions from the wells Tønder-1–5 have been used in the lithological interpretation and the petrophysical evaluation (**Figure 9**) of the upper Bunter reservoir. The results of the reservoir evaluation were presented in (Mathiesen et al. 2010a), but in the note the reservoir parameters have been extended to include estimated reservoir permeability (**Table 1**). Prior to calculating reservoir parameters for the upper Bunter reservoir, cut-offs were applied to examine the sensitivity to variations in porosity (PHIE) and shale content (Vshale).

Table 1: Reservoir parameters of the upper Bunter reservoir for net sand: Shale cut-off applied, porosity cut-off applied. Net sand defined as sandstone with < 30% shale, and porosity > 15%.

Well	**Reservoir interval** (m TVDSS)	**Reservoir thickness** (m)	**Gross sand thickness** (m)	**Net sand thickness** (m)	**N/G**	**Avg. porosity** (%)	**Estimated gas perm.** (mD)	**Estimated res. perm.** (mD)
Tønder-1	1623–1673	50	30	N/A	N/A	N/A	N/A	N/A
Tønder-2	1941–1989	48	29	N/A	N/A	N/A	N/A	N/A
Tønder-3	1624–1671	47	40	22.7	0.48	21.2	221	276
Tønder-4	1625–1675	50	37	24.1	0.49	22.7	300	375
Tønder-5	1687–1730	43	24	16.4	0.39	19.2	143	179

A 30% Vshale cut-off was applied to exclude claystones and shaly sandstones with a poor reservoir potential. Furthermore, a porosity cut-off of 15 % was applied in order to qualify and characterize the potential of the reservoir sandstones. This analysis results in an assessment of the accumulated net sand thickness based on this porosity cut-off. It is not possible to assess net sand for the wells Tønder-1 and -2 due to insufficient data.

The net-to-gross ratio, which is abbreviated N/G in **Table 1**, is calculated as "net sand thickness" of the upper Bunter reservoir divided by the "gross sand thickness" of the upper Bunter reservoir.

The estimated gas permeability is not a direct measurement, but it is estimated from a porosity-permeability relationship that has been derived from core analysis data. The core analysis data is extracted from the regional GEUS database and includes several data from areas outside the Tønder area. This can introduce uncertainty on local permeability estimates.

The estimated gas permeability is multiplied with a factor of 1.25 in order to estimate the permeability at reservoir conditions (column to the far right in **Table 1**).

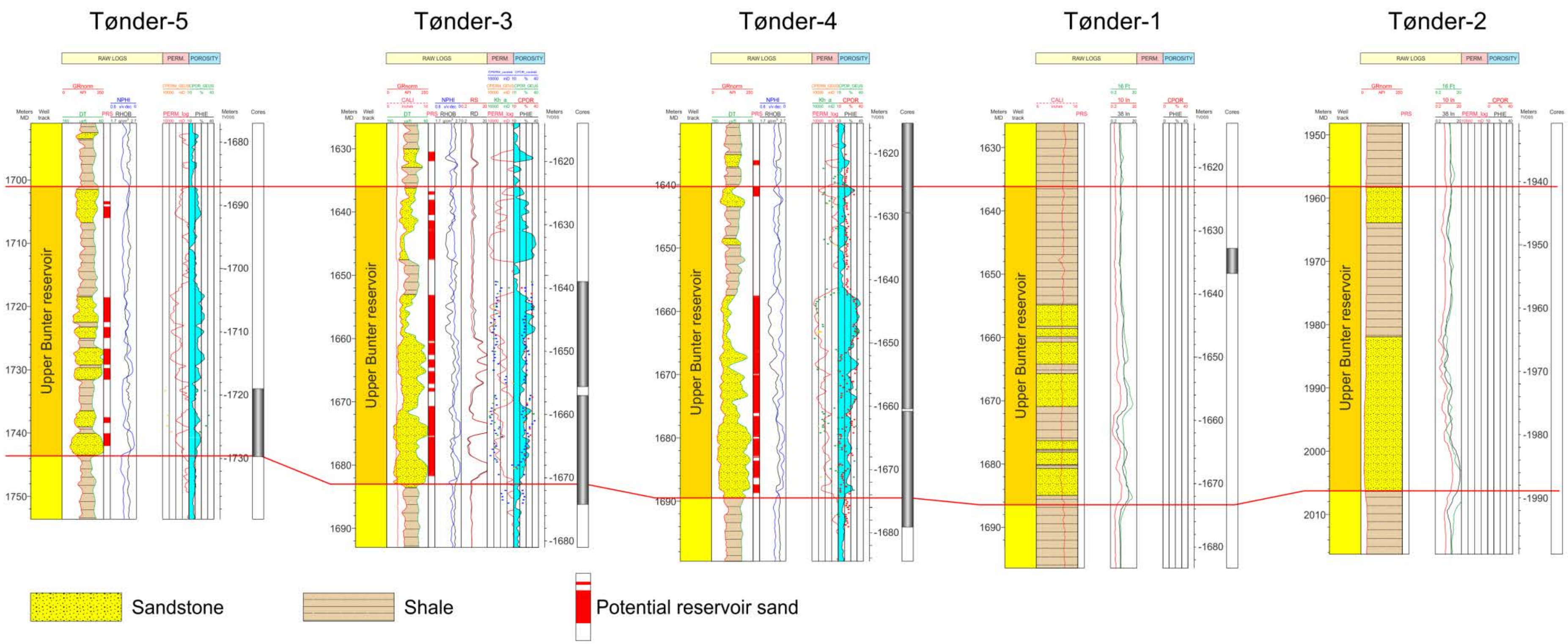

Figure 9: Petrophysical evaluations of the Tønder wells going from Tønder-5 to the south to Tønder-2 to the north. The top of the upper Bunter reservoir is used as datum line.

In **Figure 4** it was indicated that the upper Bunter reservoir can be subdivided into a lower sandy unit with good continuity and an upper more fine-grained unit with questionable continuity. Based on this information the lower unit is expected to exhibit better reservoir properties than the upper unit. A 7-day long term test performed in the Tønder-4 well by DONG (Dansk Olie og Naturgas A/S 1984b) has confirmed this theory with the lower and upper units demonstrating permeabilities of c. 257 mD and 4.5 mD, respectively. Further, the log evaluation (**Figure 9**) and core analysis data also clearly indicate higher productivity in the lower part of the upper Bunter reservoir (**Figure 10**).

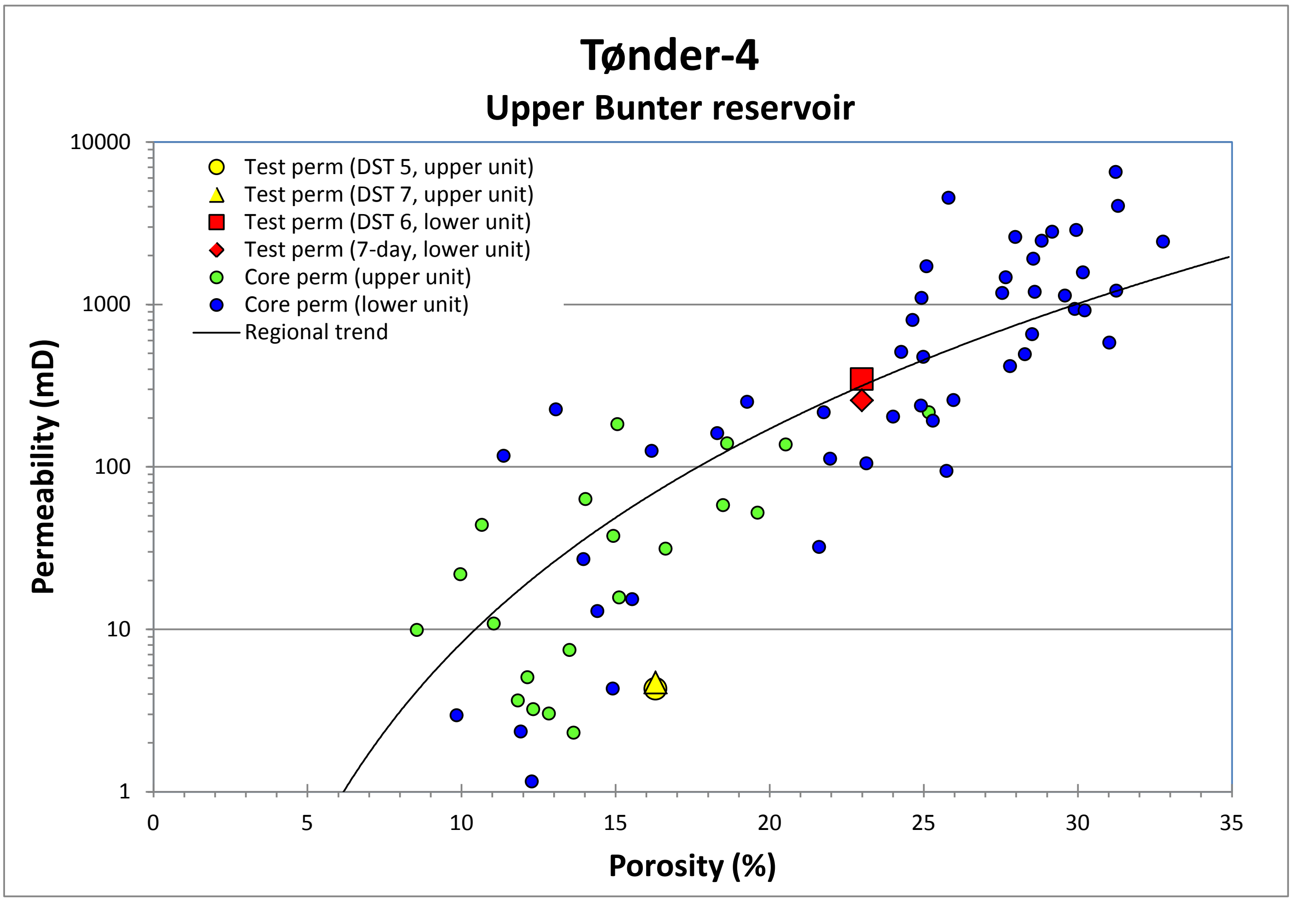

Figure 10: Porosity vs. permeability for the upper Bunter reservoir based on core analysis and well test data (Dansk Olie og Naturgas A/S 1984b) of the Tønder-4 well. Note that core and test permeability data have been sorted according to upper and lower unit. DST refers to drill stem test, 7-day refers to 7-day long term test (production test). The regional trend includes all formations in all onshore wells. Porosities for well test data are based on average PHIE values for the perforated intervals.

The permeabilities obtained in the well tests (Dansk Olie og Naturgas A/S 1984b) are in **Figure 10** plotted against porosities based on average log-derived PHIE values for the perforated intervals. The well tests conducted in the lower unit (DST-6 and 7-day) correspond well with core analysis data (**Figure 10**). On the other hand, the well tests conducted in the upper unit (DST-5 and DST-7) correspond poorly with core analysis data (**Figure 10**) which may be the result of too high porosities caused by dissolution of halite cement during sample cleaning.

7 Temperature assessment

A temperature prognosis for the Tønder area (**Figure 11**) can be derived based on data from the Tønder and Løgumkloster wells (Poulsen et al. 2013). As indicated in **Figure 11** the temperature gradient in the Tønder area is higher (28 °C/km) than the regional temperature gradient (27 °C/km). From the prognosis the temperature at any depth can be estimated using the expression:

$$\text{Temperature} \quad = \quad 0.028\ °\text{C/m} \cdot \text{depth} + 8\ °\text{C}.$$

The uncertainty is ±10%. **Table 2** presents calculated reservoir temperatures at depths corresponding to the middle of the upper Bunter reservoirs in the Tønder-1–5 wells.

Table 2: Reservoir temperature calculated for the centers of the upper Bunter reservoirs in the Tønder-1–5 wells.

Well	**Reservoir interval** (m TVDSS)	**Depth to center of reservoir** (m TVDSS)	**Temperature** (°C)
Tønder-1	1623–1673	1648	54
Tønder-2	1941–1989	1965	63
Tønder-3	1624–1671	1648	54
Tønder-4	1625–1675	1650	54
Tønder-5	1687–1730	1709	56

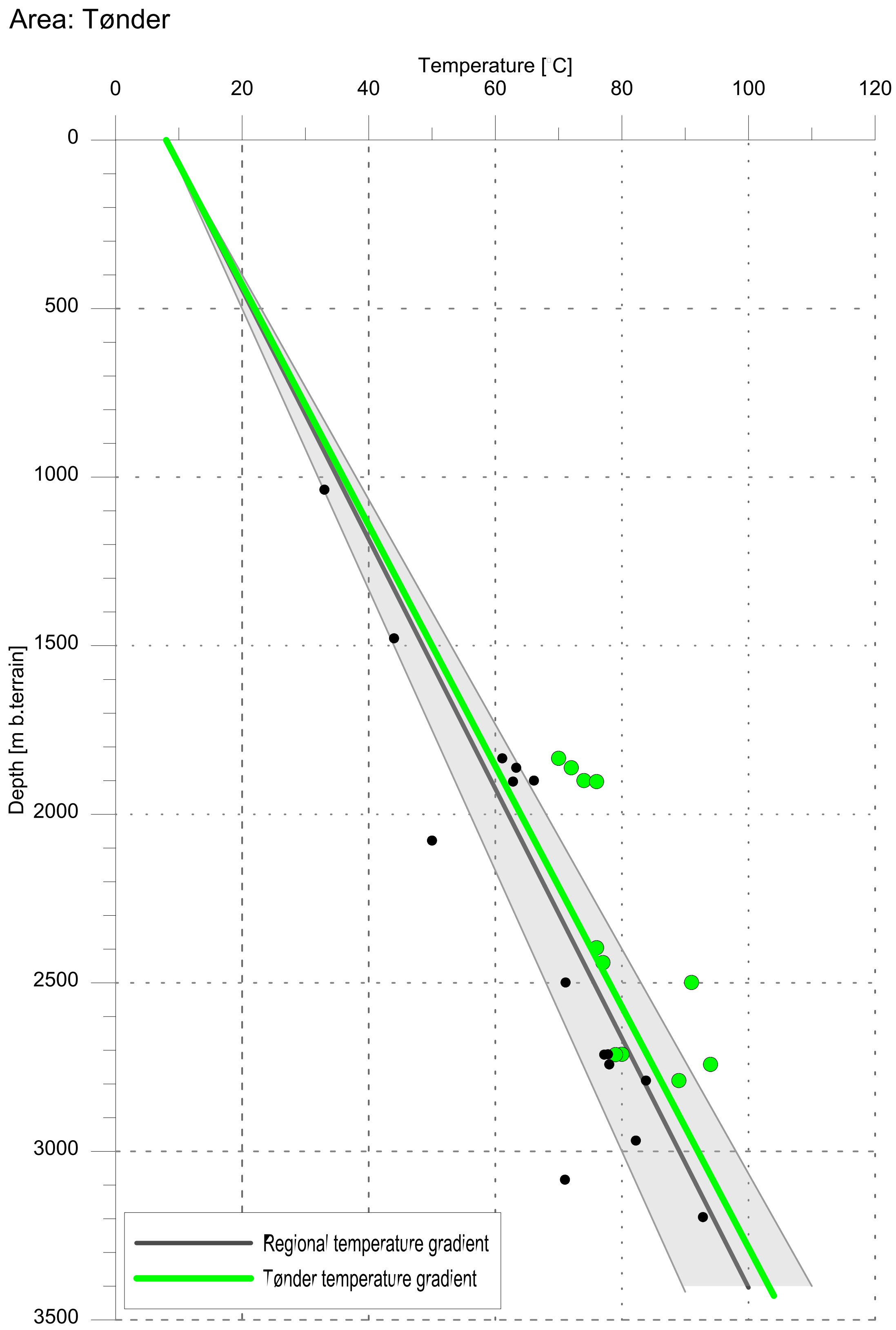

Figure 11: Temperature prognosis based on data from the Tønder and Løgumkloster wells (Poulsen et al. 2013). Notice that the temperature gradient in the Tønder area (green line); is 28°C/km is expected to be a little higher than the regional temperature gradient (gray line with a gray uncertainty band of ±10%). The green-dot temperature data represents updated estimates of equilibrium formation temperature values while the black-dot data represents original bottom hole temperature (BHT) measurements. The average annual surface temperature is assumed to be 8°C.

8 Evidence of halite cement

Evidence of salt precipitation in pores (halite cement) was found in the large discrepancy in rock porosity and permeability obtained from well logs and core analyses of the Tønder-3 well located near top of the Tønder structure. Therefore, special precautions were taken to document the presence of halite in cores of the Bunter Sandstone Formation that were recovered in the two succeeding wells Tønder-4 and -5.

8.1 Halite cement reduces porosity and permeability

The much higher porosity and permeability values obtained by core analyses compared to logs of the Tønder-3 were thought to be due to removal of salt, halite cement, during normal laboratory cleaning of cores prior to analysis. Therefore, core analyses of the new wells were performed on core plugs prior to conventional cleaning (pore fluid removal by methanol reflux) as well as after cleaning of identical plugs. A large increase in both porosity (from approximately 5 % to 25 %) and permeability (from <1 mD to over 1000 mD) was seen moving from not-cleaned to cleaned core plugs (see **Table 3**). The largest difference was observed for the more sandy units of compared to the more clayey units of the core.

Table 3: Porosity and permeability variations between uncleaned and cleaned core plugs. Table 1 in Laier & Nielsen (1989).

TABLE I

Porosity and permeability of uncleaned and cleaned core plugs from the upper Bunter sand of the Tønder-5 well

Depth (m)	Porosity (%)		Permeability (mD)	
	uncleaned	cleaned	uncleaned	cleaned
1738.44	4.4	13.6	0.17	0.18
1738.63	19.4	19.8	15.5	14.5
1739.09	17.3	17.9	3.04	2.8
1739.47	19.1	18.8	3.37	4.6
1740.94	19.3	20.0	4.07	7.2
1741.11	5.5	23.5	0.25	607
1741.64	6.2	26.3	0.64	n.m.p
1741.97	4.4	24.9	0.39	1119
1742.43	4.2	24.0	0.41	n.m.p.
1742.80	3.5	23.6	0.29	1738
1743.24	3.1	17.1	0.25	621
1743.55	4.5	13.3	0.27	286
1743.83	4.4	13.9	0.18	248

n.m.p. = no measurement performed. The plugs were drilled with air and dried at ~40°C. Cleaning was done with methanol in a Soxhlet apparatus. Porosity measurements were performed with He and permeability measurements were made with air.

8.2 Vertical distribution of halite cement

A more complete view of the vertical distribution of halite cement was obtained by KOALA log interpretation on four different types of logs, combining assumed log responses for various rock minerals including halite, water and gas (**Figure 12**).

The percent volume occupied by halite cement given by the KOALA log interpretation agreed very well with results obtained by chemical analyses of a number of core plugs, (**Table 4**), and presence of formation water at different levels was confirmed by centrifuge extraction including chemical analysis (Laier & Nielsen 1989) supporting the credibility of the log interpretation regarding halite.

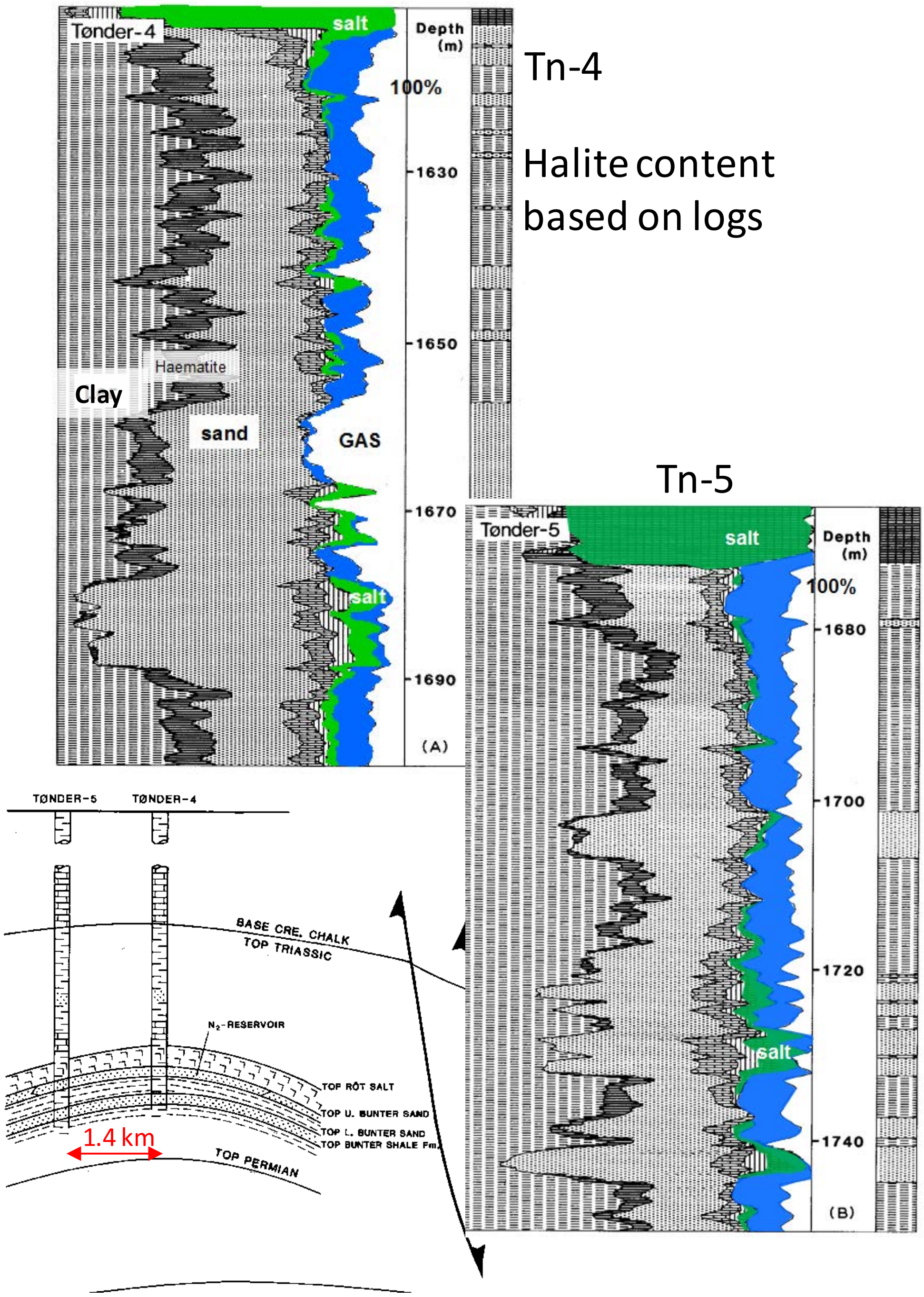

Figure 12: Computerized reconstructed lithological logs of the upper Bunter reservoir showing variations in amount of various phases including halite (salt), water and gas. Fig 3. in Laier & Nielsen (1989).

Table 4: Volume percentages of cementing halite (salt) determined by chemical and KOALA log analysis. Table 2 in Laier & Nielsen (1989).

TABLE II

Volume percentages of cementing halite in the upper Bunter sand, determined by chemical analysis and log analysis

Well	Depth (m)	Halite (vol.%)	
		chemical analysis*	log
Tønder-*4*	1641.30	0	0
	1659.15	0	0
	1667.30	8.1	9.0
	1670.50	8.2	3.5
	1673.50	8.3	9.0
	1678.25	3.4	4.2
	1680.00	7.8	10.0
Tønder-*5*	1741.17	14	6.6
	1742.07	17	10.7

*The halite in the Tønder-*4* plugs was extracted with methanol in a Soxhlet apparatus. The halite in the Tønder-*5* plugs was extracted by percolating distilled water through the plugs.

Halite cement was exclusively found in the upper reservoir of the Bunter Sandstone Formation where nitrogen was also present (**Figure 12**). No indication of halite cement in the lower Bunter reservoir was found.

8.3 Lateral distribution of halite cement and nitrogen gas

From the investigation on the occurrence of halite cement it was concluded the halite was formed after most diagenetic reactions had taken place, and that it most likely formed as a result of ion filtration during formation water displacement by nitrogen gas migrating into the structure. Thus, it is tempting to conclude that halite cement only occurs where nitrogen gas also is also present. However, the lateral extension of the gas cap cannot easily be determined from seismic data alone even though the free gas causing a seismic bright spot was the reason for drilling the Tønder-3 exploration well in the first place. According to seismic data alone the gas-water contact (GWC) is located up-hill of the Tønder-5 well, which is obviously true, see **Figure 8**. The gas to water ratio is clearly much less in Tønder-5, which is located approximately 60 m below top of the structure where Tønder-4 is located (**Figure 3**, **Figure 8** and **Figure 12**).

Given the reduction of gas to water ratio from Tønder-4 to Tønder-5, we find it safe to conclude that the amount of gas in the upper Bunter reservoir at the planned Tønder-6 location 190 m below the top of the structure is insignificant (see also Nielsen 2012a). We also conclude that the amount of halite cement, which could cause a reduction in porosity and permeability, is insignificant, too.

9 Assessment of productivity in upper Bunter reservoir

The productivity of the upper Bunter reservoir was assessed in previous studies models (Nielsen 2011, 2012b; Savvatis & Stoyke 2014).

In Savvatis & Stoyke (2014) a single well completed in both the upper and lower Bunter reservoirs has a productivity (mean value, table 10 in the reference) of 46.5 l/s (168 m3/h) for a drawdown of 60 bar. For the same well configuration, but only with well completion in the lower Bunter reservoir the productivity is 32.7 l/s (118 m3/h). In a rough estimate; the lower Bunter reservoir delivers approximate 70% of the flow compared to the approximate 50-50 split in the model(s) of Nielsen (2011, 2012b) for a well doublet setup, cf. table 1 in Nielsen (2012b).

9.1 Explaining variations in different productivity simulations

The different studies returns some variation in the simulated reservoir productivity, but the differences can mainly be explained in the way the individual simulation models are populated with porosity values and to some extend the setup of the well completion. Further the simulated draw down was 60 bar in Savvatis & Stoyke (2014) for a single well and 70 bar in Nielsen (2012b) for a doublet. A doublet returns a higher productivity cf. table 5 in Savvatis & Stoyke (2014) due to the pressure support to the production well from the injection well.

In Nielsen (2011, 2012b) a relative high porosity was modelled for the uppermost 6 m of the upper Bunter reservoir compared to the porosity modelling in the forecast model in Savvatis & Stoyke (2014). The high porosity interval results in a high permeability pathway for fluid flow, calculated from the porosity permeability relationship as discussed in Nielsen (2011) with a warning of risk of early breakthrough of cooled water.

The porosity modelling for the two models differs in the averaging of the porosity well logs. In only the Tønder-4 and Tønder-5 wells were used as the Tønder-3 well was discarded because the upper part of the Tønder structure is assessed to be gas bearing (N2 gas) and this affects the log interpretation of the Tønder 3 well. The porosity log for the Tønder 3 well has low numbers for the uppermost part of the upper Bunter in large contrast to the porosity interpretation for Tønder-4, which has a relative high interpreted porosity.

Further, the well(s) are completed differently; the wells in the models of Nielsen (2011, 2012b) were chosen to be completed in the entire Bunter Sandstone Formation, i.e. from top of the upper Bunter reservoir to the base of the lower Bunter reservoir compared to the well(s) only completed in the specific reservoir intervals in Savvatis & Stoyke (2014). It was the assessment at the time that running a slotted liner through the total interval was practical feasible. This affect the simulation results especially for the results in Nielsen (2012b), where the model was populated with permeability data without a cut off value on the porosity to discriminate between non-reservoir and reservoir, this was done following discussions in the project on how the relative thick interval between the two specific reservoir interval could contribute. The porosity for the intermediate was on average just below 15% resulting in a relative low permeability but to some extend justified by the thickness and thereby a contribution to the overall transmissivity.

As discussed previously the different models (Nielsen 2011, 2012b, 2013; Savvatis & Stoyke 2014) returns comparable simulation results when the different model setups and conditions are respected.

But the present discussion points out that an overall re-evaluation on the porosity interpretation in the uppermost approximate 6 m of the upper Bunter reservoir should be considered.

10 Reservoir properties of the upper Bunter reservoir at the Tønder-6 well site

In the sections above, the current knowledge of the upper Bunter reservoir in the Tønder area has been summed up with respect to depositional environment, reservoir continuity, reservoir properties, nitrogen content and halite cementation. Also, the reservoir productivity has been modelled. In the following this information is combined to produce an assessment of the reservoir properties of the upper Bunter reservoir at the Tønder-6 well site.

10.1 Depositional system

The upper Bunter reservoir is divided into an upper and lower unit; focus will be concentrated on the 23–32 m thick lower unit as only this unit seems the more prosperous. The reservoir characteristics at the Tønder-6 well site are highly dependent on the development of the depositional system from north to south. If the facies changes from ephemeral braided stream to sabkha and lake facies as suggested by Clemmensen (1985) and Olsen (1987) (**Figure 3–Figure 4**) it is likely that the spatial distribution of sandstone bodies may be significantly reduced compared to Tønder-3–5 or, at best, correspond to the Tønder-5 well. On the other hand, if the facies associations encountered in the Tønder-3–5 wells represent the facies variation within a braided stream complex, as suggested by the geothermal group at GEUS, the lithology encountered in the Tønder-6 well may correspond to the lithology in one of the Tønder-3–5 wells (**Figure 3**).

10.2 Burial depth of the upper Bunter reservoir

Based on the 3D seismic survey the seismic depth (TWT) to the near top Bunter Sandstone Formation at the Tønder-6 well site is estimated to be c. 1400 msec. corresponding to c. 1790 m TVDSS using a time-depth relation based on velocity data from the Tønder-5 well (Depth = $0.0003 \cdot TWT^2 + 0.8629 \cdot TWT - 8.9916$). The depth to top Bunter Sandstone Formation at the Tønder-5 well site is c. 1660 m TVDSS, i.e. the Bunter Sandstone Formation at the Tønder-6 well site is buried 130 m deeper than at the Tønder-5 well. Assuming the clay section above the upper Bunter reservoir to be identical (~30 m) for the Tønder-5 and -6 wells (only insignificant variations between the Tønder-1–5 wells) implies that the upper Bunter reservoir at the Tønder-6 well site is buried c. 130 m deeper (1820 m) compared to the Tønder-5 well (1687 m).

10.3 Thickness of the upper Bunter reservoir

As indicated in **Table 1** there is little variation in the reservoir thickness of the upper Bunter reservoir (43–50 m) in the Tønder wells. The thickness of the upper Bunter reservoir at the Tønder-6 well site is considered to be in the same range based on indications from seismic data.

10.4 Reservoir continuity

Reservoir continuity depends on the depositional system. In the braided stream-sabkha-lake model (Clemmensen 1985; Olsen 1987) Tønder-6 will be located distally and the connectivity between sandstone bodies will, expectedly, be reduced. If Tønder-6 is located within the braided fluvial system the connectivity between sandstone bodies will expectedly be good. A thorough analysis of the 3D seismic data may provide information on lateral extent and continuity of the sandstone bodies.

10.5 Nitrogen content and halite cementation

With a location c. 190 m below the top of the Tønder structure the upper Bunter reservoir of the Tønder-6 well is expected to contain insignificant amounts of nitrogen and halite.

10.6 Reservoir parameters

As the depositional system controls the amount of gross and net sand as well as porosity, permeability and reservoir continuity two possible depositional scenarios controlling reservoir parameters are presented:

10.6.1 Scenario 1:

The stream-sabkha-lake scenario (Clemmensen 1985; Olsen 1987): Moving in a southerly direction from Tønder-3–4 over Tønder-5 to Tønder-6 leads to continuously finer-grained sediments with less reservoir potential. Accordingly, the reservoir parameters presented for Tønder-5 (**Table 5**) is assumed to represent the high case for Tønder-6; most likely reservoir parameters will be poorer. However, as the upper Bunter reservoir at the Tønder-6 well site is buried c. 130 m deeper compared to Tønder-5, porosities and permeabilities in **Table 5** are depth corrected (**see appendix 1**). The corrected gas permeability is multiplied with a scaling factor of 1.25 to obtain the corrected estimated reservoir permeability.

Table 5: Estimated high case reservoir parameters of the upper Bunter reservoir for net sand at the planned Tønder-6 well site estimated for scenario 1 (the fluvial-sabkha-lake scenario). High case based on depth corrected Tønder-5 data. Shale cut-off applied, porosity cut-off applied. Net sand defined as sandstone with < 30% shale, and porosity > 15%.

Reservoir parameters at the Tønder-6 well site: scenario 1 (fluvial-sabkha-lake)								
Well: Tønder-6	**Reservoir interval** (m MD)	**Reservoir thickness** (m)	**Gross sand thickness** (m)	**Net sand thickness** (m)	**N/G**	**Avg. porosity** (%)	**Estimated gas perm.** (mD)	**Estimated res. perm.** (mD)
High case	1830–1873	43	24	16.4	0.39	18.8	128	160

10.6.2 Scenario 2:

The ephemeral braided stream scenario: The sediments of Tønder area are controlled by braided streams which over time switch position. Tønder-3 and -4 penetrate sandy intra-channel fills with good reservoir properties; thus, the reservoir parameters presented for Tønder-4 (**Table 6**) represents the high case for Tønder-6 or may be better. Tønder-5 penetrates sandy intra-channel fills with less good reservoir properties; thus, the reservoir parameters presented for Tønder-5 (**Table 6**) represents the low case for Tønder-6. Assuming equal probability of encountering the reservoir parameters of the wells Tønder-3, -4 and -5 at the

Tønder-6 well site each reservoir parameter at the Tønder-6 well site should be calculated as an average of the wells Tønder-3, -4 and -5. However, as the upper Bunter reservoir at Tønder-6 is buried c. 130–190 m deeper compared to the Tønder-3–5 wells, porosities and permeabilities in **Table 6–Table 7** are depth corrected (see **appendix 1**). The corrected gas permeability is multiplied with a scaling factor of 1.25 to obtain the corrected estimated reservoir permeability.

Table 6: Estimated low and high case reservoir parameters of the upper Bunter reservoir for net sand at the planned Tønder-6 well site estimated for scenario 2 (the braided stream scenario). Low case based on depth corrected Tønder-5 data, high case based on depth corrected Tønder-4 data. Shale cut-off applied, porosity cut-off applied. Net sand defined as sandstone with < 30% shale, and porosity > 15%.

Average reservoir parameters at the Tønder-6 well site: scenario 2 (braided stream)								
Well: Tønder-6	**Reservoir interval** (m MD)	**Reservoir thickness** (m)	**Gross sand thickness** (m)	**Net sand thickness** (m)	**N/G**	**Avg. porosity** (%)	**Estimated gas perm.** (mD)	**Estimated res. perm.** (mD)
Low case	1830–1873	43	24	16.4	0.39	18.8	128	160
High case	1830–1880	50	37	24.1	0.49	22.1	261	327

Table 7: Estimated average reservoir parameters of the upper Bunter reservoir for net sand at the planned Tønder-6 well site estimated for scenario 2 (the braided stream scenario). Reservoir parameters based on depth corrected average values of the Tønder-3–5 wells. Shale cut-off applied, porosity cut-off applied. Net sand defined as sandstone with < 30% shale, and porosity > 15%.

Reservoir parameters at the Tønder-6 well site: scenario 2								
Well: Tønder-6	**Reservoir interval** (m MD)	**Reservoir thickness** (m)	**Gross sand thickness** (m)	**Net sand thickness** (m)	**N/G**	**Avg. porosity** (%)	**Estimated gas perm.** (mD)	**Estimated res. perm.** (mD)
Average	1830–1877	47	34	21	0.45	20.5	193	241

10.7 Temperature

The reservoir temperature for the upper Bunter reservoir can be estimated using the relation based on Poulsen et al. (2013). Assuming a depth to the center of the upper Bunter reservoir of 1854 m the temperature at this depth can be estimated to ~60ºC with an uncertainty of ±10% (**Table 8**).

Table 8: Reservoir temperature calculated for the center of the upper Bunter reservoirs in the Tønder-6 well.

Well	**Reservoir interval** (m TVDSS)	**Depth to center of reservoir** (m TVDSS)	**Temperature** (°C)
Tønder-6	1830–1877	1854	60

11 Conclusions

In the Tønder area the upper Bunter reservoir is subdivided into a lower sandy unit with good continuity and an upper fine-grained unit with expectedly less good continuity.

The amount of nitrogen gas in the upper Bunter reservoir at the planned Tønder-6 location, c. 190 m below the top of the structure, is insignificant.

The amount of halite cement, which could cause a reduction in porosity and permeability in the upper Bunter reservoir, is also insignificant at the planned Tønder-6 location as the amount of halite cement is expected to be linked directly to nitrogen content.

Several reservoir simulation models have been set up for the upper and lower Bunter reservoirs. According to these simulations the productivity of the upper Bunter reservoir accounts only for c. 30% of the total productivity of the Bunter reservoirs. The difference in productivity between the upper and lower Bunter reservoirs is primarily ascribed to differences in reservoir properties.

A regional depositional system, dominated by ephemeral river complexes with occasional presence of local sabkha and lake systems, covered large parts of Southern Denmark, and this system is believed to have been a major controlling factor on reservoir quality. Two depositional scenarios controlling the reservoir quality at the Tønder-6 well site are presented:

Scenario 1 assumes the upper Bunter reservoir at the Tønder-6 well site to possess no better reservoir parameters than the Tønder-5 well. Including depth correction this means a net sand thickness less than 16.4 m, an average porosity of less than 18.8% and an estimated reservoir permeability of less than 160 mD.

Scenario 2 assumes the reservoir parameters of the upper Bunter reservoir at the Tønder-6 well site to correspond to a depth corrected average of the reservoir parameters of the Tønder-3–5 wells. This means a net sand thickness of 21 m, an average porosity of 20.5% and an estimated average reservoir permeability of 241 mD.

In GEUS’ opinion scenario 2 is considered the most probable scenario as the depositional system associated with this model is assumed to be similar across the entire Tønder area, and when comparing the Tønder-3–5 wells only Tønder-5 displays somewhat reduced reservoir properties.

The increased burial depth of the upper Bunter reservoir at the Tønder-6 well site results in a reservoir temperature of c. 60 °C, a temperature increase of c. 4 °C compared to Tønder-4 at the top of the Tønder structure.

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13 Appendix 1

Both porosity and permeability are reduced with increasing depth and a method to correct for this effect should be applied. The method presented below is based on methods described in Hjuler et al. (2014).

13.1 Depth correction of porosity

The upper Bunter reservoir at the Tønder-6 well site is buried 130–200 m deeper compared to the Tønder-3–5 wells. The increased burial depth is expected to involve a reduction in porosity and permeability at the Tønder-6 well site which should be accounted for. As porosity and permeability values at the Tønder-6 well site are calculated including the Bunter Sandstone Formation from porosity and permeability data of the shallower Tønder-3–5 wells a depth correction is applied.

Fig. A1 shows a depth-porosity relation derived for the Gassum Fm. 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 provides a regional depth-porosity trend (**Fig. A1**). The expression for the regional trend (y = -0.0033 x depth + 28.474) may be used for estimating porosity when formation depths are known. Despite being based on Gassum Formation data from another depositional basin this relation is assumed to be applicable to all sandstone formations including the Bunter Sandstone Formation.

13.1.1 Example: Converting Tønder-5 porosity to Tønder-6 porosity

The vertical midpoint of the upper Bunter reservoir in Tønder-5 is 1723 m; at the Tønder-6 well site it is 1853 m. The porosity reduction can be estimated using the depth-porosity expression:

Porosity reduction = (–0.0033 x 1723) + 28.474) – (–0.0033 x 1853 + 28.474)
= 0.4%

Thus, the corrected porosity for the planned well site is:

Por_Tønder-6 = 19.2% - 0.4%
= ~18.8%

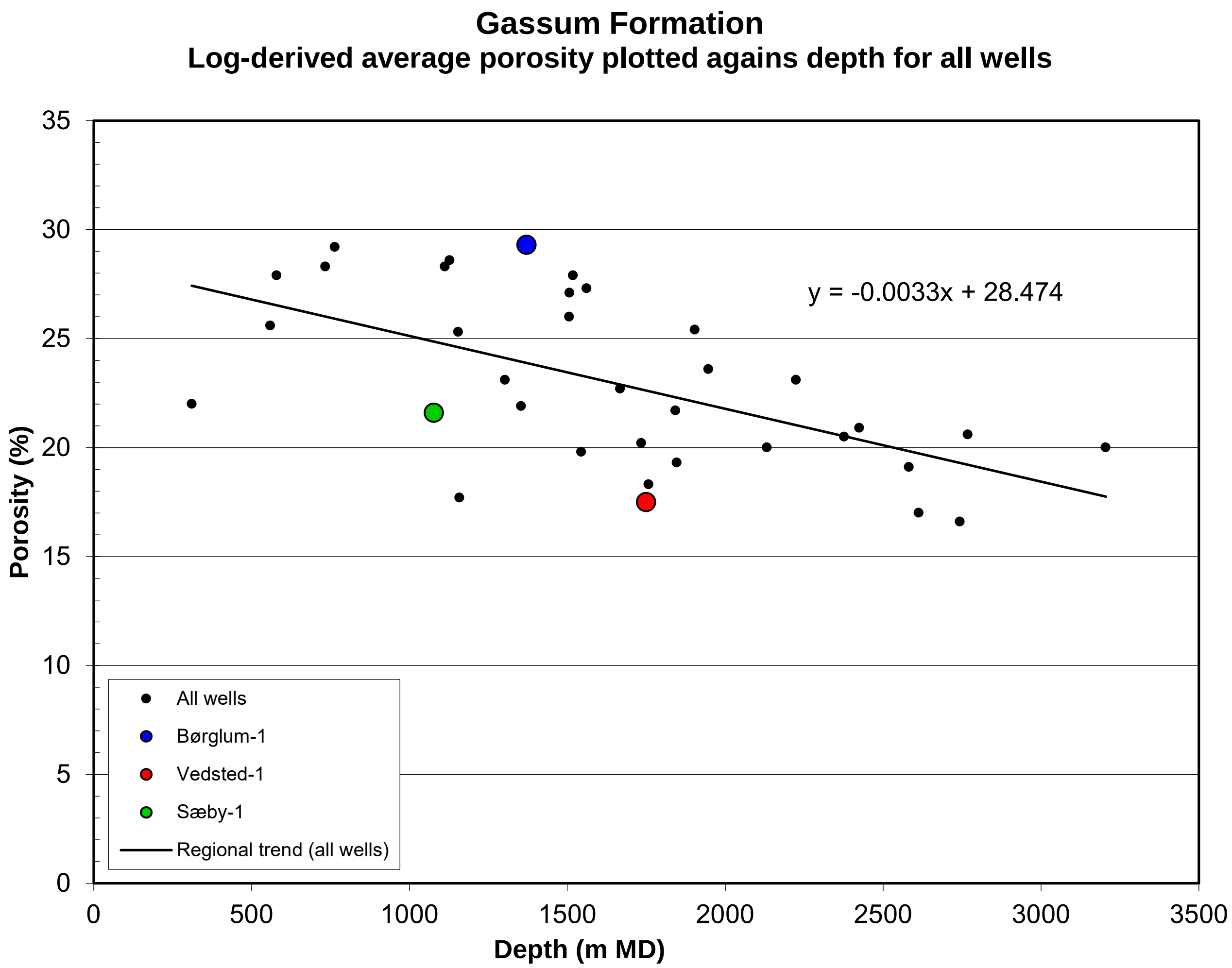

Figure A1: Depth-porosity relation for the Gassum Formation based on well log data from 35 onshore wells. Each data point represents the depth to the top of the Gassum Formation plotted against average effective porosity of net sand for one well. The depth-porosity trend is used to estimate porosity at a given depth.

13.2 Depth correction of permeability

Fig. A2 shows a porosity-permeability relation for all onshore sandstone formations based on core analysis data. The expression for this relation is used to calculate a new depth corrected gas permeability. First a permeability reduction factor is calculated using the expression with "Average porosity" and the "Depth corrected porosity" as input. The reduction factor is multiplied with the "Estimated gas permeability" to obtain the "Depth corrected gas permeability".

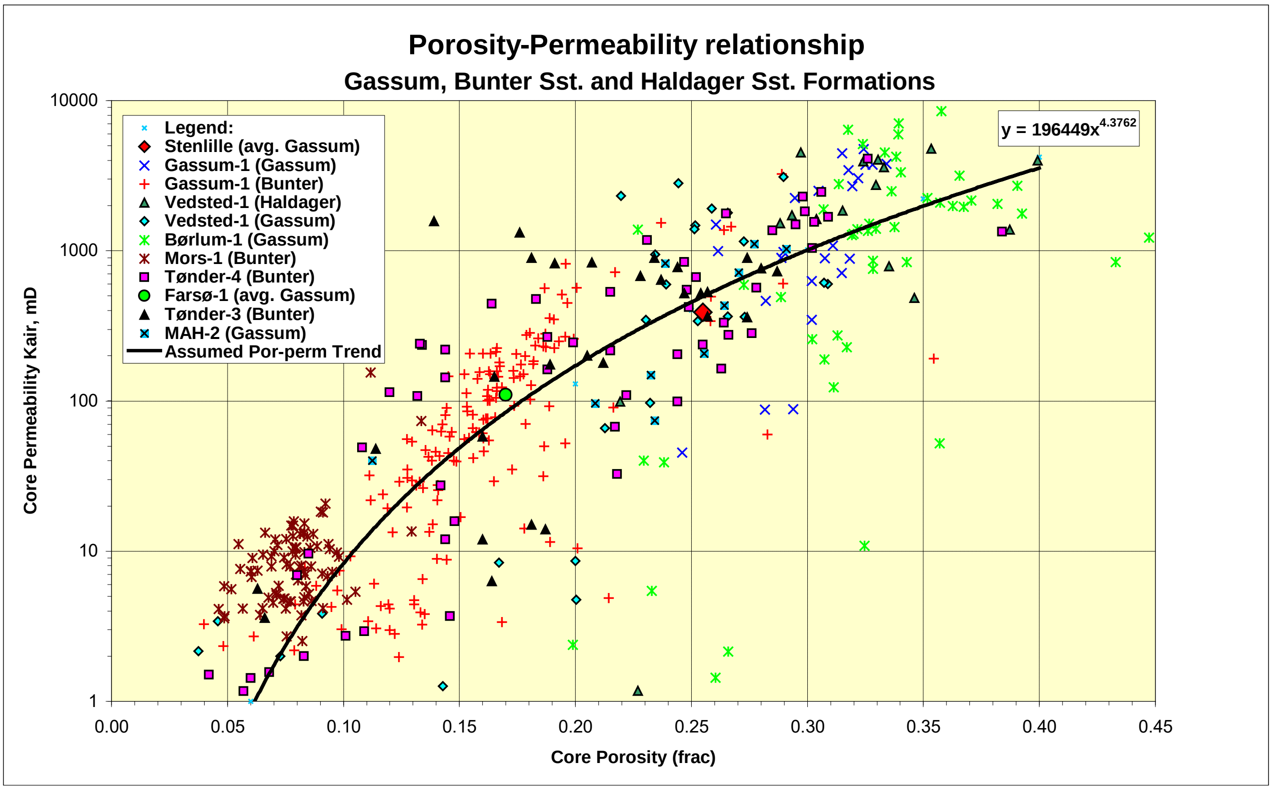

Figure A2: Generalised relation between porosity and permeability for sandstones based on conventional core analysis data from selected Danish onshore wells in the Danish Basin. The underlying database includes core data from the Bunter Sandstone, Gassum and Haldager Sand formations. Note that the core permeability data are gas/air permeabilities.

13.2.1 Example: Converting Tønder-5 permeability to Tønder-6 permeability

The estimated gas permeability at the Tønder-6 well site is, as a starting point, assumed identical to the estimated gas permeability in the Tønder-5 well:

Perm_Tønder-6 = Perm_Tønder-5 = 143 mD

However, the expected lower porosity at the Tønder-6 well site (18.8%) compared to Tønder-5 (19.2%) will cause a gas permeability reduction:

Perm_reduction_factor = (196449 x (18.8/100)^4.3762) / (196449 x (19.2/100)^4.3762)

= 0.89

The estimated gas permeability at a porosity of 18.8% is calculated as:

Perm_Tønder-6 = 143 mD x 0.89

= 128 mD