Detailed assessment of geothermal potential by integration of a wide range of geological data: Preliminary results of a case study from a Lower Triassic low-enthalpy reservoir in the Tønder area in southern Denmark

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ABSTRACT

In the Tønder area in southern Denmark, the Lower Triassic Bunter Sandstone Formation constitutes a potential source of low-enthalpy geothermal energy. The formation is situated in the northern part of the North German Basin and is present at depths of c. 1600–2100 m in the Tønder area. The data coverage is excellent as it includes 7 wells plus 2D and 3D seismic surveys. A multidisciplinary study including interpretation of petrophysical logs, core analysis data, seismic reflection data, diagenesis, pore-water chemistry, burial history, sediment provenance and temperature data is used to estimate the geothermal potential in the Tønder area. The formation contains two primary reservoir units of porous permeable sandstone, of which the lower unit represents the Volpriehausen Member and the upper unit belongs to the Solling Member. The characteristics of the two reservoir units are dissimilar since they were deposited during different climatic conditions in different depositional settings, and the subsequent diagenesis has enhanced the differences. A high-saline brine and the presence of halite cement and nitrogen gas in the upper reservoir unit control reservoir continuity and performance. The lower reservoir unit is widely distributed and displays excellent reservoir properties, whereas the upper reservoir unit has variable reservoir properties due to large variations in reservoir architecture. An integrated understanding of the properties that control the reservoir quality is invaluable in assessing the geothermal potential through a detailed interpretation of the geological parameters. A state-of-the-art geological model has been established by combining data from various disciplines, and the model is used as input to a 3D simulation study of reservoir performance.

1. INTRODUCTION

This study presents the preliminary results of a more comprehensive ongoing investigation.

In recent years low-enthalpy geothermal energy has received increasing attention as a source of renewable, clean energy in onshore Denmark. Several local district heating companies have been granted licenses for exploration of geothermal energy from sandstones in the Danish subsurface with subsequent commission of reservoir quality assessment (e.g. Mathiesen 2010a; Hjuler et al. 2014). Nationwide mapping of geothermal potential has been performed by Mathiesen et al. (2009, 2010b), screening of geothermal potential in major cities has been performed (Mathiesen et al. 2004; Ea Energianalyse et al. 2015) and a geothermal WebGIS portal has been developed (Vosgerau et al. in press). Currently, three geothermal plants are producing hot water for district heating from the Upper Triassic Gassum Formation at Thisted and Sønderborg and the Lower Triassic Bunter Sandstone Formation at Margretheholm.

The temperature gradient in the Danish subsurface is 25–30 °C/km with only minor, local temperature anomalies and generally the geothermal window is defined as the depth interval 800–3000 m with formation temperatures ranging from 25–90 °C (Mathiesen et al. 2010b). The shallow depth limit is selected to ensure sufficient formation temperature, and the deep depth limit is chosen to avoid insufficient porosity and permeability caused by mechanical compaction and diagenetic alterations. As a rule of thumb only sandstone reservoirs with a thickness greater than 25 m are considered potential geothermal prospects. Several formations containing sandstone reservoirs with geothermal potential have been discovered in the Danish subsurface with the Gassum and Bunter Sandstone formations being main targets.

1.1 The Tønder area

Structurally, the Ringkøbing-Fyn High separates the Danish subsurface into the Norwegian-Danish Basin to the north and the North German Basin to the south (Fig. 1a). South of the Ringkøbing-Fyn High the presence of the Gassum Formation is patchy and with limited geothermal potential (Mathiesen et al. 2010a). In contrast, the Bunter Sandstone Formation forms a 100–300 m thick coherent body occurring at burial depths of c. 1300–1900 m and including thick sandstone layers suitable for storage and transport of warm pore fluids for geothermal exploitation (Mathiesen et al. 2010b. In the Tønder area the Bunter Sandstone Formation includes two 30–50 m thick sandstone sequences (e.g. Clemmensen 1985), informally termed the upper and lower Bunter sands. The thickness of these sandstone layers remains relatively constant within the Tønder area (as seen from the wells Tønder-1–5 and Løgumkloster-1–2), but show significant variations in the wells Borg-1, Hønning-1, Arnum-1 and Brøns-1 to the north and Rødekro-1 to the east (Olivarius et al. 2015) (Fig. 1c).

In order to function efficiently as geothermal reservoirs the upper and lower Bunter sands must possess sufficient porosity and permeability. The efficiency of fluid distribution is attributed to factors such as grain size, clay content and clay species, and the susceptibility of reservoir rock minerals to diagenesis, i.e. generation of cements, secondary porosity and pore clogging clay minerals (Weibel et al. submitted). Continuity as well as reservoir properties of the sandstone bodies are controlled by depositional environment and influence of subsequent depositional, erosional and tectonic history.

The Tønder area has been particularly well studied due to the presence of a gently doming salt pillow, the Tønder structure, forming a potential hydrocarbon and/or gas trap beneath the town of Tønder (Fig. 1b). The extensive exploration and evaluation activities performed during the last 60+ years in this area can be divided into three phases related to hydrocarbons (1948–c. 1992), gas storage (1981–c. 1995) and geothermal energy (2010–ongoing).

During the first phase a seismic survey conducted in 1948 incited drilling of the Tønder-1 and Tønder-2 wells in 1951 and 1952 (Fig. 1b) to evaluate the hydrocarbon potential of carbonates in the Zechstein Group. A number of seismic surveys conducted from 1962 to 1992 led to the drilling of the Løgumkloster-1 well in 1980 and the Løgumkloster-2 well in 1993 in the Tønder Graben to the immidiate north of the Tønder Structure (Fig. 1c). The Tønder-3 well was drilled in 1981 (Fig. 1b) in order to evaluate the gas potential of the upper and lower Bunter sands within the Bunter Sandstone Formation. Nitrogen gas was found in the upper Bunter sand of the Tønder structure changing utilization focus to gas storage.

During the second phase, evaluation of the gas storage potential led to acquisition of the seismic lines D8117 and D8118 in 1981 (Figs 1b, c), drilling of the Tønder-4 and -5 wells in 1983 and production and injection testing of the lower and upper Bunter sands (Dansk Olie og Naturgas A/S 1997). Encouraging

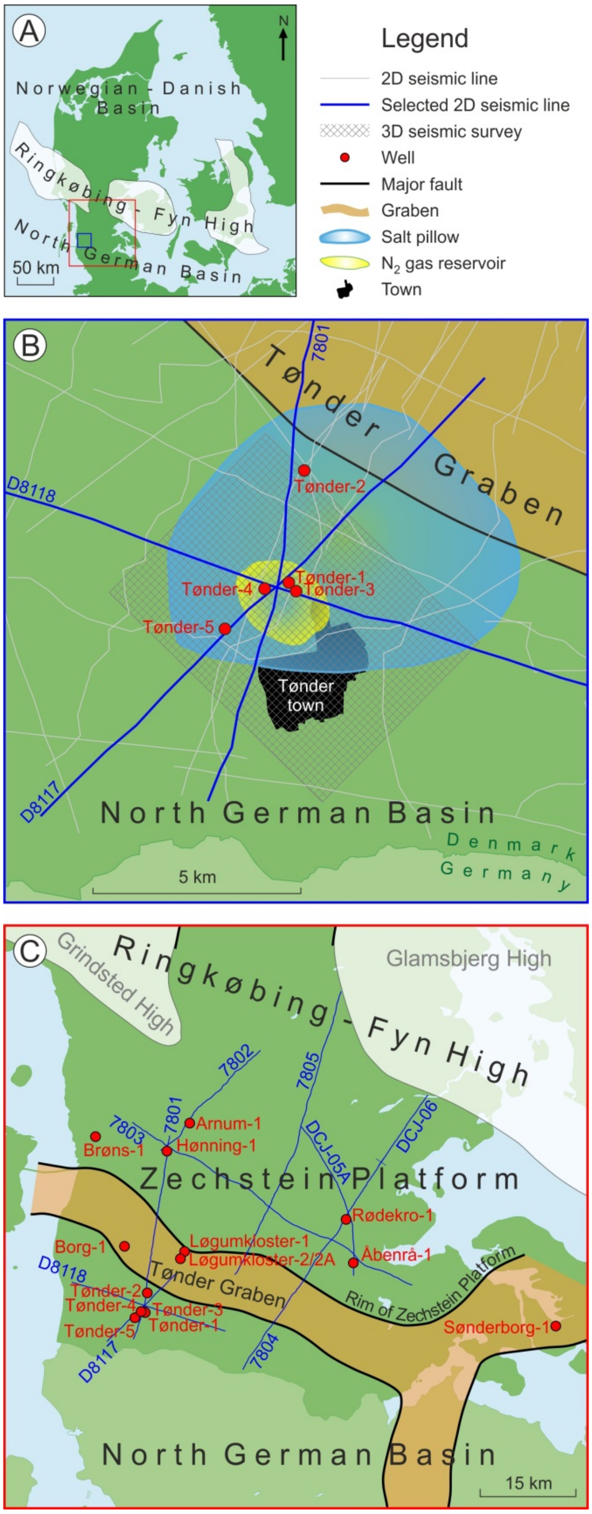

Figure 1: (A) Map of Denmark showing the Ringkøbing-Fyn High separating the Norwegian-Danish Basin from the North German Basin. The blue and red squares outline the areas shown in (B) and (C). (B) Principal structural elements, wells and selected seismic lines in the larger Tønder area. (C) Principal structural elements, wells and selected seismic lines south of the Ringkøbing-Fyn High.

results were followed by a 3D-seismic survey in 1995 providing data for considerably more detailed descriptions of the Tønder structure and reservoirs which confirmed the suitability of the upper and lower Bunter sands for gas storage (Dansk Olie og Naturgas A/S 1997). However, the occurrence of halite cement in the upper Bunter sand and highly saline formation water were causes of concern (e.g. Laier and Nielsen 1989). In the end the gas storage activities were abandoned in the mid 1990'ies due to resistence from the local community.

Plans of geothermal exploitation of the Bunter Sandstone Formation was described in Dansk Olie- & Gasproduktion A/S (1984), but not realized until plans for construction of a geothermal plant in the town of Tønder was decided and Mathiesen et al. (2010a) presented a full evaluation of the geothermal potential in the Tønder area. Due to its complex stratigraphic nature the upper Bunter sand was further evaluated with respect to spatial extent and geothermal properties (Hjuler et al. 2014), potential challenges regarding salt precipitation in installations (Laier 2013), halite cementation in the formation (Laier and Nielsen 1989), presence of nitrogen (Mathiesen et al. 2010a), and formation pressure (Springer and Kristensen 2012). Further, an assessment of reservoir temperature has been provided by Poulsen et al. (2013) and lifespan and production capacity of a geothermal plant have been simulated (Nielsen 2013). Detailed provenance studies of the upper and lower Bunter sands Olivarius et al. (in press) together with presentation of a refined porosity-permeability relation of the Bunter Sandstone Formation (Olivarius et al. 2015) have improved our understanding of spatial distribution of the reservoirs,depositional system, and the accuracy of predicting porosity and permeability.

1.2 Geological setting

The Bunter Sandstone Formation was deposited during the Early Triassic period when the intra-continental North German Basin was subject to regional subsidence (Doornenbal and Stevenson 2010). A coarsening of the clastic input marks the transition from the finer-grained earliest Triassic Bunter Shale Formation to the sandier Bunter Sandstone Formation. In the northernmost part of the North German Basin, including the Tønder area, deposition of the Bunter Sandstone Formation took place during most of the Olenekian and the earliest Anisian (Fig. 2A).

The Bunter Sandstone Formation was defined for the southern North Sea Basin by Rhys (1974) and for the Danish onshore area by Bertelsen (1980). Michelsen and Clausen (2002) recommended a subdivision of the Bunter Sandstone Formation into the Volpriehausen, Detfurth, Hardegsen and Solling members corresponding to the established German nomenclature of Mittlerer Buntsandstein (Fig. 2B). The lower Bunter sand is referred to the

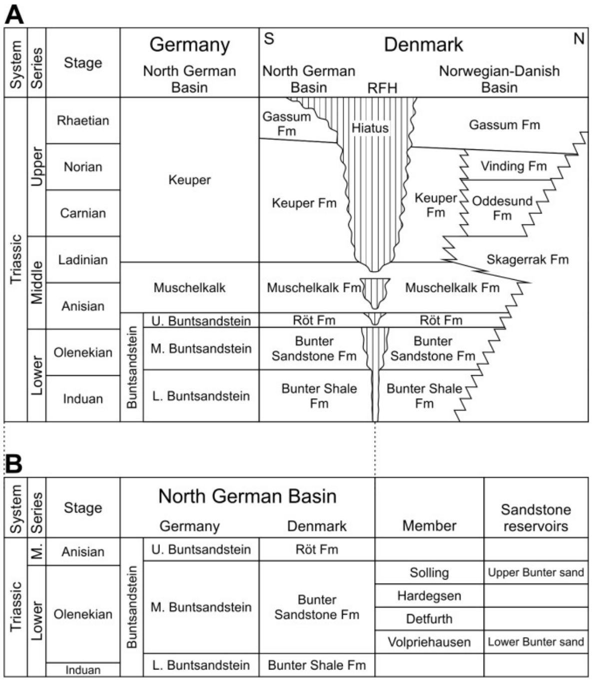

Figure 2: (A) Lithostratigraphic scheme of the Triassic succession in the onshore regions of Denmark and Germany. (B) A more detailed lithostratigraphic subdivision of the northern part of the North German Basin with main sandstone reservoirs marked. Modified from Olivarius et al. (2015)

Volpriehausen Member and the upper Bunter sand is referred to the Solling Member (Olivarius et al. 2015) (Fig. 2B).

In western onshore Denmark, south of the Ringkøbing-Fyn High, the Bunter Sandstone Formation is encountered at burial depths of c. 1.3–1.9 km (Nielsen and Japsen 1991) and despite of the Ringkøbing-Fyn High and adjacent basins being subjected to uplift during Middle Jurassic–Early Cretaceous (Nielsen 2003) the formation has not experienced deeper burial than today according to Weibel and Friis (2004). Formation thicknesses up to 500 m are found in the central North German Basin and more than 1000 m in the grabens. In the northern part of the North German basin burial depth becomes shallower and formation thickness becomes reduced and rarely exceeds 300 m in the Danish onshore area. The formation wedges out towards the Ringkøbing-Fyn High (Michelsen and Clausen 2002).

The Volpriehausen and Solling Members cover most of the northern part of the North German Basin, the former with little variation in thickness, the latter showing pronounced thickness variations (Olivarius et al. in press). In the same area the Detfurth Member is partly missing and the Hardegsen Member is only present in the southernmost part. The entire Bunter

Sandstone Formation is missing in the Borg-1 well and the Sønderborg-1 well.

Deposition of the Volpriehausen Member took place in a warm and arid climate with aridity decreasing during deposition of the subsequent Detfurth, Hardegsen and Solling members. The facies primarily comprise aeolian, ephemeral fluvial and playa or lake deposits (Clemmensen 1985; Fine 1986; Olsen 1987). The sedimentary succession of each member consists of basal red-brown fine-grained sandstone, grading to siltstone and shale in the upper parts. As an overall trend the sand content decreases towards the center of the North German Basin (Bertelsen 1980).

After deposition of the Bunter Sandstone Formation sediment accumulation continued during the Late Triassic and Early Jurassic subjecting the Bunter Sandstone Formation to steady burial until the Middle Jurassic to Early Cretaceous when thermal rifting in the Central North Sea resulted in uplift of the Ringkøbing-Fyn High (see Nielsen 2003 for discussion). Furthermore, the Zechstein salt, underlying the Bunter Sandstone Formation was moved into pillows, e.g. the Tønder structure.

2. METHODS

2.1 Seismic interpretation

South of the Ringkøbing-Fyn High a large number of seismic lines of varying quality are present, especially in the Tønder area which includes a 39 km^2 3D survey (Fig. 1b, c).

2.2 Core analysis

All available porosity and permeability measurements of Bunter Sandstone Formation material from the Danish onshore area have been considered in order to construct a robust database of porosity and permeability data; see Olivarius et al. (2015) for a more detailed description.

2.3 Petrography study

Petrographical results were extracted from Olivarius et al. (2015) and are based on point counting, optical and backscatter electron (BSE) microscopy of thin sections, and scanning electron microscopy (SEM).

2.4 Provenance study

Results of the sediment provenance were extracted from Olivarius et al. (in press) and are based on zircon U–Pb geochronometry and heavy mineral analysis.

2.5 Petrophysical log interpretation

Petrophysical well logs from all deep wells south of the Ringkøbing-Fyn High (see Fig. 1c) were used to assess reservoir parameters; see Hjuler et al. (2014) for method description.

The log-derived *gas permeability* (κ_{gas}) was determined using the power function presented in Olivarius et al. (2015) and expressed in equation 1:

$$\kappa_{gas} = 0.0003 \cdot PHIE^{4.43} \quad [1]$$

The log-derived permeability has been multiplied with a scaling factor with the value of 1.25 developed by GEUS for Danish onshore conditions to obtain the reservoir permeability ($\kappa_{reservoir}$) as expressed in equation [2]:

$$\kappa_{reservoir} = \kappa_{gas} \cdot 1.25 \quad [2]$$

Transmissivity ($T_{reservoir}$) and κ_{fluid} are related by equation [3]:

$$T_{reservoir} = \kappa_{reservoir} \cdot H_{reservoir} \quad , \quad [3]$$

where $H_{reservoir}$ is the height of the net sand interval.

2.6 Reservoir temperature assessment

A temperature prognosis for the Tønder area was derived based on data from the Tønder and Løgumkloster wells (Poulsen et al. 2013). The temperature at any depth can be estimated using the general equation [4]:

$$T = 0.028\ °C/m \cdot depth + 8\ °C \quad , \quad [4]$$

where 8 °C is the average annual temperature at the surface.

2.7 Pore water analysis

The results of the pore water analysis were extracted from Laier and Nielsen (1989) and Hjuler et al. (2014).

3. RESULTS

3.1 Structural development of the Bunter Sandstone Formation

The Bunter Sandstone formation thickens from the Arnum-1 and Hønning-1 wells to the Tønder-4 and Tønder-5 wells (Seismic section 7801, Fig. 3). A broad WNW–ESE-oriented fault zone is present north of the Tønder area separating the platform area to the north from the basin area to the south. The boundary between these areas corresponds to the Zechstein Platform Break in Stemmerik and Frykman (1989) (Fig. 1c). The platform area is gently inclined towards the basin, and is characterized by parallel, continuous reflectors in the north. The southern part of the platform area, however, has parallel reflectors that are cut by channels (Fig. 3).

3.2 Core analysis

The relation between porosity and permeability in the Bunter Sandstone Formation is illustrated in four plots showing stratigraphy, sampling locality, grain size and depositional environment influence reservoir quality (Fig. 4). The porosity and permeability correlate, and the majority of the sediments has intermediate to high porosities (>13%) and high permeabilities (>100 mD).

The porosities and permeabilities of the sandstones in the Volpriehausen Member are generally high (>17%; >100 mD), but considerably lower in the Detfurth Member (c. 14–18%; c. 5–125 mD) and a wide range is found in the Solling Member (c. 2–34%; c. 0.03–5000 mD) (Fig. 4A).

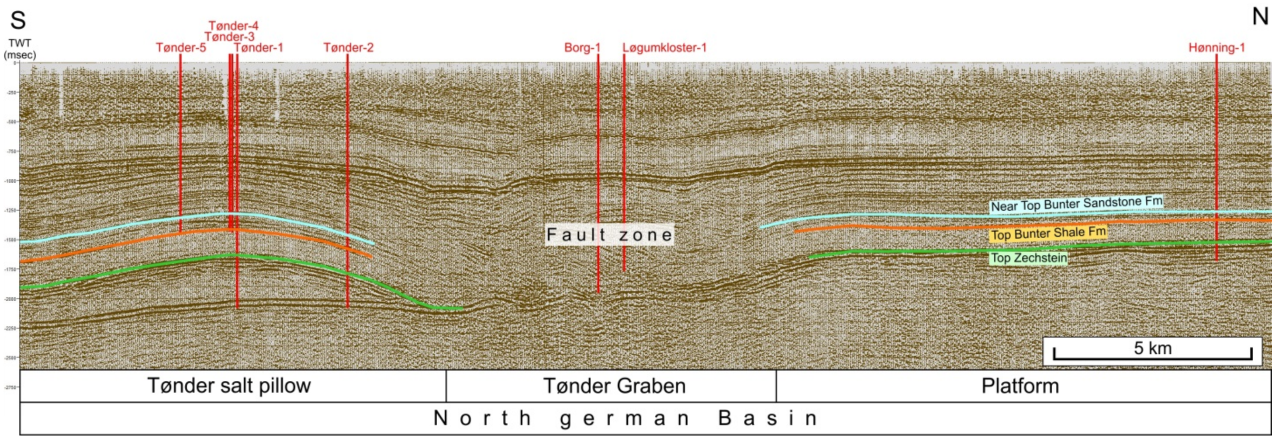

Figure 3: Seismic section (7801) showing the development of the Bunter Sandstone Formation from the platform area to the north, across the fault zone known as Tønder Graben and to the Tønder salt pillow to the south. A surface trace of the seismic profile, Tønder Graben and salt pillow are shown in Fig. 1b, c.

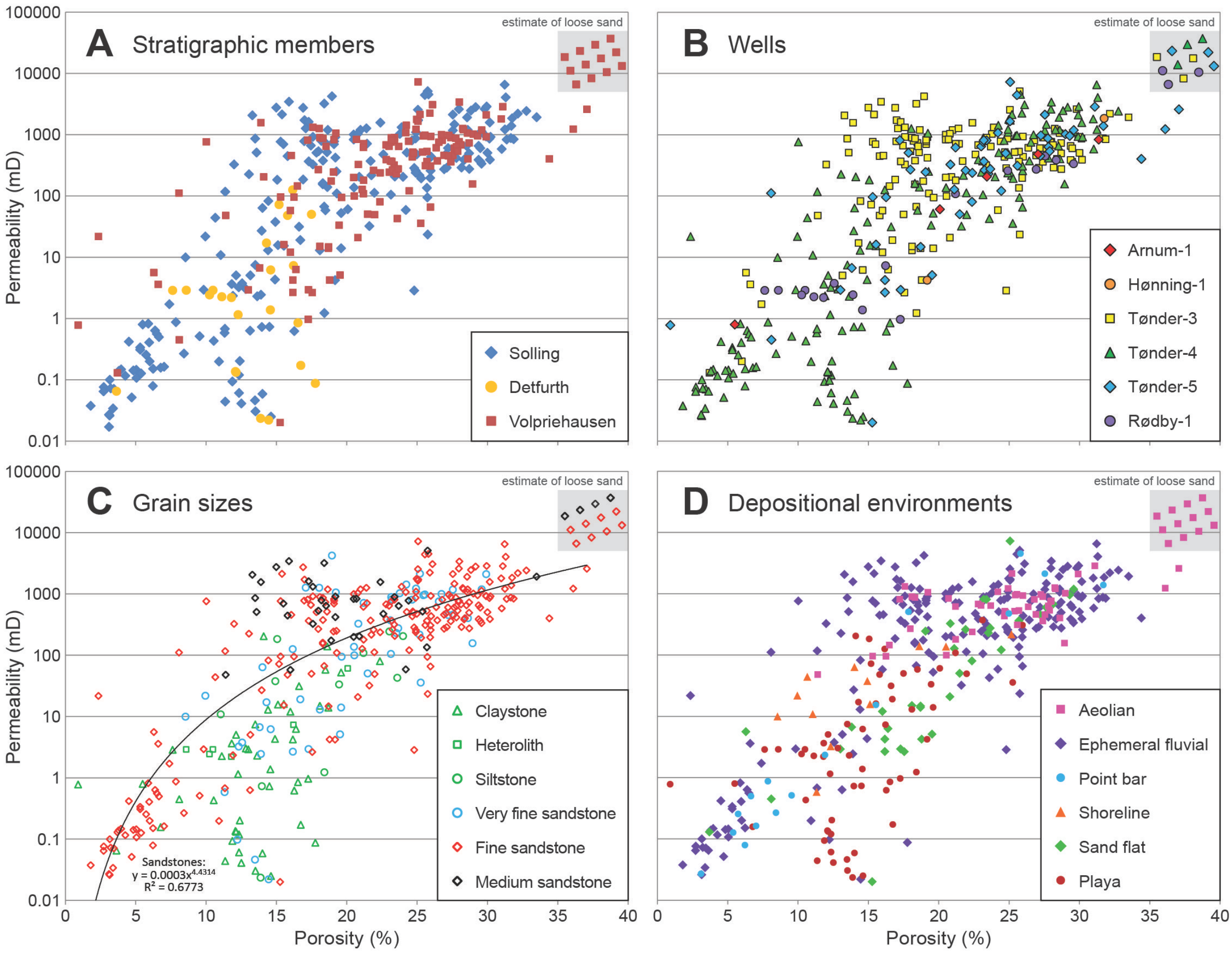

Figure 4: Porosity-permeability plots for the Bunter Sandstone Formation showing variations of porosity and permeability between stratigraphic members, wells, grain sizes and facies. After Olivarius et al. (2015).

The sandstones are divided into very fine-grained (≥63–125 µm), fine-grained (≥125–250 µm) and medium-grained (≥250–500 µm) in Fig. 4C. The very fine-grained sandstones plot primarily below the trendline of the sandstones due to low permeabilities. The medium-grained sandstones plot predominantly above the trendline as a result of higher permeabilities. The claystones, siltstones and heteroliths have low to intermediate porosities and permeabilities (c. 6–24%; c. 0.02–200 mD).

Samples from shoreline facies have intermediate porosities and low to intermediate permeabilities (c. 9–21%; c. 3–100 mD) (Fig. 4D) whereas they are generally higher in the sand flat deposits (c. 13–28%; c. 3–1000 mD). The majority of the ephemeral fluvial sediments have high permeabilities of >100 mD. Poor reservoir quality corresponding to porosity <10% and permeability <1 mD is found in a group of ephemeral fluvial and point-bar sediments from the Tønder-4 well (Fig. 4B, D). Only few of the point-bar sandstones have good reservoir quality (Fig. 4D).

The measured reservoir properties of the aeolian sandstones (Fig. 4D) are not representative since measurement of the loosest deposits was impossible.

3.3 Petrography

Patchy cement is present in both the lower and upper Bunter sand, but in largest amounts in the upper reservoir since it here consists of both anhydrite and carbonate, whereas only carbonate cement has precipitated in the lower reservoir (Olivarius et al. 2015). These cementations are not fatal for the reservoir quality since the flow can move around the cement patches. The same is true for the clay clasts present in the upper Bunter sand because they act as oversize grains. However, pervasive halite, anhydrite and carbonate cementations are present in some intervals of the upper Bunter sand and they close all pore spaces. The flow is also efficiently obstructed in the upper reservoir when inter-granular clay is present; whether as infiltration or authigenic clay. The lower and upper Bunter sands are generally fine-grained, but medium-grained deposits form part of the upper Bunter sand in some areas.

Arid conditions prevailed when the lower Bunter sand was deposited by aeolian activity, and the climate had changed to semi-arid conditions when the upper Bunter sand was laid down by ephemeral fluvial channels. The lateral distribution of the depositional environments is related to distance to provenance, amount of subsidence, local topography, faulting activity and precipitation rate. The very high porosity and permeability of the lower Bunter sand (Fig. 4A) are related to the well-sorted, clay-free composition of the initially deposited sand combined with the limited formation of anhydrite cement during burial. The porosity and permeability of the upper Bunter sand are more difficult to predict due to the local occurrence of pervasive cement and inter-granular clay (Olivarius et al. 2015).

3.4 Provenance

The lower Bunter sand is widely distributed in the North German Basin since much of the sand was supplied from the Variscan belt south of the basin (Olivarius et al. in press) (Fig. 5). The lower Bunter sand consists mainly of aeolian sand sheets deposited during sandstorm (Clemmensen 1985).

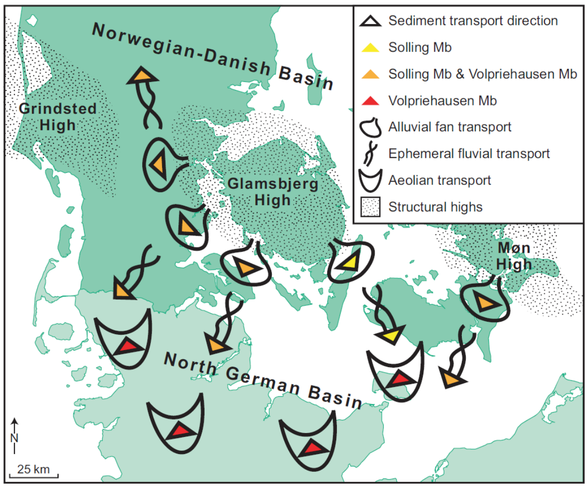

Figure 5: Sediment transport mechanisms and transport directions responsible for forming the Volpriehausen and Solling members. After Olivarius et al. (2015b).

The lateral continuity, the constant thickness and the weakly cemented to loose nature of the lower Bunter sand result in excellent reservoir quality (Olivarius et al. 2015, in press). Ephemeral fluvial sandstones are interbedded with the aeolian deposits in some intervals, but their high quartz and low mica contents reveal that they mostly consist of reworked aeolian sediments and thus have good reservoir quality. The lower Bunter sand is present in the basin area which is delimited by a fault zone north of the Tønder area (Fig. 3) that separates the basin area from the platform area present south of the Ringkøbing-Fyn High (Olivarius et al. in press). Overbank claystones and very fine-grained alluvial and ephemeral fluvial sandstones were deposited in the platform area while the lower Bunter sand was deposited in the basin area.

A local provenance of the upper Bunter sand has been interpreted from the uniform and unique heavy mineral assemblage, the zircon ages matching the basement in the Ringkøbing-Fyn High and the sediment transport directions interpreted from seismic reflection data (Olivarius et al. in press). The sand was transported southwards from the Ringkøbing-Fyn High by small alluvial fans that passed into ephemeral fluvial channels (Olivarius et al. 2015, in press) (Fig. 5). Some of the channels reached the playa lake during episodes of heavy rainfall whereby shoreline sand was deposited. The upper Bunter sand reservoir consists primarily of ephemeral fluvial deposits interbedded with overbank claystones, so the architecture of the reservoir is difficult to predict since the channels often changed their course. Thus, it is probably a fine reservoir in some areas, but has a marked lateral and vertical variability (Olivarius et al. in press).

3.5 Reservoir properties

The Tønder-1–5 wells constitute central wells in the area of interest with respect to geothermal exploitation of the lower and upper Bunter Sands (Fig. 1b, c). However, as the depositional system is a major reservoir property controlling factor (e.g. Hjuler et al. 2014; Olivarius et al. 2015, in press) net sand thickness, porosity and gas permeability have been determined for all wells south of the Ringkøbing-Fyn High (where possible) in order to provide the best foundation for understanding the connection between reservoir properties and depositional system of the Tønder area (Table 1 and Fig. 6). Thus, data from the Løgumkloster-1–2 wells situated in the Tønder Graben and the Arnum-1, Hønning-1 and Brøns-1 wells situated in the western Zechstein Platform area and the Rødekro-1 and the Åbenrå-1 wells situated in the eastern Zechstein Platform area are included (Fig. 1c). The Borg-1 well is excluded as it does not include the Bunter Sandstone Formation. As seen from Table 1 the lower and upper Bunter sands can only be identified with certainty in the Tønder and Løgumkloster wells. Further, net sand thickness, porosity and gas permeability is not determined in several wells due to lack of data or poor data quality.

3.6 Reservoir temperature

A temperature-depth relation, equation [4], has been developed and temperature estimates for the reservoir centers have been calculated and are presented in Table 1.

3.7 Pore water analysis

The much higher porosity and permeability values obtained by core analyses compared to logs of the Tønder-3 well were thought to be due to removal of salt during normal laboratory cleaning of cores prior to analysis (Hjuler et al. 2014). Therefore, core analyses of the new wells were performed on core plugs prior to conventional cleaning as well as after cleaning of identical plugs. A large increase in both porosity (from c. 5 % to 25 %) and permeability (from <1 mD to over 1000 mD) was seen moving from not-cleaned to cleaned core plugs. The largest difference was observed for the more sandy units of compared to the more clayey units of the core. Halite cement was exclusively found in the upper Bunter sand where nitrogen was also present. No indication of halite cement in the lower Bunter sand was found.

From the investigation on the occurrence of halite cement it was concluded that 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 (Laier and Nielsen 1989). Thus, it is tempting to conclude that halite cement only occurs where nitrogen gas also is 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. According to seismic data alone the gas-water contact (GWC) is located up-hill of the Tønder-5 well. The gas to water ratio is clearly much less in Tønder-5, which is located approximately 60 m below the top of the salt structure where Tønder-4 is located.

Table 1: Reservoir parameters of the lower and upper Bunter sands in the Bunter Sandstone Formation: Shale cut-off and porosity cut-offs have been applied resulting in a definition of net sand as sandstone with <30% shale, and porosity >15%. N/G defined as net sand thickness divided with reservoir thickness.

Well	Sandstone interval	Reservoir interval (m TVDSS)	Reservoir thickness (m)	Gross sand thickness (m)	Net sand thickness (m)	N/G	Avg. porosity (%)	Avg. gas permeability (mD)	Avg. reservoir permeability (mD)	Trans-missivity (Dm)	Reservoir temperature (°C)
Tønder-1	U. Bunter	1624–1673	49	30	-	-	-	-	-	-	54
	L. Bunter	1775–1809	34	33	-	-	-	-	-	-	58
Tønder-2	U. Bunter	1940–1989	49	30	-	-	-	-	-	-	63
	L. Bunter	2064–2096	32	32	-	-	-	-	-	-	66
Tønder-3	U. Bunter	1626–1671	45	40	32	0.71	23	536	670	21	54
	L. Bunter	1775–1808	33	39	30	0.91	23	451	564	17	58
Tønder-4	U. Bunter	1625–1674	49	36	30	0.61	23	532	665	20	54
	L. Bunter	1777–1812	35	35	31	0.89	23	454	568	18	58
Tønder-5	U. Bunter	1687–1730	43	24	16	0.37	19	194	243	4	56
	L. Bunter	1840–1875	35	30	28	0.80	25	589	736	21	60
Løgumkloster-1	U. Bunter	1737–1765	28	6	3	0.11	21	291	364	1	57
	L. Bunter	1831–1866	35	33	32	0.91	23	399	499	16	60
Løgumkloster-2	U. Bunter	1818–1851	33	22	2	0.06	22	309	386	1	59
	L. Bunter	1907–1937	30	28	0.5	0.02	16	71	89	0	62
Løgumkloster-2A	U. Bunter	1798–1838	40	4	0	0.00	-	-	-	-	59
	L. Bunter	1901–1935	34	27	3	0.09	17	96	120	0	62
Borg-1	Not present	-	-	-	-	-	-	-	-	-	-
Brøns-1	Entire Fm	1597–1738	141	37	-	-	-	-	-	-	55
Hønning-1	Entire Fm	1560–1743	183	59	-	-	-	-	-	-	54
Arnum-1	Entire Fm	1377–1502	125	28	-	-	-	-	-	-	48
Rødekro-1	Entire Fm	1331–1410	79	31	-	-	-	-	-	-	46
Aabenraa-1	Entire Fm	1477–1614	136	29	-	-	-	-	-	-	51
Sønderborg-1	Not present	-	-	-	-	-	-	-	-	-	-

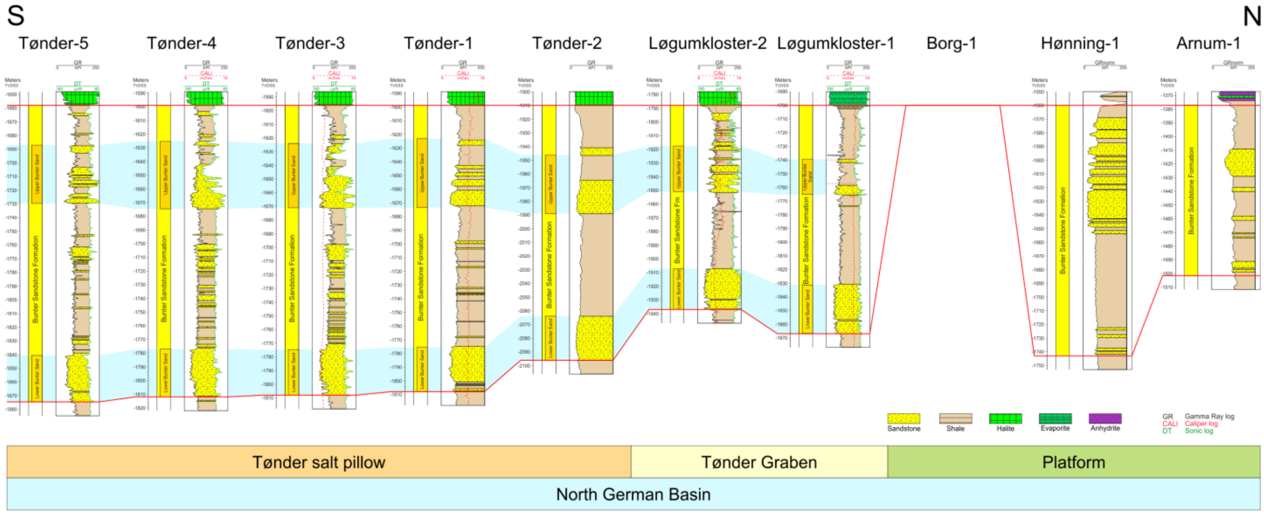

Figure 6: Log panels showing the lithological composition of the Bunter Sandstone Formation. The upper and lower Bunter sands are indicated with light blue.

4. DISCUSSION

South of the Ringkøbing-Fyn High the Bunter Sandstone Formation covers most of the Danish area displaying a rather consistent thickening trend towards the southwest as indicated by seismic data (Fig. 3) and well data (Fig. 6). The geothermally prospective lower and upper Bunter sands can be traced from the Tønder area and across the Tønder Graben but are hard to identify with certainty on the Zechstein Platform although sand layers are present (Fig. 6).

The lower and upper Bunter sands represent different depositional environments which impact on reservoir quality and particularly on predictability of reservoir quality and distribution.

4.1 The lower Bunter sand

The aeolic sand deposits of the lower Bunter sand appear to cover a large part, maybe all, of the area south of the Zechstein Platform and also the western part of the Zechstein Platform as indicated by the relatively constant layer thickness of c. 25 m seen in the Tønder, Løgumkloster and Brøns wells (Fig. 6). Otherwise, the lower Bunter sand seems to be absent on the Zechstein Platform except for well observations of a few, thin sand layers occurring in the lower part of the Bunter Sandstone Formation which may correspond to the lower Bunter Sand.

Due to its aeolic origin the lower Bunter sand is fine-grained, well-sorted and clay-free resulting in excellent porosity and permeability values as confirmed by core analysis data for the Volpriehausen Member (Fig. 4). However, the very limited cementation of the lower Bunter sand should enhance the reservoir properties even further, and since measurements were not possible on the loosest sample material the porosity and permeability values in Fig. 4 should be considered conservative.

The similar well log signals of the lower Bunter sand interval (Fig. 6) indicate a rather invariable spatial distribution which improves predictability of reservoir presence and properties.

4.2 The upper Bunter sand

The development of the upper Bunter sand is complex in terms of establishing a model for the depositional environment and thus prediction of reservoir properties in the Tønder area. Two possible scenarios are presented below:

Scenario 1: Clemmensen (1985) and Olsen (1987) described a stream-sabkha-lake model which implies that towards south the sediments become increasingly finer-grained with less reservoir potential, a trend demonstrated by the drop in porosity and permeability when moving from the Tønder-3–4 wells to the Tønder-5 well (Table 1, Fig. 6) and in general when moving towards the center of the North German Basin. Accordingly, the reservoir quality south of the Tønder-5 well will become further reduced. A temperature gain, however, is expected due to deeper burial compared to the Tønder-3–5 wells which are situated on top of the Tønder salt pillow.

Scenario 2: Deposition of sediments in the Tønder area is controlled by ephemeral braided streams which over time switch position resulting in alternating sandy channel deposits, muddy interchannel overbank deposits (Olivarius et al. 2015), or lake and sabkha deposits (Hjuler et al. 2014). The Tønder-3 and -4 wells penetrate sandy intra-channel fills with good reservoir properties whereas the Tønder-5 well penetrates both sandy intra-channel fills and interchannel fills with less good reservoir properties (Table 1, Fig. 6). The Tønder area occupies a restricted area (less than 10 · 10 km) and based on existing data it is considered unlikely that any significant trend with respect to depositional environment and reservoir properties will be present. The challenge is to predict the location of channel sands and to avoid the interchannel deposits. Unfortunately, the resolution of the seismic data is not sufficient to reveal this sort of details. However, the well log-based reservoir parameters may provide an estimate of distribution of good, less good and poor reservoirs. Good reservoir quality is found in the Tønder-3 and -4 wells (16–20 Dm), while the reservoir quality is less good in Tønder-5 (4 Dm). No reservoir properties could be established for the Tønder-1 and -2 wells due to poor data quality; however, a gross sand thickness of 30 m for both wells does not exclude the presence of good reservoir properties in the upper Bunter sand.

The Løgumkloster wells are located above a fault zone and the reservoir properties are probably affected by pronounced diagenesis. Thus, the poor transmissivity values of 0–1 Dm encountered in the wells may not be representative for a similar depositional environment outside the fault zone. However, the too low gross sand values of the Løgumkloster-1, -2 and 2A wells (6, 23 m and 4 m), exclude them from having geothermal potential.

The reservoir properties of the upper Bunter sand is good in two wells (Tønder-3 and -4), less good in one well (Tønder-5) and poor in two wells (Løgmkloster-1 and -2A). In the Tønder-1 and -2 and Løgumkloster-2 wells the reservoir properties cannot be addressed due to the limited amount of data but good reservoir in these wells properties cannot be excluded.

5. CONCLUSION

The current study demonstrates the importance of integrating a wide range of geological disciplines in order to optimize the accuracy of geothermal potential assessments. The geothermal potential of the Bunter Sandstone Formation in the Tønder area was assessed using seismic data, provenance study, petrography, core analysis, well log petrophysics, pore water analysis and temperature estimate. Focus was on the lower and upper Bunter sands included in the Volpriehausen and Solling members, respectively. The outcome of the study is a geological model that serves as input to a 3D simulation study of reservoir performance.

The lower Bunter sand provides an excellent geothermal reservoir with transmissivity values of c. 16–20 Dm, temperatures in the range of 58–66 °C and good predictability in terms of reservoir parameters.

The geothermal potential of the upper Bunter sand is much more difficult to assess due to significant variations within the depositional environment. Temperatures in the range of 54–63 °C should be expected. The chances of drilling a reservoir with excellent, medium or poor geothermal properties (c. 0–20 Dm) are assumedly similar.

Thus, exploitation of the low enthalpy geothermal energy stored in the subsurface of the Tønder area should use the lower Bunter sand as main reservoir with the upper Bunter sand as an upside potential. Precautions should be made to inhibit salt precipitation of subsurface and ground installations caused by the extreme salinity of the formation brine.

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