Towards a geothermal exploration well in the Gassum Formation in Copenhagen

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Geothermal resources in the deep subsurface in many parts of Denmark have the potential to form a central component in the future Danish energy supply for district heating. Geothermal energy is sustainable and environmentally friendly and independent of climatic and seasonal variations, in contrast to solar and wind energy. Furthermore, geothermal plants may be integrated with other green energy supplies. The sandstone reservoirs from which the warm geothermal water is extracted may also act as temporary storage for excess heat e.g. from industrial production processes or from solar-heated water in summer periods when the demand for heating is low.

Therefore, there are many good reasons to include geothermal energy in Denmark's energy mix. Despite this, only three geothermal plants exist at present at Thisted, Copenhagen and Sønderborg (Fig. 1). Several district heating companies have, however, shown interest in geothermal energy and have taken the first step towards estimating if suitable geological conditions are present within their respective district heating areas. This has been done by analysing geological and geophysical data gathered from the nearest deep wells and seismic surveys, in some cases supplemented with new seismic data. Although these analyses generally show promising geothermal potential, hesitation prevails when it comes to drilling the actual geothermal wells. Deep drilling is complicated and expensive, but necessary in order to deduce if productive reservoir sandstones are present that can produce the required volumes of geothermal water.

In order to mitigate the geological risks and facilitate utilisation of geothermal energy, publicly supported initiatives financed by research grants have been undertaken for the last 40 years. Thereby our knowledge of the Danish subsurface and the reservoir properties of deep geothermal sandstones has considerably increased, and fundamental uncertainties regarding subsurface structures and resources have been reduced. The many promising results are publicly available via the newly established Geothermal WebGIS Portal at the Geological Survey of Denmark and Greenland (Vosgerau *et al.* 2016). Furthermore, the industry is now taking more interest in geothermal exploration and sees it as a promising business case into which it is willing to invest and share the risks associated with expensive wells. The public sector facilitates this development by supporting research projects via grants from the Energy Technology Development and Demonstration Programme of the Danish Energy Agency (EUDP) and the Innovation Fund Denmark. These projects involve research institutes, district heating companies, private companies and other stakeholders.

The present paper deals with the outcome of one of these projects called the Geothermal Pilot Hole, financially supported by the EUDP. The project elucidates e.g. how drilling can be made less expensive by focusing on geothermal sandstone reservoirs at depths shallower than *c.* 2200 m, thereby allowing the use of small rigs suitable

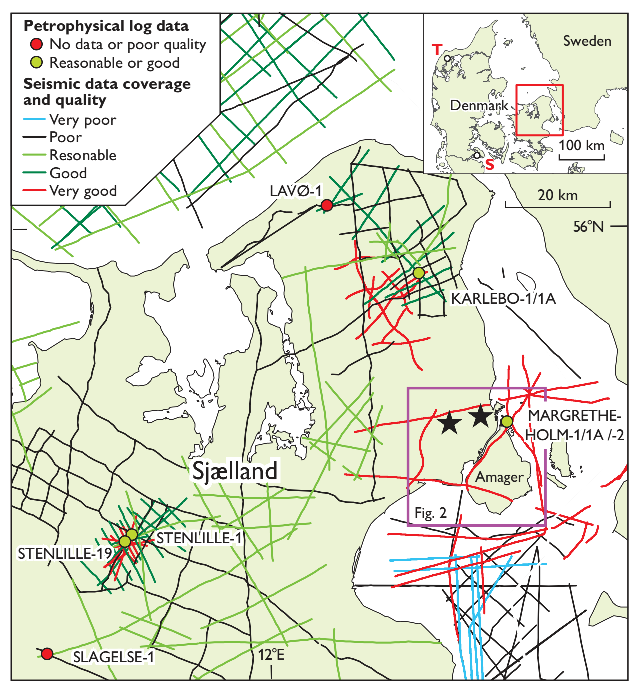

Fig. 1. Coverage and quality of seismic and petrophysical log data from deep wells in Sjælland. The quality indeces reflect to which degree the data can be used to extract information about major geothermal sandstone reservoirs in the deep subsurface. The Margretheholm wells are part of the existing geothermal plant in Copenhagen. Stars mark the approximate positions of the two areas of interest. On the inset map the locations of the Thisted (**T**) and Sønderborg (**S**) plants are shown.

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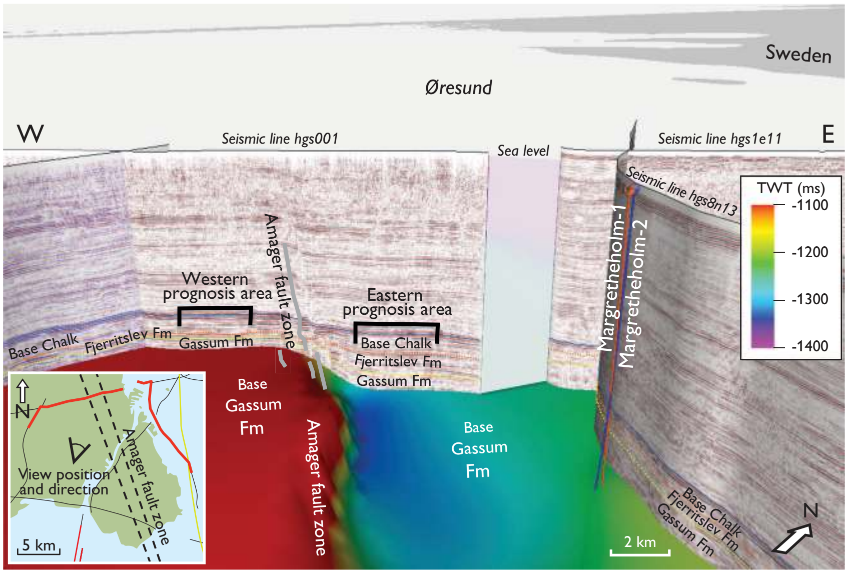

Fig. 2. Seismic lines in 3D view seen towards northern Copenhagen and Margretheholm in northern Amager. The view position and direction are shown on the inserted location map, as is the overall trend of the Amager Fault zone. The coloured surface reflects the depth and morphology of the base of the Gassum Formation, clearly illustrating the different, fault-controlled positions of the two prospect areas west and east of the fault. The thickness of the Gassum Formation, marked on the seismic profiles, increases considerably from west to east across the Amager Fault zone. Depths are shown as seismic two-way travel time, TWT.

for operation in urban areas. For comparison, the existing geothermal plant in Copenhagen utilises water from the Lower Triassic Bunter Sandstone Formation at a depth of *c.* 2.6 km. Another important part of the project is to provide a well-constrained prognosis of relevant reservoir parameters (depth, thickness, transmissivity, production capacity, temperature, etc.) of geothermal sandstone reservoirs of the Upper Triassic – Lower Jurassic Gassum Formation within two prospect areas of special interest in northern Copenhagen (Fig. 1). This activity will provide the necessary background to select the location of an exploration well in a future phase of the project yet to be granted. Previous studies have shown that the subsurface of Copenhagen contains large quantities of geothermal energy which may form a substantial contribution to domestic heating for hundreds of years to come, and the two areas in northern Copenhagen (stars, Fig. 1) have already been selected as relevant, based on suitable geological conditions and infrastructure. Copenhagen is a major city with a substantial demand for heating and like other Danish cities it has a well-established district heating network, and for these reasons it is an obvious site for geothermal energy.

The Gassum Formation constitutes the most well-known sandstone reservoir in Denmark and is exploited for geothermal energy in Thisted and Sønderborg and for gas storage at Stenlille. It is dominated by fine to medium-grained sandstones alternating with darker-coloured claystones, siltstones and thin coal seams. The sand was deposited in the Danish Basin mainly as marine shoreface sand in relatively continuous and widely distributed bodies, as well as deposits in river channels, estuaries and lagoons. In the Copenhagen area, the Gassum Formation occurs in depths of around 2000 m and has a temperature of *c.* 60°C (Balling *et al.* 2016), sufficiently high to make a district heating plant economically profitable. Furthermore, the depth is shallow enough to prevent serious diagenetic alteration under high pressure and temperature conditions which might reduce the porosity and permeability of the reservoir sandstones (Kristensen *et al.* 2016). The results of the project phases conducted so far illustrates e.g. that the subsurface geological conditions may vary considerably within a city area, thus influencing the geothermal potential.

Geological database

The critical subsurface geological information from deep wells and seismic lines in central and north-eastern Sjælland (Fig. 1) controls the reservoir prognosis for the two prospect areas in northern Copenhagen. The seismic coverage is reasonable around these two areas, especially because an E–W-trending seismic line of very good quality occurs immediately north of them. Detailed analysis of this and other nearby lines has been used to identify and estimate the depth and thickness of the Gassum Formation in the two prospect areas. The two areas are separated by the NNW–SSE-striking Amager Fault which forms part of a major regional fault zone, along which the easternmost part of Sjælland has been down-faulted (Fig. 2). The seismic mapping reveals that the Gassum Formation is thicker and occurs at a deeper level in the eastern area than in the western area.

Deep wells in north-eastern Sjælland are limited to Margretheholm-1/1A and -2, Karlebo-1/1A and Lavø-1 from which no cores of the Gassum Formation exist, and

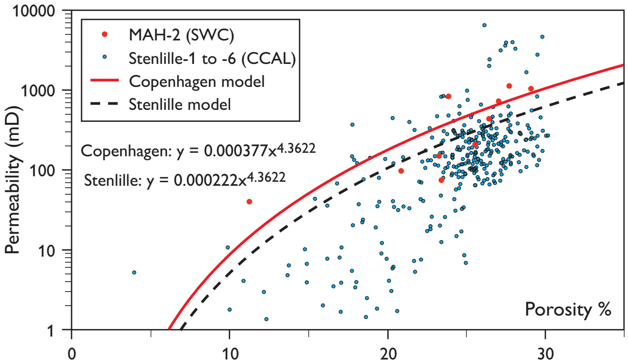

Fig. 3. Porosity–permeability models based on gas measurements on core material at laboratory conditions. The 'Copenhagen model' represents the eastern prospect area and is based on measurements on sidewall cores from the Margretheholm-2 well, whereas the 'Stenlille model' represents the western prognosis area and is based on conventional core analysis data from several Stenlille wells. The methodology for establishing local porosity–permeability models is described in Kristensen *et al.* (2016).

the petrophysical log data from Lavø-1 are of poor quality. However, a large amount of good quality petrophysical log and core data exist from the Stenlille area in the central part of Sjælland, *c.* 60 km west of the two areas of interest (Fig. 1), although not all of the well data are equally relevant for setting up a reservoir prognosis for the Gassum Formation in the prospect areas. Representative well data have been chosen based on e.g. sequence stratigraphic and biostratigraphic analysis and on similarities to the prospect areas in terms of structural setting, depositional environment, inferred distance from the palaeoshoreline, sediment sources, petrography, burial depth, diagenetic alternation, etc. In general, the data from the Margretheholm and Karlebo-1/1A wells are considered the most relevant for the eastern prospect area, as also these wells are located on the eastern, down-faulted side of the Amager Fault (Fig. 2). The locations of the Lavø-1 and the Stenlille wells west of the Amager Fault justify a higher weighting of data from these wells in the prognosticating of the western area.

Estimated reservoir values

Based on the seismic data, the Gassum Formation is estimated to be around 200 m thick with its top at *c.* 2000 m below sea level in the eastern of the project areas in Copenhagen, and around 150 m thick with its top at *c.* 1750 m below sea level in the western area (Table 1). Core and petrophysical well log data form the basis for estimating the reservoir properties of the sandstones including local porosity–permeability models (Fig. 3). The porosity and permeability values are estimated to be slightly lower in

Table 1. Estimated reservoir values for the Gassum Formation in two potential areas§

Prospect areas in Copenhagen	western	eastern
Macro reservoir parameters		
Depth to top of formation (m below sea level)	1750	2000
Thickness (m)	150	200
Thickness, potential reservoir sand (m)	75	80
Water-conducting properties (reservoir sand)		
Porosity (%)	25	21
Gas permeability (mD)	300	250
Reservoir permeability (mD)	375	313
Reservoir transmissivity (Kh) (Dm)	28	25
Temperature (°C), middle of formation	57	65

§See Kristensen *et al.* (2016) for details.

the eastern than in the western area, most likely related to its deeper burial depth and corresponding higher pressure–temperature conditions (Table 1). The reservoir transmissivity, given by multiplying the estimated thickness of potential reservoir sand with the estimated reservoir permeability, is an important parameter as it expresses the overall performance of the reservoir. As a rule of thumb, the transmissivity of a sandstone interval in the Danish subsurface should be greater than 10 Darcy-m in order to constitute a potential geothermal reservoir. Both areas fulfil this criterion as the estimated reservoir transmissivity for the Gassum Formation is 25 and 28 Darcy-m, respectively, for the two areas. Although the estimated porosity, permeability and transmissivity values are slightly higher in the western area, this does not necessary qualify this as better for geothermal exploitation. This is because the geothermal water of the Gassum Formation in the eastern area benefits from being hotter than in the western area (65°C versus 57°C, Table 1) as a consequence of its greater depth.

Reservoir model simulations

Reservoir simulations in both of the prospect areas have shed further light on the suitability of the Gassum Formation for geothermal exploitation. The reservoir data and interpreted regional seismic surfaces have thus been used to simulate flow rates and the time span before cooled water from injection wells will reach the production wells. In each of the simulations, separate production and injection wells supplemented with a vertical spud well were used. Simulation runs with different well spacings show that the distance between the production and injection wells at depth can be kept as low as 900 m without cold-water breakthrough at the production well within the simulation period of 25 years. Given that the injection and production wells would typically originate from the same surface position, short distances between the injection and production wells at the reservoir level are preferred in order to minimise the inclination of the well trajectory. This will lower the drilling risks, as drilling generally becomes more complicated with increasing inclination.

Overall, the simulations showed suitable production capacities for both locations but that the eastern location is more favourable because of higher production and injection rates for the same pressure applied to the wells, a more favourable production temperature profile, as well as thicker reservoir intervals which will delay breakthrough of cold water from the injection to the production well because the cold-water front is spread over a thicker reservoir interval.

Concluding remarks and perspectives

The various geological and geophysical analyses presented here indicate that the Gassum Formation is suitable for geothermal exploitation in both of the prospect areas. The production may be further enhanced if geothermal energy is produced simultaneously from the Gassum Formation and from sandstones in the lower part of the overlying Fjerritslev Formation. This formation largely consists of tight mudstones, but in eastern Sjælland its basal part contains several sandstones which may contribute to a geothermal production. Although the simulations point out the eastern area as being more favourable for a geothermal production, other factors must also be considered in a final selection of a borehole location, such as drilling costs related to different drilling depths and non-geological parameters such as the position of the well in relation to the district heating and other surface infrastructure.

Well data from eastern Sjælland are scarce and of varying quality. Especially the lack of cores from penetrated sandstones is a shortcoming, as such material is very valuable in estimating reservoir properties as shown by the extrapolation of core data from the Stenlille wells for the prospect areas in Copenhagen. Several packages of sandstones and intervening mudstones in the Gassum Formation have thus been correlated between the wells at Stenlille and eastern Sjælland and are therefore also expected to be present in the two prospect areas themselves. Regional seismic mapping, palynological analysis and comparison of petrophysical log data patterns furthermore indicate that the paleogeographic setting and depositional environments during the deposition of the Gassum Formation were broadly similar in Stenlille and in the prospect areas. In addition, U-Pb radiometric dating of detrital zircon grains from the Gassum Formation indicates that all of these deposits were sourced mainly from reworking of the Lower Triassic Bunter Sandstone Formation on the Ringkøbing–Fyn High, a regional basement ridge forming the southern margin of the Danish Basin.

Extrapolation of the Stenlille data as far as to eastern Sjælland inevitably implies some uncertainties. A new well in Copenhagen from which cores, petrophysical log data and hydraulic test data can be collected and analysed will considerably increase the accuracy of predictions of reservoir properties of the Gassum Formation in greater Copenhagen as well as in the Hillerød and Farum areas in northeastern Sjælland, where initial investigations have also been performed. Hence, the geological and economic risks associated with the establishment of a geothermal plant will be reduced, not only in Copenhagen but in eastern Sjælland as a whole. Furthermore, a new well will make it possible to compare existing core data (including direct porosity and permeability measurements) with petrophysical log data and hydraulic test data from intervals of penetrated reservoir sandstone, and will thus provide a unique possibility to verify to what extent traditional petrophysical log data can be used to estimate the reservoir properties of geothermal sandstones. This knowledge is important for evaluation of the geothermal potential in a specific area based on data from existing wells, and for selecting suitable log tools for estimation of the porosity, permeability and injectivity of potential reservoir sandstones in general.

Acknowledgements

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