

Pre-drilling geothermal assessment of porosity and permeability of the Bunter Sandstone Formation, onshore Denmark

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Denmark constitutes a low-enthalpy geothermal area. Current geothermal production takes place from two sandstone-rich formations: the Bunter Sandstone and Gassum Formations. These formations form major potential geothermal reservoirs, but information about the permeability of the potential sandstone reservoirs is difficult to obtain. This may be explained by deposition in a variety of environments under different climatic conditions, and by variable diagenetic overprint (Olivarius *et al.* 2015). Thus, the sandstone characteristics and properties are diverse, and in areas where wells are scarce, the assessment of the extent and reservoir properties of sandstone layers is associated with much uncertainty. In order to reduce exploration risk it is therefore essential to develop a robust method for prediction of porosity and permeability prior to drilling.

Kristensen *et al.* (2016) presented a five-step method for predicting porosity and permeability averages of prospective geothermal formations in Danish onshore areas with low data density. The method is based on the sandstone reservoir characteristics of the Gassum Formation from geological and petrophysical data acquired in deep wells. The main purpose was to reduce the uncertainties associated with prediction of reservoir properties.

The study presented here investigates the efficiency of the five-step method when applied to the Bunter Sandstone Formation. The study area extends from the west coast of Denmark to the east coast of southernmost Sweden, and from the Danish border with Germany to just north of the Ringkøbing–Fyn High (Fig. 1). Farther north, the Bunter Sandstone Formation grades into the partly contemporary Skagerrak Formation. Eighteen wells provided well-log and core-analysis data from the formation.

The five-step method

Kristensen *et al.* (2016) developed the five-step method by integrating well log data from the Gassum Formation with porosity and permeability measurements obtained from conventional core analysis (CCAL). The main concept behind the method is that the porosity is related primarily to depth, whereas the permeability depends on a range of parameters including porosity, mineralogy, grain size and sorting. Thus, if the burial depth for a particular potential reservoir layer is known, a relatively reliable porosity estimate may be derived (step 1). A permeability estimate may then be obtained from a porosity–permeability rela-



Fig. 1. The approximate extent of the Bunter Sandstone Formation in southern Denmark and adjacent areas (as delimited by the map frame), showing major structural elements and locations of investigated wells. Maps showing e.g. the extent, thickness and data sources of the Bunter Sandstone Formation are available from the WebGIS portal at the Geological Survey of Denmark and Greenland (<http://dybgeotermi.geus.dk/>).

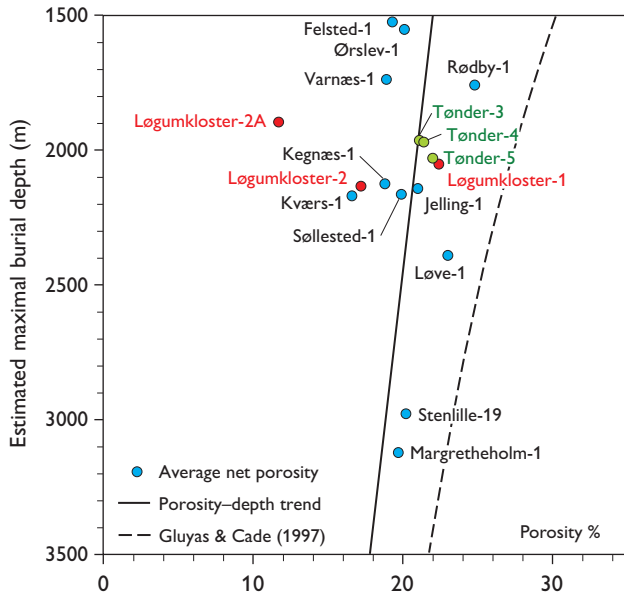


Fig. 2. Porosity–depth model (step 1) for the Bunter Sandstone Formation. The shown model (black line) is an estimate by the authors; the Løgumkloster wells were excluded from the model (see text) due to their location in a fault zone. A mechanical compaction curve (Gluyas & Cade 1997) is shown for comparison. Modified from Kristensen *et al.* (2016).

tion (steps 2–4), and finally, the uncertainty can be assessed (step 5). Therefore the depth of the sandstone layer is required. In areas with no wells, the depth can only be estimated from seismic data, which therefore indirectly control whether the five-step method can be applied. Below, the main components of the five steps are defined and explained; for a detailed description of the concept, refer to Kristensen *et al.* (2016).

Step 1: Porosity–depth model. In order to predict the porosity of a formation, a regional porosity–depth relation is established. Log-derived, effective porosity data subjected to cut-off by shale content (<30%) and porosity (>15%) are averaged for each well and plotted against estimated maximum burial depth. The resulting relation, the porosity–depth model, is expressed as $\phi_{\log} = a + b \times D$ (Equation 1), where ϕ_{\log} is the log-derived porosity, D is the burial depth and a and b are constants.

Step 2: Initial permeability model. An initial, basin-wide porosity–permeability relation based on core-analysis data is established in order to predict permeability. Subsequent to porosity cut-off (15%), this relation, i.e. the initial permeability model, is expressed as $k_{\text{ini}} = a \times \phi_{\text{core}}^b$ (Equation 2), where k_{ini} is the core-gas permeability, ϕ_{core} is the core porosity and a and b are constants.

Step 3: General permeability model. This model uses log-derived, averaged permeabilities with the purpose of incorporating a dataset encompassing the entire formation

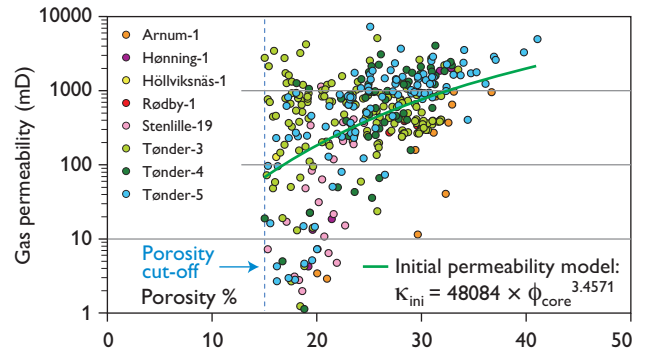


Fig. 3. Initial permeability model (step 2) for the Bunter Sandstone Formation.

and not only covering parts of the formation as is mostly the case with the core-based dataset used in step 2. Equation 2 is used to calculate permeability estimates from the log-derived porosity. Shale and porosity cut-offs of 30% and 15%, respectively, are applied. A cross-plot between log-derived and averaged porosity and permeability data points forms the basis for definition of a general permeability model expressed as $k_g = a \times \phi_{\log}^b$ (Equation 3), where k_g is the log-derived permeability, ϕ_{\log} is the log-derived porosity and a and b are constants.

Step 4: Local permeability model. The general permeability model is adapted to local conditions by multiplying Equation 3 with a constant, C . Thus, the general permeability model constitutes a template for the local permeability model, which may be expressed as $k_L = C \times k_G$ (Equation 4), where k_L is the local permeability.

Step 5: Permeability-uncertainty range. A local area featuring several wells with a sufficient amount of appropriate log data is selected and a local permeability model is established. The extensive source data ensure a statistically well-restrained model and a consistent uncertainty range, which is assumed to be applicable to local models within the same formation in other parts of the Danish area. Below, the results of applying the five-step method to the Bunter Sandstone Formation in Denmark are described.

Application of the five-step method

Fourteen wells (Fig. 1) provided data for the generation of a porosity–depth model for the Bunter Sandstone Formation (Fig. 2); data from the Løgumkloster-1, 2 and 2A wells were excluded because of their location in a fault zone (Fig. 1) where tectonic activity may have altered the sandstone properties.

The porosity–depth model (step 1). Unfortunately, the scattered data distribution prevented derivation of a mathematically defined trend line, and thus a reliable poros-

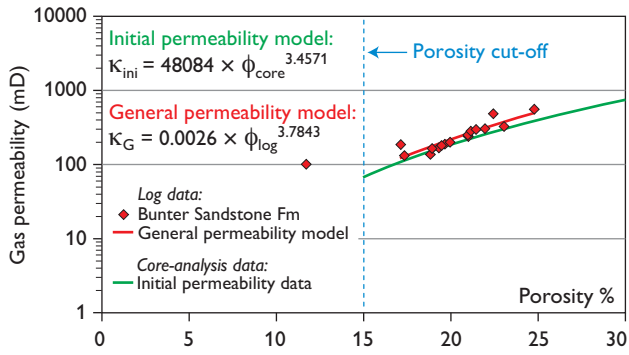


Fig. 4. Initial and general permeability models (steps 2, 3) for the Bunter Sandstone Formation after averaging the log-derived permeability and porosity.

ity–depth model could not be generated. The shown trend line is the authors’ best estimate based on their general experience and knowledge of petrographic characteristics and diagenetic overprints. The generation of a permeability–depth model was attempted as an alternative to the porosity–depth model, but without success as the scattered data distribution prevented establishment of a well-defined trend line.

The initial permeability model (step 2). Eight of the wells shown in Fig. 1 provided core-analysis data for the initial permeability model (Fig. 3). In order to generate a reliable porosity–permeability relation based on comparable measurements, only permeabilities obtained from cleaned, unflawed plugs of productive lithologies, measured under similar testing conditions were used. Data from uncleaned plugs and data points representing low permeabilities (<1 mD) and unproductive lithologies (claystone/shale) were removed from the dataset. Subsequently, shale and porosity cut-offs of 30% and 15%, respectively, were applied. The initial permeability model is based on 360 data points and is expressed by Equation 5: $k_{ini} = 48084 \times \phi_{core}^{3.4571}$, where k_{ini} is in mD and ϕ_{core} is in per cent.

The general permeability model (step 3). The log-derived permeability was calculated for 16 wells (Fig. 1) using Equation 5 with the log-derived porosity as input. Løgumkloster-2A was discarded due to porosity cutoff. Subsequently, the log-derived permeability was averaged and a cross-plot between averaged log-derived porosity and permeability was generated (Fig. 4). The general permeability model is expressed by Equation 6: $k_g = 0.0026 \times \phi_{log}^{3.7843}$ (Fig. 4). The introduction of the general permeability model imposes a slightly higher specific permeability estimate than that calculated from the initial permeability model, i.e., $k_g > k_{ini}$ (Fig. 4).

The local permeability model (step 4). Local permeability models were generated for the Tønder and Stenlille areas

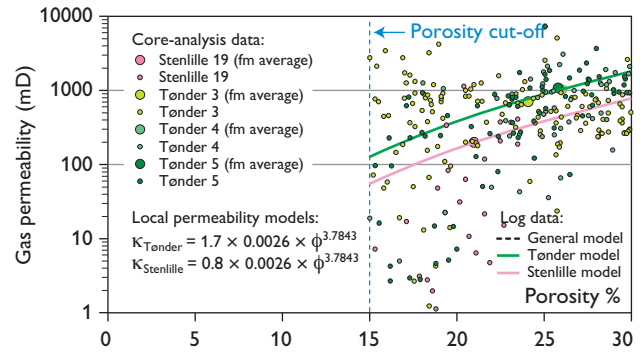


Fig. 5. Local permeability models (step 4) for the Bunter Sandstone Formation in the Tønder and Stenlille areas.

in order to demonstrate the variability of sandstone reservoirs within the Bunter Sandstone Formation (Fig. 5). For the Tønder area, the local permeability model is expressed as $k_{Tønder} = 1.7 \times (0.0026 \times \phi^{3.7843})$ (Equation 7) and for the Stenlille area as $k_{Stenlille} = 0.8 \times (0.0026 \times \phi^{3.7843})$ (Equation 8).

Permeability-uncertainty range (step 5). Only the Tønder area provides the data density needed for establishing an uncertainty range for a local permeability model. However, the number of data-supplying wells is limited to 3 (Tønder-3–5), and the statistical basis from the available Bunter Sandstone Formation data is insufficient to assess the uncertainty range.

Results and discussion

Porosities of the Bunter Sandstone Formation are lower than derived from the mechanical compaction curve for uncemented sandstones (step 1, Fig. 2), indicating that most of these sandstones contain clay and diagenetic cement (Kristensen *et al.* 2016). At greater depths, the sandstones preserve relatively high porosity due to microporosity within detrital clays and diagenetic iron oxide/hydroxide coatings that seemingly retard quartz cementation (Olivarius *et al.* 2015). Although a well-defined porosity–depth model (step 1) could not be created for the Bunter Sandstone Formation, the range of log-derived average porosities from 17% to 25% within the 1500–3100 m depth interval indicates favourable porosity conditions irrespective of maximum burial depth (Fig. 2). A corresponding averaged permeability range was calculated using the general permeability model (step 3, Equation 6) with 17% and 25% as porosity inputs. Within these bounds the permeability ranges from 132–557 mD (Fig. 6). From this observation, the geothermal prospectivity of the Bunter Sandstone Formation is significant, provided sufficient reservoir thickness and temperature are present.

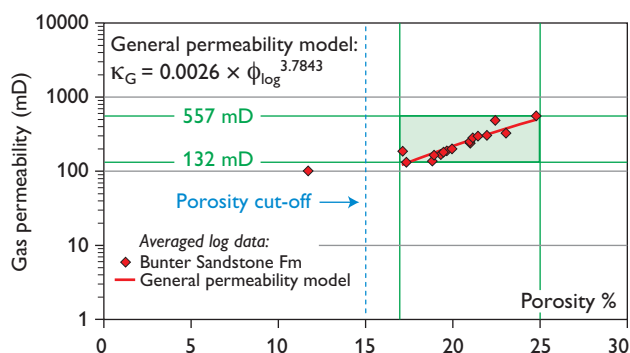


Fig. 6. Porosity and permeability range for the Bunter Sandstone Formation in the investigated wells in Denmark.

The vast majority of data behind the initial permeability model (k_{ini} , step 2) belong to the Tønder-3–5 wells. Therefore, k_{ini} represents the Tønder area rather than the entire study area. This data distribution issue was resolved by applying the averaging technique, whereby each well is represented by a single data point in the porosity–permeability plot. Thus, by using averaged data, each well becomes equally influential in the general permeability model (k_G , step 3), see Fig. 4. Further benefits of averaging the data are a dramatic reduction of the scatter of core-analysis measurements (Fig. 3) and a significant narrowing of the uncertainty band associated with average permeability estimates. In step 4, the local permeability models generated for the Tønder and Stenlille areas, $k_{Tønder}$ and $k_{Stenlille}$, demonstrate the importance of including local geological data when establishing local permeability models. At any porosity, $k_{Tønder}$ is 1.7 times higher than k_G and more than twice that of $k_{Stenlille}$. In contrast, $k_{Stenlille}$ is 0.8 times lower than k_G . These permeability variations may be explained by variations in deposition environment and maximum burial depth. At Tønder, aeolian deposition favoured the generation of well-sorted, clay-free sandstones which, subsequent to maximum burial of *c.* 2000 m, resulted in high average porosities and permeabilities (*c.* 22% and 300 mD, respectively); the presence of nitrogen gas may play a porosity-preserving role. At Stenlille, the sandstones were deposited in alluvial fan and braided river systems (Olivarius & Nielsen 2016) and maximum burial occurred at *c.* 3000 m, i.e. 1000 m deeper than at Tønder (Fig. 2), possibly causing the lower porosity (*c.* 19%) and permeability (*c.* 180 mD) due to poorer sorting and a higher degree of mechanical compaction and diagenesis.

It was not possible to establish a permeability uncertainty band for the Bunter Sandstone Formation (step 5). However, assuming that the Bunter Sandstone and Gassum Formations respond similarly to the geological factors controlling permeability variations, it is suggested that the uncertainty range derived for the Gassum Formation by Kristensen *et al.* (2016) is also applicable to the Bunter Sandstone Formation. Therefore, the uncertainty range may be expressed by multipliers of 2 and 0.5.

Conclusions

It was not possible to generate a reliable porosity–depth model (step 1) for the Bunter Sandstone Formation based on data and modelling from the Gassum Formation. However, using averaged porosities and permeabilities from all available wells (step 3), porosities from 17–25% and permeabilities from 132–557 mD can be modelled in the depth range 1500–3100 m. Local permeability models (step 4) for the Bunter Sandstone Formation in the Tønder and Stenlille areas differ significantly from the general permeability model (step 3), which emphasises the importance of using local geological data for calibration of the general permeability model. A permeability uncertainty band (step 5) could not be established for the Bunter Sandstone Formation due to insufficient data; however, the uncertainty range developed for the Gassum Formation in Kristensen *et al.* (2016) may be applied.

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