

Stratigraphy and geothermal assessment of Mesozoic sandstone reservoirs in the Øresund Basin

– exemplified by well data and seismic profiles

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The Øresund Basin in the transnational area between Sweden and Denmark forms a marginal part of the Danish Basin. The structural outline and stratigraphy of the Mesozoic succession is described, and a novel interpretation and description of the subsurface geology and geothermal potential in the North Sjælland Half-graben is presented. The subsurface bedrock in the basin includes several Mesozoic intervals with potential geothermal sandstone reservoirs. Parts of the succession fulfill specific geological requirements with regard to distribution, composition and quality of the sandstones. A characterisation of these is presently of great interest in the attempt to identify geothermal reservoirs suitable for district heating purposes. The results presented in this paper include for the first time a comprehensive description of the stratigraphic intervals as well as the characteristics of the potential Mesozoic geothermal reservoirs in the Øresund region, including their distribution, composition and physical properties. This is illustrated by seismic cross-sections and well sections. In addition, results from analyses and evaluations of porosity, permeability, formation fluids and temperature are presented. Six potential geothermal reservoirs in the Mesozoic succession are described and assessed. Primary focus is placed on the characteristics of the reservoirs in the Lower Triassic and Rhaetian–Lower Jurassic succession. The study shows that the Mesozoic reservoir sandstones vary considerably with respect to porosity and permeability. Values range between 5–25% for the pre-Rhaetian Triassic sandstones and are commonly >25% for the Rhaetian–Lower Jurassic and Lower Cretaceous sandstones. The corresponding permeability rarely reaches 500 mD for the pre-Rhaetian Triassic reservoirs, while it is commonly above one Darcy for the Rhaetian–Lower Jurassic and the Lower Cretaceous sandstones. The interpreted formation temperatures are 45–50°C at 1500 m, 60–70°C at 2000 m and 70–90°C at 2500 m depth. The combined results provide a geological framework for making site-specific predictions regarding appraisal of viable geothermal projects for district heating purposes in the region as well as reducing the risk of unsuccessful wells.

Keywords: Geothermal reservoirs, depth structure maps, formation fluids, porosity, permeability, temperature gradient, geothermal potential.

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The Øresund region includes the cities of Helsingør, Helsingborg, Landskrona, Malmö, Lund and Copenhagen (Fig. 1) and is the most densely populated region in Scandinavia with c. 3.8 million inhabitants. Despite favourable geological and socio-economical conditions, geothermal energy has not yet been uti-

lised to any great extent. So far only two of the cities, Copenhagen and Lund, have incorporated geothermal energy in their district heating systems, even though geological investigations have indicated significant possibilities for other urban areas and communities in the region (Mahler & Magtengaard 2010).

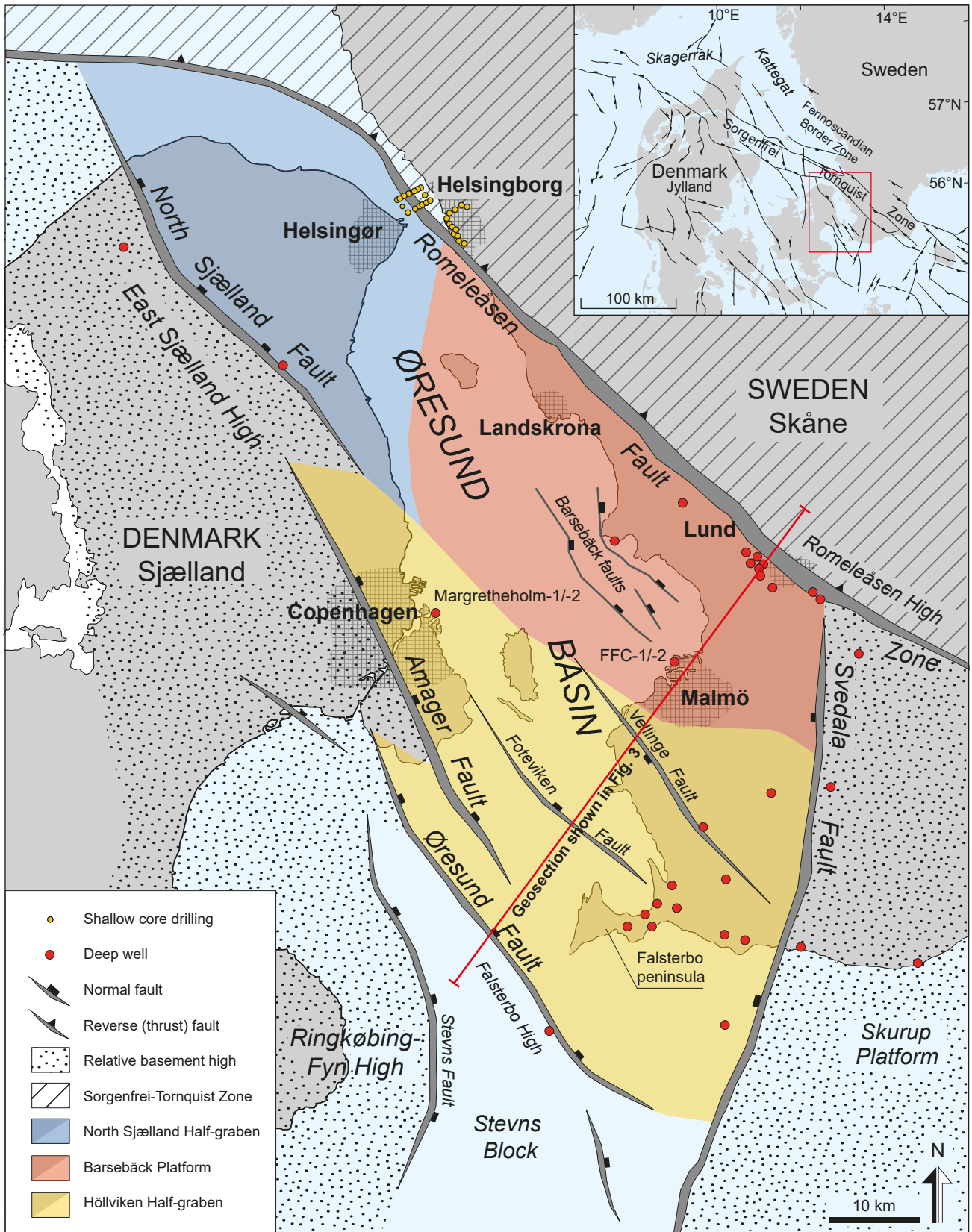


Fig. 1. Schematic structural map showing the location of the main structural elements in the Øresund Basin. Land areas have darker colours, sea-covered areas have lighter colours.

In accordance with the EU Renewable energy sources directive (Directive 2009/28/EC of the European Parliament and the Council), there is presently increasing interest in assessing and exploiting the geothermal resources from deep reservoirs, particularly in Denmark where several areas of geothermal potential have been identified (Nielsen *et al.* 2004; Mathiesen *et al.* 2009). Until now, 12 licenses for geothermal exploration in Denmark have been approved (Danish Energy Agency 2013). One of these license areas covers most of eastern Sjælland, including the urbanised zone between the cities of Copenhagen

and Helsingør along the Danish coastline of the sound Øresund. The geology of this area has been relatively poorly constrained, which has stressed the need for a comprehensive geological description and interpretation of the subsurface geology. Besides being a natural seaway between Denmark and Sweden, the Øresund has acted as a geographical barrier between the two countries. This is also apparent in geology where, traditionally, Swedish geologists have used one nomenclature for the lithostratigraphy of the Mesozoic succession and Danish geologists have used another. This has so far hampered correlation as well

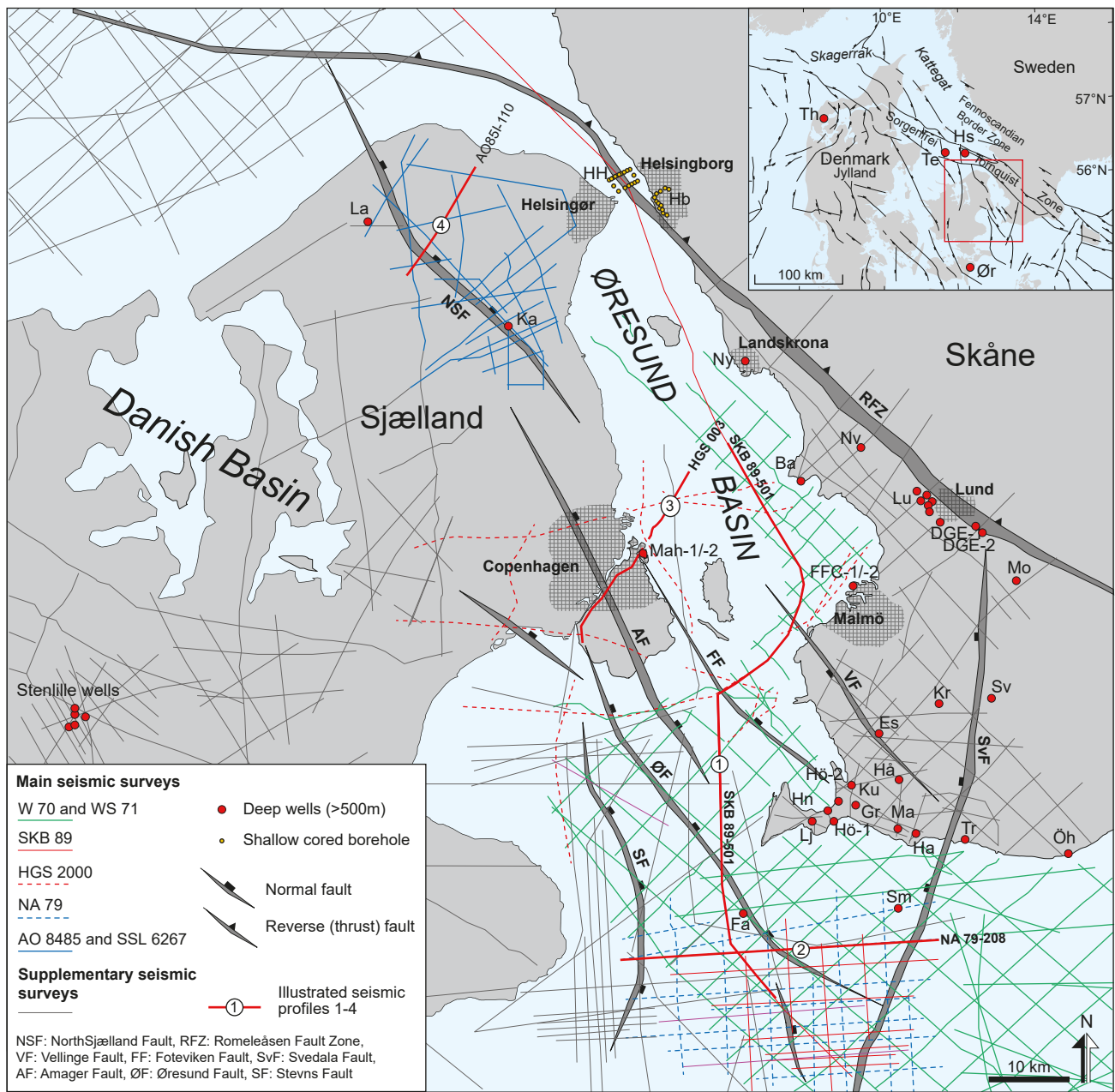


Fig. 2. Overview map showing locations of wells and seismic lines in the studied area. Locations of the profiles illustrated in Fig. 4 are also shown. The well abbreviations are explained in Table 1.

Table 1. Summary of well information including operator, year of drilling, total depth and reached stratigraphic level

Borehole	Abbreviation in Fig. 2	Total depth, metres below mean sea level	Reached stratigraphic level	Operator/year
Barsebäck-1	Ba	2255	Precambrian	OPAB/1972
DGE-1	DGE-1	3673	-“-	Lund Energy AB/2003
DGE-2	DGE-2	1901	-“-	Lund Energy AB/2004
Eskilstorp-1	Es	2463	L. Cambrian	OPAB/1971
Falsterborev-1	Fa	1396	L. Cambrian	OPAB/1973
FFC-1	FFC-1	2100	Precambrian	Sydkraft/EON/2002
FFC-2	FFC-2	2110**	-“-	EON/2003
Granvik-1	Gr	1254*	L. Cretaceous	Nordstjernan/1947
Hans-1	Hs	3028	U. Carboniferous	DUC/1983
Hammarlöv-1	Ha	2369	L. Cambrian	OPAB/1971
Helsingborg	Hb	30–40	Rhaetian–Hettangian	Helsingborg city/2006, 2009
Helsingør-Helsingborg	HH	40–120	Jurassic–Cretaceous	Geoteknisk Institut/1968
Håslöv-1	Hå	2554	L. Cambrian	OPAB/1972
Höllviken-1	Hö-1	1411	U. Jurassic	SGU/1941–43
Höllviken-2	Hö-2	1919	L. Triassic	SGU/1943–47
Höllviksnäs-1	Hn	2605	L. Cambrian	OPAB/1971
Karlebo-1/1A	Ka	2260**	U. Triassic	Tethys Oil/2006
Kungstorp-1	Ku	2066	L. Triassic	OPAB/1971
Lavø-1	La	2413	-“-	DAPCO/1959
Kruseberg	Kr	508	U. Cretaceous	Swedegas AB/1994
Ljunghusen-1	Lj	2276	Silurian	SGU/1954–55
Lund wells	Lu	611–802	Campanian	Lund Energy/1981–85
Margretheholm-1	Mah-1	2677	Precambrian	HGS, DONG/2002
Margretheholm-2	Mah-2	2750**	-“-	HGS, DONG/2003
Maglarp-1	Ma	1938	Silurian	OPAB/1971
Mossheddinge	Mo	1785	Precambrian	OPAB/1973
Norrevång-1	Nv	2127	-“-	OPAB/1971
Nyhem-1	Ny	1068	Santonian	Lund University/1981
Smygehuk-1	Sm	1660	Silurian	OPAB/1973
Svedala-1	Sv	1628	-“-	SGU/1948–51
Terne-1	Te	3361	L. Cambrian	Amoco/1985
Thisted-3	Th	1208	U. Triassic	DONG/1983
Trelleborg-1	Tr	1201	L. Cretaceous	SGU/1947
Ørslev-1	Ør	2537	Carboniferous	DUC/1968
Östratorp hamn	Öh	338	U. Cretaceous	SGU/1948

* Depth from rotary table ** Deviated well, depth converted to true vertical depth

Table 2. General information regarding the main seismic surveys on which the subsurface characterisation of the Øresund Basin has been performed

Seismic survey	Company	Acquisition date	Quality	Format
W 70	OPAB	September 1970	Fair	Scanned jpg
SKB 89	SECAB	May 1989	Good	Scanned jpg
WS 71	OPAB	June–August 1971	Fair	Scanned jpg
NA 79	OPAB	May–July 1979	Good	Scanned jpg
HGS 2000	DONG	2000	Excellent	SEGY
AO 8485	Phillips Petroleum	1984–85	Fair-poor	SEGY
SSL 6267	Mærsk Oil	1962–67	Poor	Scanned jpg

as assessment of potential geothermal reservoirs, but with increasing demands for geothermal energy an evaluation of these reservoirs is warranted (Nielsen *et al.* 2004; Mahler & Magtengaard 2010; Røgen *et al.* 2015). In addition, there is a need for characterising the lateral changes in lithofacies in the Mesozoic succession across the Øresund region, i.e. between the distal and marginal parts of the Danish Basin, and to establish a stratigraphic framework for these deposits.

The aims of this paper are, firstly, to describe the geological setting and geothermal properties of the Mesozoic reservoirs and provide an assessment of the geothermal potential, and secondly to contribute to the geoscientific understanding of the Øresund Basin in order to reduce the geological risks of unsuccessful geothermal wells.

Data and Methodology

By utilising the gearchives at the Geological Survey of Denmark and Greenland (GEUS) and the Geological Survey of Sweden (SGU), a comprehensive database combining Danish and Swedish seismic surveys and well data has been compiled (Fig. 2; Tables 1 and 2). This includes, for the first time, previously unpublished petrophysical and hydraulic properties of the reservoirs. Most of the information comes from well data and seismic surveys acquired between 1960 and 2003. Consequently, the data varies considerably with regard to format, quality and extent.

Seismic data set

The southern and central part of the studied area is covered by a relatively dense grid of seismic surveys, in contrast to the north-eastern part of Sjælland and the area between Helsingør and Landskrona, where seismic lines are few (Fig. 2). Most of the Swedish seismic surveys consist of low resolution data acquired during the 1970s (WS 71 and W 70 surveys). Relatively high quality surveys (NA 79 and SKB 89) exist in the southernmost part of the investigated area (Fig. 2). The SKB 89-501 line is a key line that transects the central part of the Øresund Basin and enables the tracing of marker horizons across the southern, central and northern parts of the Øresund Basin. Older analogue seismic lines have been digitised and integrated with the newer lines in SEG-Y format, a standard format for storing geophysical data established by the Society of Exploration Geophysicists (Hagelund & Levin 2017). The seismic data also include the HGS 2000 survey, which was performed for geothermal purposes around Copenhagen and Malmö and in the

sea between the two cities (Fig. 2). In addition, a set of older survey lines (AO 8485 and SSL 6267) located on northern Sjælland were reprocessed, which increased the quality and usefulness of the data. A compilation of pertinent survey data included in the study is shown in Table 2.

The depth maps presented here were constructed using the combined Danish and Swedish seismic data. Interpretation and seismostratigraphic mapping was performed by tracing marker horizons in wells in the western, eastern and southern parts of the study area, namely the Karlebo-1/1A, Margrethholm-1 and -2, Stenlille-19, Falsterborev-1, Smygehuk-1 and Ørslev-1 wells (Fig. 2).

Well data

A substantial amount of well information is derived from cored boreholes on the Falsterbo peninsula drilled by the Geological Survey of Sweden (SGU), and from hydrocarbon exploration wells in south-west Skåne drilled by the Swedish Oil and Gas Prospecting Company (OPAB) during the 1970s. More recently, comprehensive data obtained from four geothermal project wells drilled in Copenhagen (Margrethholm-1 and -2) and Malmö (FFC-1 and -2) in 2002–2003, a hydrocarbon exploration well (Karlebo-1/1A) drilled in 2006 in northern Sjælland, geothermal wells in the Lund area (1981–1985) and shallow cored boreholes in Helsingborg (2006–2009) have provided additional data (Table 1).

Results from geophysical wire-line logging obtained during the different drilling operations have been valuable, as amounts and quality of available geological material (cores and cuttings), analytical results and descriptions from the boreholes vary greatly.

Bottom hole temperature data primarily come from recordings performed during the wire-line logging operations. Data from two temperature profiles performed in FFC-1 and Ljunghusen-1 were recorded after drilling and reflect normalised temperature conditions.

Porosity and permeability measurements performed on sandstone beds in the cored boreholes (Höllviken-1, -2 and Ljunghusen-1), sidewall cores (FFC-1 well), and from outcrops and cores in the Helsingborg area, have provided actual data on these properties and have also been used for calibration of the geophysical wire-line log data (Springer 1997; Hjuler *et al.* 2014).

Data on formation fluids and gases were gathered from unpublished reports on performed analyses in the geothermal projects in Malmö and Lund (Bjelm & Alm 1995; Laier 2003).

The stratigraphic framework used for the correla-

tion of the different Mesozoic sandstone reservoirs in the Øresund Basin is largely based on palynological data presented in Lindström & Erlström (2011) and Lindström *et al.* (2017).

Geological setting

The Øresund Basin constitutes a local structure within the Danish Basin and is located in the transition zone between the Danish Basin to the west and south-west and the Fennoscandian Shield to the north-east. The subsurface bedrock in this transnational area between Sweden and Denmark is composed of a several kilometres thick succession of Phanerozoic strata overlying the Precambrian crystalline basement. Lower Palaeozoic strata in the area are so far only verified in parts of the Höllviken Half-graben (Figs 3, 4, 5). The Danish Basin formed as a result of Late Carboniferous–Early Permian rifting (Sørensen 1986; Liboriussen *et al.* 1987; Vejrbæk 1997). Due to the Sorgenfrei-Tornquist Zone (STZ) bordering the Øresund Basin to the north-east, Late Palaeozoic to Cenozoic deposits in this area reflect a complex tectonic history including periods of extension as well as compression of the bedrock in this marginal eastern part of the Danish Basin (e.g. Erlström *et al.* 1997; Nielsen 2003). The NW–SE oriented STZ is characterised by extensive block-faulting along the south-western margin of the Fennoscandian Shield (Sorgenfrei & Buch 1964; Rolle *et al.* 1979; Liboriussen *et al.* 1987). The STZ has been repeatedly active since Late Palaeozoic times with the main events occurring during the Mesozoic Era. Several Triassic–Jurassic extensional episodes are recognised (Norling & Bergström 1987), but these and older Palaeozoic events are often obscured due to Late Cretaceous–Palaeogene inversion tectonics (Norling & Bergström 1987; Michelsen & Nielsen 1991, 1993; Mogensen 1994; Michelsen 1997; Erlström *et al.* 1997; Mogensen & Korstgård 2003). The western and south-western margin of the Øresund Basin is outlined by the Øresund, Amager and North Sjælland faults and the East Sjælland High (Fig. 1).

The structural outline of the Øresund Basin is controlled by a set of right-stepping normal extension faults to the west and by the reverse Romeleåsen Fault Zone to the east, which constitutes the boundary to the STZ. The normal faults to the west were initiated during Carboniferous–Permian rifting and reactivated during Triassic E–W tension (Erlström *et al.* 1997; Sivhed *et al.* 1999). Extension and subsidence in the Early and Middle Triassic resulted in localised accommodation space and thickening of the corresponding strata towards the delimiting faults,

especially the Øresund, Amager and North Sjælland faults. The displacements on the faults vary as the individual fault dies out laterally. This is especially seen along the Øresund Fault which dies out to the north-north-west and the North Sjælland Fault where the displacement fades out to the south-south-east. A geo-section illustrating main tectonic events and stratigraphical representation in a SW–NE oriented transect across the southern parts of the Øresund Basin is presented in Fig. 3.

The marginal position of the Øresund Basin, with the Fennoscandian Border Zone and the Sorgenfrei-Tornquist Zone to the north-east, has resulted in the formation of a Mesozoic sedimentary succession that is largely composed of deposits formed in shallow marine to fluvial environments. This has resulted in several sandstone-dominated intervals with potential as geothermal reservoirs.

During Triassic–Jurassic time, erosion of the Fennoscandian Shield delivered material to the thermally controlled, post-rift subsiding Øresund and Danish basins (Liboriussen *et al.* 1987; Vejrbæk 1989; Erlström *et al.* 1997).

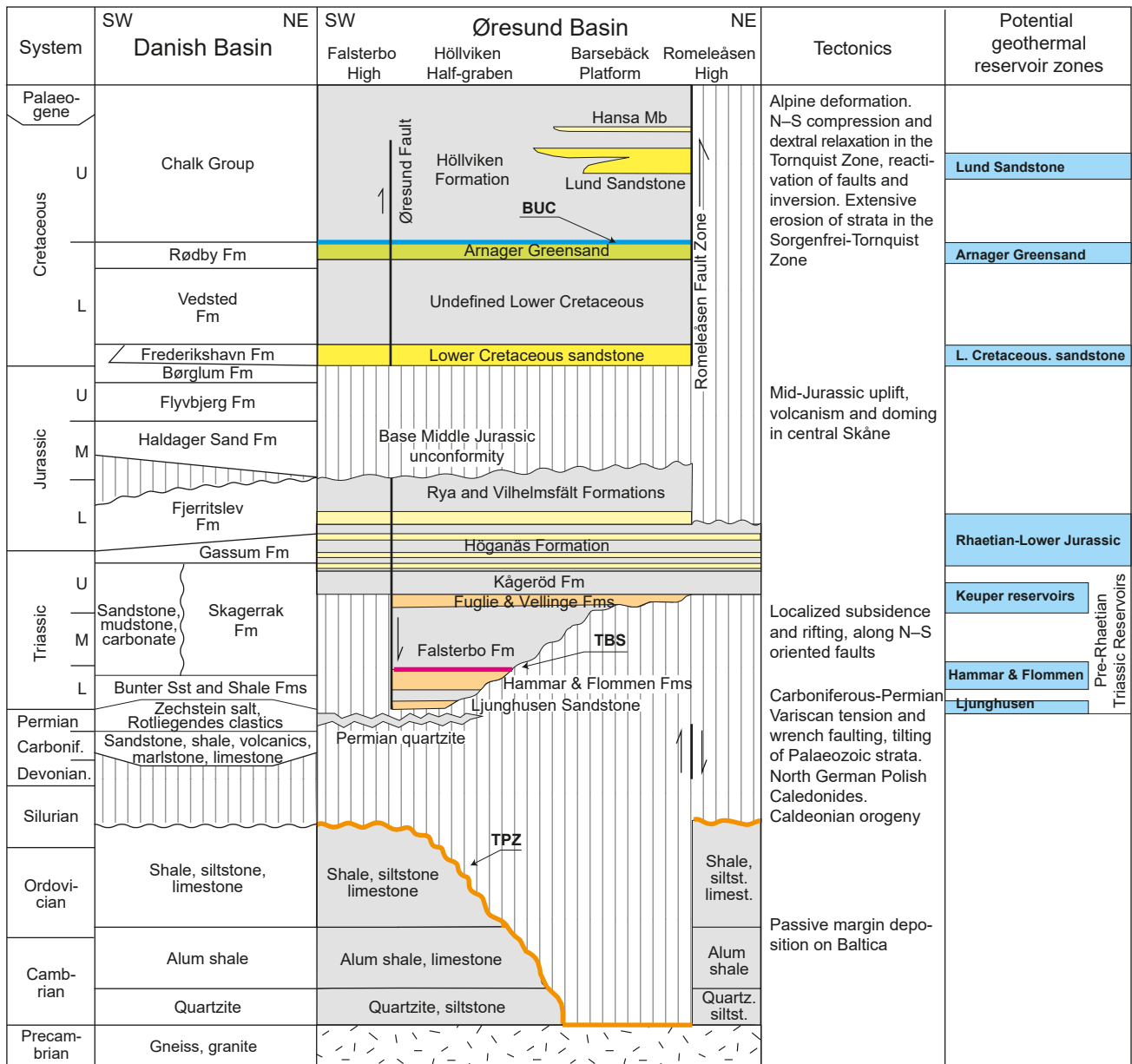
The Øresund Basin is divided into the Höllviken Half-graben, the Barsebäck Platform and the North Sjælland Half-graben (Fig. 1). The Barsebäck Platform constitutes a transfer zone between the North Sjælland and Höllviken half-grabens. The platform is characterised by horizontally bedded strata and a relatively thin Triassic succession overlying the Precambrian basement, in contrast to the Höllviken Half-graben which displays successively increasing thicknesses and representation of strata towards the Øresund, Amager and North Sjælland faults. (Figs 3, 4).

Interpreted key profiles

The general subsurface structure of the Øresund Basin is illustrated by four interpreted seismic key profiles (Fig. 4). Profile 1, oriented N–S through the southern part of the Øresund Basin, displays the lateral variation of thicknesses and stratigraphic representation of the sedimentary succession, as the profile crosses not only the Barsebäck Platform but also the Höllviken Half-graben and the Øresund Fault (Fig. 4). The profile, which corresponds to a large part of the SKB 89-501 line, displays a southward dipping and thickening pre-rift Lower Palaeozoic succession in the Höllviken Half-graben, as well as a syn-rift Triassic succession with increasing thickness towards the Øresund Fault. The data shows that the Triassic–Jurassic succession is relatively thin (c. 350 m) on the Barsebäck Platform, whereas it is up to 700 m thick adjacent to the Øresund

Fault. A corresponding, however less pronounced, lateral increase in thickness of the Jurassic–Lower Cretaceous interval towards the Øresund Fault is also indicated in the interpreted profile (Fig. 4). The

Upper Cretaceous–Palaeogene succession increases in thickness towards the Romeleåsen Fault Zone. This is verified by an up to 1800 m thick Upper Cretaceous–Palaeogene succession in the Barsebäck-1 and



Potential geothermal reservoirs

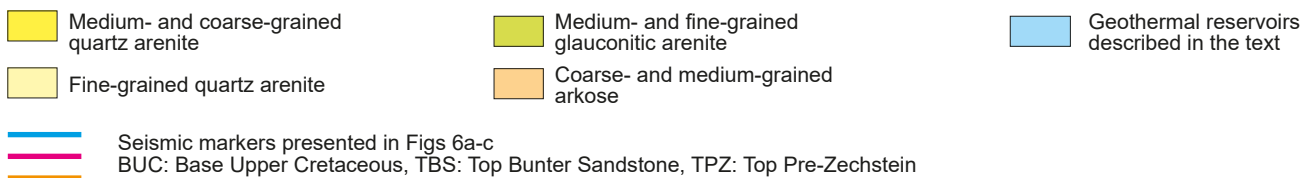


Fig. 3. Geo-section of the Øresund Basin representing a section from the north-east to the south-west, covering the southern parts of the basin. The location is shown in Fig. 1. For comparison, the lithostratigraphic division of the Danish Basin is summarised in a separate column. The right column shows the position of the potential geothermal reservoir intervals which are discussed in the text.

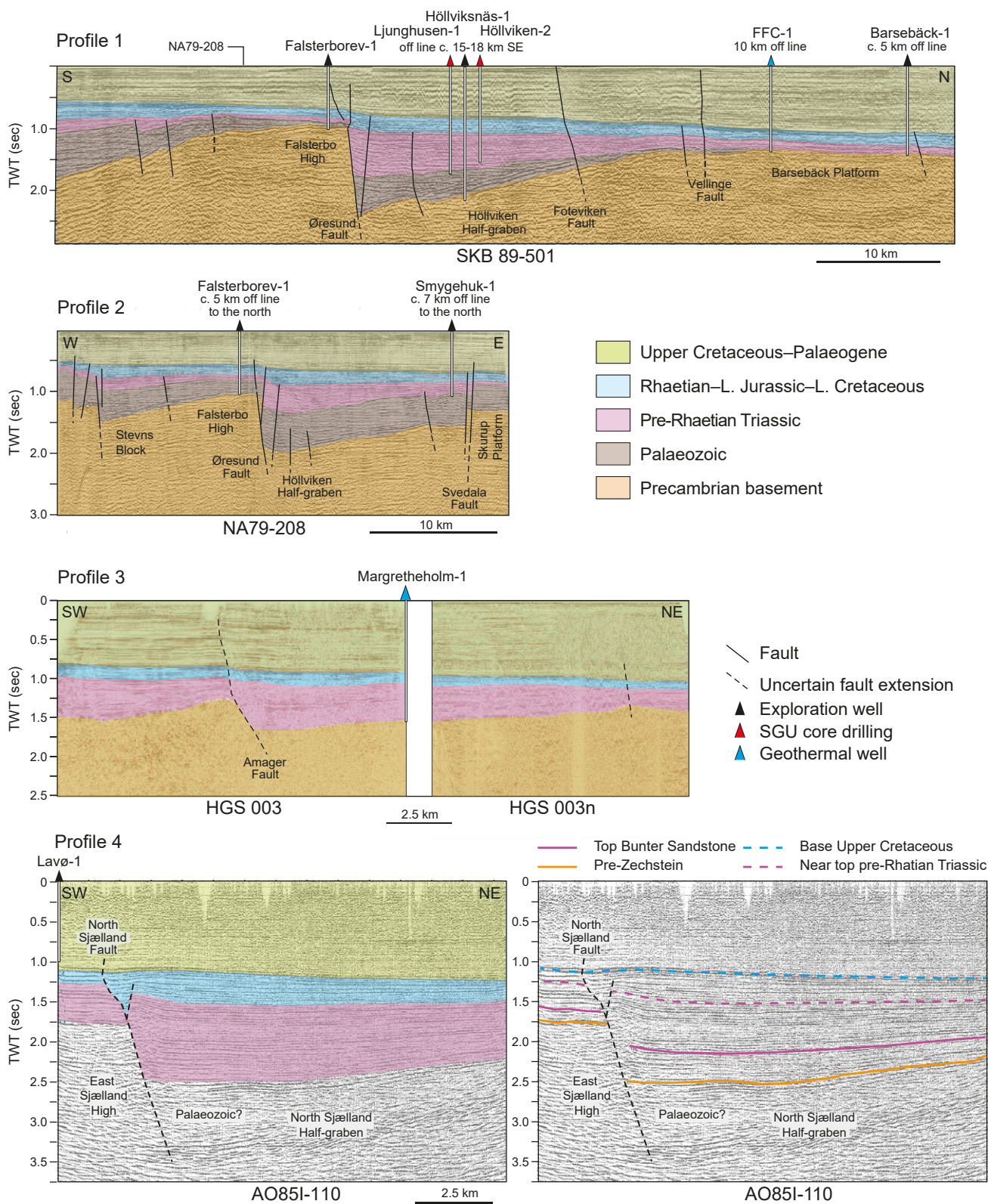


Fig. 4. Interpreted profiles 1–4 based on the seismic lines SKB 89-501, NA79-208, HGS003 and AO851-110. The profile on northern Sjælland is also illustrated with the marker horizons shown. The profile locations are shown in Fig. 2.

Norrevång-1 wells adjacent to the Romeleåsen Fault Zone (Sivhed *et al.* 1999), while the same interval is only c. 900 m thick in the south part of the profile, e.g. in the Falsterbørev-1 well (Fig. 5). This lateral variation is caused by greater subsidence in the eastern parts of the Øresund Basin, linked to Late Cretaceous to Palaeogene inversion of the Sorgenfrei-Tornquist Zone. This has created accommodation space for a several hundred metres thick syn-tectonic Campanian sandstone (the Lund Sandstone) adjacent to the Romeleåsen Fault Zone, and here this sandstone contributes significantly to the total thickness of the Upper Cretaceous (Erlström 1994; Erlström *et al.* 1997).

The Na 79-208 line (Fig. 4, profile 2) crosses the south parts of the Höllviken Half-graben perpendicular to profile 1. The Lower Palaeozoic succession is here clearly visible in the seismic data, as is the increasing thickness of the pre-Rhaetian Triassic succession against the Øresund Fault. A similar lateral increase in thickness is also seen in the gently dipping Stevns Block west of the Falsterbo High towards the Stevns Fault. The seismic data also indicate that the Triassic as well as the Jurassic–Lower Cretaceous succession is <200 m thick on the Skurup Platform. In the Svedala-1 well, the pre-Rhaetian Triassic succession is only 66 m thick (Erlström & Sivhed 2012) and the Jurassic–Lower Cretaceous succession is 86 m thick, including the Cenomanian Arnager Greensand (Sivhed *et al.* 1999).

The interpretation of the HGS 003 line (Fig. 4, profile 3) is largely based on data from the Margretheholm (Mah-1/-2) geothermal wells. The profile shows a similar thickening of the pre-Rhaetian Triassic succession towards the Amager Fault as observed towards the Øresund Fault in profile 1. This is mainly due to increased thickness of the Lower and Middle Triassic strata, which is verified in the Mah-1/-2, Ljunghusen-1, Höllviksnäs-1 and Höllviken-2 wells. Profiles 1 and 3 show a gently dipping half-graben with only minor faulting outside the main delimiting faults. Similar subsurface structures and depths are also indicated in profile 4 in the northern part of the Øresund Basin; this profile extends over parts of the North Sjælland Half-graben and crosses the North Sjælland Fault (Fig. 4). The seismic signature is interpreted to represent a sedimentary succession similar to that in the Höllviken Half-graben. It is significant that the seismic data indicates an even thicker Triassic succession in comparison to the Höllviken Half-graben, reaching perhaps a total thickness in excess of 1000 m. Furthermore, the seismic signature indicates that there may be an up to 6500 m thick sedimentary succession in the deepest parts of the North Sjælland Half-graben. This suggests the presence of thick Palaeozoic deposits underlying the Triassic, similar to the geological setting in the Höllviken Half-graben (Fig. 4, profiles 1 and 2).

Well correlation

The seismic profiles were carefully matched with stratigraphical and geophysical data from several wells, especially the geothermal wells Mah-1/-2 and FFC-1/-2 in Copenhagen and Malmö, but data from Falsterbørev-1, Höllviksnäs-1, Barsebäck-1 and Karlebo-1/1A were also important. A well-log panel for these wells displays the drilled pre-Upper Cretaceous sedimentary succession, which shows a heterogeneous Triassic–Lower Cretaceous succession with several rock types represented (Fig. 5). Significant lateral variation is evident within the pre-Rhaetian Triassic interval, as well as changes in thickness of the Rhaetian–Jurassic interval. In contrast, the Lower Cretaceous strata appear more consistent in thickness, with e.g. the Lower Cretaceous sandstone beds and the Cenomanian Arnager Greensand displaying a more uniform regional distribution than what is observed for the underlying succession.

Individual beds, especially in the Triassic–Lower Jurassic interval, are difficult to correlate between wells due to frequent lateral shifts in lithofacies in the proximal depositional setting. There is, however, an overall greater proportion of geothermally interesting sandstone beds in the pre-Rhaetian succession that can be correlated between wells, *i.e.* the Lower Triassic Ljunghusen Sandstone, the Hammar–Flommen Formations and the Middle Keuper Vellinge Formation (Fig. 3).

Depth structure maps

Three marker horizons (Fig. 3): the Top Pre-Zechstein, the Top Bunter Sandstone Formation (corresponding to the Hammar and Flommen Formations in the Øresund Basin) and the base Chalk/Upper Cretaceous have been mapped and are presented as depth maps in Figs 6a–c. One additional map shows the gross thickness of the Base Chalk/Upper Cretaceous–Top Pre-Zechstein interval (Fig. 6d), the purpose of which is to visualise the gross thickness of the interval in which the various potential geothermal reservoirs described in this paper are found, with the exception of the Upper Cretaceous Lund Sandstone.

Top Pre-Zechstein surface

The Top Pre-Zechstein surface occurs at depths varying from 1100 m to 6500 m (Fig. 6a). Its shallowest levels are in the southern part of the study area approaching the Ringkøbing-Fyn High, and in the central part of the area on the East Sjælland High.

The Top Pre-Zechstein surface is found at its deepest level in the North Sjælland Half-graben adjacent to the North Sjælland Fault and in an area in the south in the Höllviken Half-graben close to the Øresund Fault (Fig. 6a). The outline of the Top Pre-Zechstein surface is intersected by several normal faults (Ste-

vns, Øresund, Amager, North Sjælland, Foteviken, Vellinge and Svedala faults). These faults are oriented NW–SE, however, the Svedala Fault in the easternmost part of the area is oriented more or less N–S. The faults and their interpreted offset on the individual seismic profiles, together with the depth to the Top

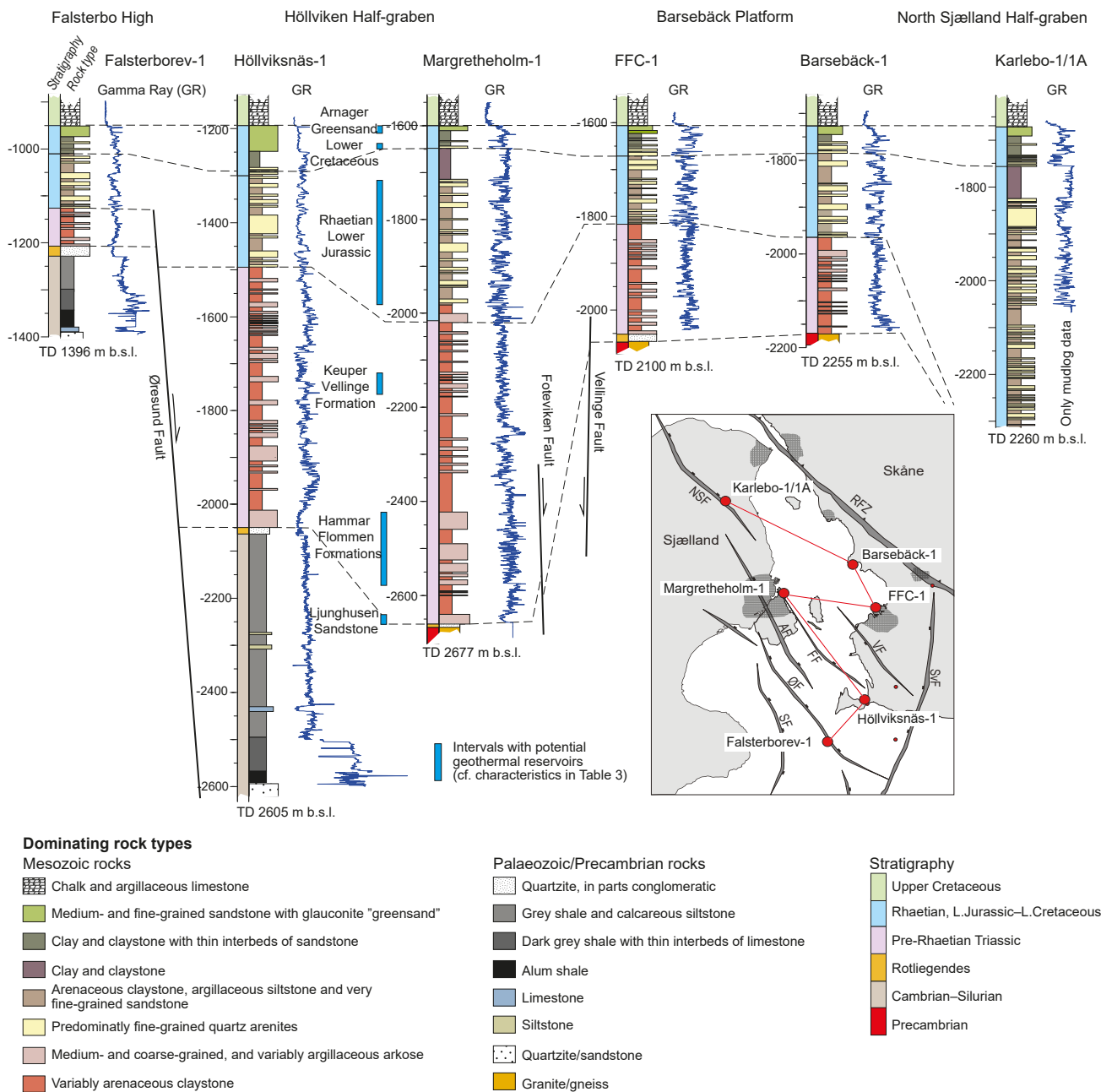


Fig. 5. Illustration showing a stratigraphic well correlation panel including the wells Karlebo-1/1A, Barsebäck-1, FFC-1, Margretheholm-1, Höllviksnäs-1 and Falsterborev-1. The wells illustrate the sedimentary succession in different parts of the area, *i.e.* the Höllviken Half-graben, the Barsebäck Platform and the North Sjælland Half-graben. The well paths are flattened to the top Arnager Greensand, *i.e.* top Cenomanian. The correlation is based on a combination of data from well site geology reports, geophysical wire line logs and biostratigraphical data (e.g. Lindström & Erlström 2011). The main geothermal reservoir intervals are presented for the Margretheholm-1 well. Their characteristics are summarised in Table 3.

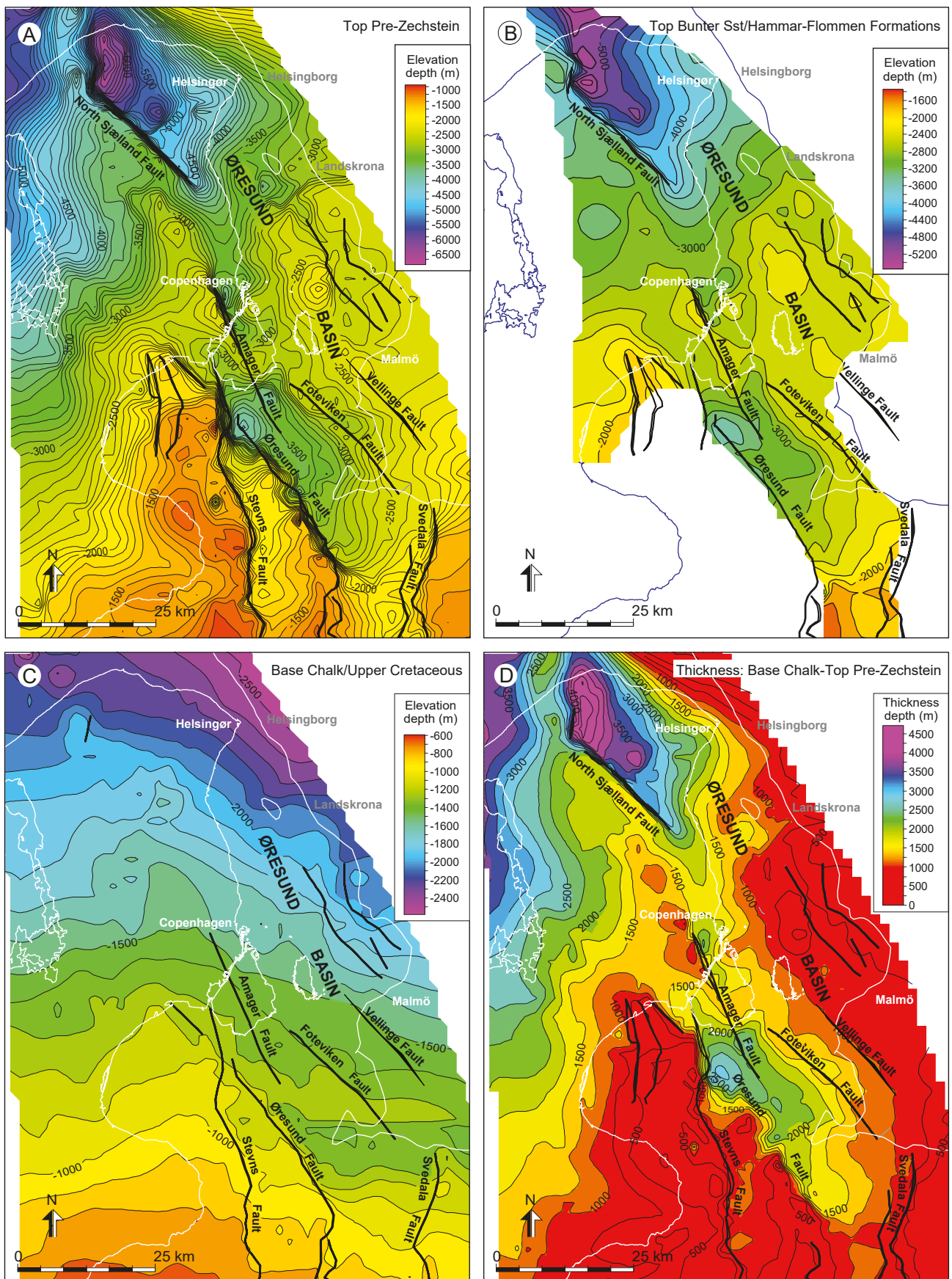


Fig. 6. Depth maps. A: Top Pre-Zechstein. B: Top Bunter. C: Base Chalk/Upper Cretaceous. D: Map illustrating the gross thickness of the interval between the Top Pre-Zechstein and Base Chalk/Upper Cretaceous, in which the assessed potential geothermal reservoirs are found, except for the Upper Cretaceous Lund Sandstone.

Pre-Zechstein, show that most faults are organised in arrays. This influences the depth map by causing an irregular depth pattern of the Top Pre-Zechstein reflector, especially close to the faults. The depth map shows several half-grabens that are generally down-faulted to the west (Fig. 6a). As exemplified by profile 1 in Fig. 4, the lower part of the Triassic exhibits onlap towards the successively elevated Top Pre-Zechstein surface which corresponds to the Top Palaeozoic or the Top Precambrian. Only the uppermost part of the Triassic succession is more uniformly distributed in the Øresund Basin.

Top Bunter Sandstone Formation (Top Hammar–Flommen) surface

In the Danish Basin, the Top Bunter surface corresponds to the top or near top of the Bunter Sandstone Formation. Eastward tracking of this seismic reflector into the Øresund Basin is complicated by a change in acoustic impedance caused by the transition between claystone and sandstone beds near the top of the Hammar and Flommen Formations.

The Top-Bunter surface onlaps the Top Pre-Zechstein surface on the flanks of the Ringkøbing Fyn High and the East Sjælland High (Figs 1, 6b). Consequently, the Bunter Sandstone Formation is thin or absent immediately south-west of the Øresund Fault. Towards the north, the Top-Bunter surface can be traced west and east of the Amager and North Sjælland faults. Its deepest level occurs in a NNW–SSE oriented area delimited to the west by the Øresund, Amager and North Sjælland faults. The surface is located at its deepest level in the deepest parts of the half-grabens outlined by the Top Pre-Zechstein reflector (Fig. 6b).

Base Chalk/Upper Cretaceous surface

In the Øresund Basin, the Base Chalk surface corresponds to the base of the Upper Cretaceous (*i.e.* Höllviken Formation; Sivhed *et al.* 1999). It represents a pronounced reflector occurring at the interface between the Arnager Limestone and the Arnager Greensand and is present throughout the study area. The surface reaches its highest level close to the Ringkøbing-Fyn High and the East Sjælland High (Fig. 1). The Base Chalk/Upper Cretaceous surface exhibits a general dip towards the NE in the Øresund Basin (Fig. 6c). It is intersected by a few faults in the southern part of the study area between the Øresund and Svedala faults, with minor offsets affecting the lower third of the Upper Cretaceous succession (profile 1, Fig. 4). Farther to the north, e.g. around the Amager Fault, the seismic profile indicates subsequent inversion. Faulting appears to have taken place later, as the Chalk

strata only appear affected within approximately 50 m depth below the sea floor.

Gross thickness of the Base Chalk/Upper Cretaceous–Top Pre-Zechstein interval

In the Øresund Basin, this interval commonly ranges between 500 m and 2000 m in thickness. East of the East Sjælland High there are two depocentres where thicknesses exceed 2500 m, namely the North Sjælland Half-graben and the Höllviken Half-graben. These are separated by the Barsebäck Platform which exhibits a much thinner succession (Fig. 6d). The northern depocentre, the North Sjælland Half-graben, is delimited by the North Sjælland Fault and the gross thickness here is interpreted to be as much as 4500 m (Fig. 6d). The Höllviken Half-graben depocentre can be subdivided into three parts. One part is located adjacent to and along the Øresund Fault. The maximum thickness of the Base Chalk/Upper Cretaceous–Top Pre-Zechstein interval is here about 2700 m. The second part of the Höllviken Half-graben depocentre is bounded by the Amager Fault to the west, and the maximum thickness of the Base Chalk/Upper Cretaceous–Top Pre-Zechstein interval is here close to 2300 m. To the north along the Amager Fault a third subarea of the Höllviken depocentre is outlined by the seismic data. Here the maximum thickness is estimated to reach 1800 m, decreasing towards the north-east. The depocentres related to the Amager Fault display different seismic characteristics indicating a somewhat variable geological development, possibly involving a separation of the Amager Fault into two fault segments, at least periodically.

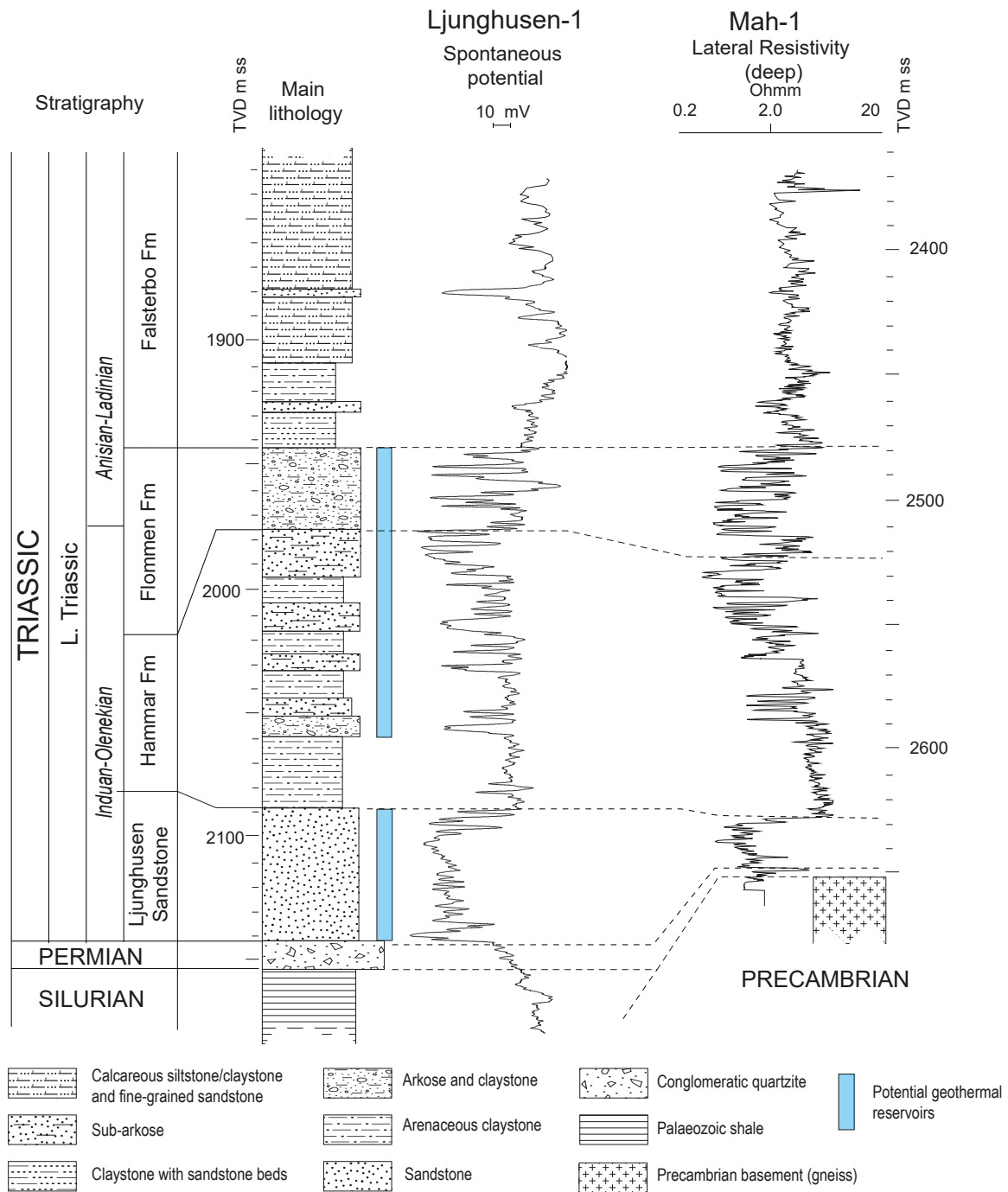
Geothermal reservoirs in the southern and central part of the Øresund Basin

Pre-Rhaetian Triassic reservoirs

The lithostratigraphic subdivision of the Triassic in the Øresund Basin corresponds in many parts to the German-type Facies Province and the Danish Basin (Bertelsen 1980; Beutler & Schüler 1987; Beutler 1998; Michelsen & Clausen 2002; Erlström & Sivhed 2012). However, it is difficult to fully extrapolate the German stratigraphy into the Øresund Basin, mainly due to its predominantly proximal position compared to the North German and Danish basins (Erlström & Sivhed 2012). There is a pronounced lack of biostratigraphically important fossils in the Øresund Basin, which hampers age dating and correlation. However, a few

marker beds in the Höllviken Half-graben have been identified, and these provide correlation of at least parts of the Triassic succession to the German-type Facies Province and stratigraphy (Erlström & Sivhed 2012). One example is the Falsterbo Formation in Skåne and equivalent beds in the Danish Basin and

Danish Central Graben which have been assigned a late Ladinian–early Carnian age based on palynology (Bertelsen 1975; Piasecki 2005; Lindström *et al.* 2009; Lindström *et al.* 2017). In the Höllviken Half-graben these sediments consist of argillaceous, dark grey beds with coal fragments and thin coal layers, which inter-



TVD m ss: True Vertical Depth in metres below sea level

Fig. 7. Composite well log panel of Ljunghusen-1 and Margrethholm-1 (Mah-1), illustrating the main lithology and selected electrical log responses for the Lower–Middle Triassic Ljunghusen Sandstone and Hammar–Flommen reservoirs.

rupt the otherwise reddish argillaceous–arenaceous and poorly sorted pre-Rhaetian Triassic succession (Erlström & Sivhed 2012). The palynofloras enable correlation between the Falsterbo Formation and the Lower Keuper Erfurt Formation, also named Lettenkohle or Lettenkeuper (Beutler & Schüler 1987; Beutler 1998; Piasecki 2005).

The possibly continuous Triassic succession in the Höllviken Half-graben is exemplified by a thick pre-Rhaetian Triassic succession in the wells Ljunghusen-1 (638 m) and Höllviksnäs-1 (569 m) on the Falsterbo peninsula. The Triassic rests on Precambrian crystalline rocks or on the Pre-Zechstein surface represented by an up to 40 m thick conglomeratic quartzite of presumably Permian (Rotliegendes) age on top of truncated Lower Palaeozoic successions of shale, limestone and quartzite (Erlström & Sivhed 2012; Fig. 7). The pre-Rhaetian Triassic succession is shown in a selection of wells in Figs 5 and 7.

Three main geothermal reservoirs are recognised in the pre-Rhaetian Triassic interval in the Höllviken Half-graben, namely the Ljunghusen Sandstone, the Hammar–Flommen Formations and the Keuper reservoir interval, which includes primarily the Vellinge Formation (Figs 5, 7).

The Bunter Sandstone Formation in the Danish Basin is defined as Lower Triassic, predominantly reddish, poorly sorted sub-arkose interbedded with thin beds of claystone (Rhys 1974; Bertelsen 1980). The formation is widely recognised in the North Sea and in North Germany. North of the Ringkøbing-Fyn High, the formation interfingers with the lower part of the Skagerrak Formation (Fig. 3) and displays more varied lithologies and thicknesses in comparison to south of the Ringkøbing-Fyn High in the North German Basin (Bertelsen 1980; Nielsen & Japsen 1991; Michelsen & Clausen 2002; Olivarius & Nielsen 2016). In the Lower Triassic succession in the North German Basin there are four distinct sandstone units separated by thick claystone-dominated intervals and informally named Volprieshausen, Detfurth, Hardeggen and Solling sandstones of the Buntsandstein (Lepper & Röhling 1998; Bachmann 1998; Beutler 1998; Hagdorn *et al.* 1998; Bachmann *et al.* 2005).

Based on correlation of geophysical well-logs, the reservoirs in the Ljunghusen Sandstone and Hammar–Flommen Formations exhibit a relatively uniform lateral continuity with regard to their petrophysical and lithological properties, while the Keuper reservoir interval is more heterogeneous both laterally and vertically. The three pre-Rhaetian Triassic reservoirs are described below, and overall predictions and empirical data on the characteristics of these units are summarised in Table 3.

Ljunghusen reservoir

The Ljunghusen Sandstone occurs at 2088–2150 m in the Ljunghusen-1 well, at 2010–2063 m in the Höllviksnäs-1 well and at 2640–2658 m depth in the Margrethholm-1 well (Table 3). Thin occurrences are found in the Kungstorp-1 well and possibly also in the Eskilstorp-1 well (Erlström & Sivhed 2012). From these observations it is judged that the Ljunghusen reservoir has a wedge-like distribution restricted to the deepest parts of the Höllviken Half-graben, where it thickens towards the bounding Amager and Øresund faults in the west and south-west. It is unclear if it occurs in the North Sjælland Half-graben.

In the Ljunghusen-1, Höllviksnäs-1 and Margrethholm wells, the formation is composed of relatively homogeneous, reddish to pinkish, medium- and coarse-grained, well-sorted sandstone with siltstone layers and traces of carbonate cement. Thin iron coatings are common on the grains. Quartz grains are dominantly smooth and rounded, occasionally also with a frosted grain surface. Accessory minerals are subordinate and mica is lacking. These characteristics indicate an aeolian depositional setting (Nielsen 2001). Even though the corresponding parts of the Bunter Sandstone Formation is dominated by fluvial sandstone and lacustrine claystone deposited in ephemeral river systems and lakes, aeolian deposits are known both from the marginal parts of the Danish Basin and in the North German Basin (Mader & Yardley 1985).

The Ljunghusen reservoir is well-defined by the log response. The spontaneous potential and resistivity logs indicate a porous homogeneous unit, clearly distinguished from the overlying arenaceous claystone (Fig. 7). The basal boundary is defined by a presumed Permian (Rotliegendes) dense, conglomeratic quartzite which occurs beneath the Triassic in most wells in the Höllviken Half-graben (Fig. 7).

The Ljunghusen Sandstone is interpreted to be contemporaneous with the Volprieshausen Sandstone in the lower Middle Buntsandstein in Northern Germany, which constitutes the lowermost of four sandstone units in the Buntsandstein that are recognised in the Netherlands and in North Germany along the south side of the Ringkøbing-Fyn High (Aigner & Bachman 1992; Lepper & Röhling 1998).

To date, no hydraulic well tests or porosity and permeability analyses have been carried out on the Ljunghusen Sandstone interval. Despite this, it is still considered to be a potentially good geothermal reservoir. This is based on petrographic studies on cuttings from Höllviksnäs-1 that indicate a uniform, well-sorted sandstone with only minor cementation and (in contrast to other pre-Rhaetian Triassic intervals) low clay matrix content. Evaluations of wire-line logs give an average effective porosity of 22.5% (Nielsen 2001).

Hammar-Flommen reservoir

Coarse- and medium-grained, sub-arkosic sandstone beds interbedded with variably coloured red-green-brown and purple claystone are found at 2470–2660 m in the Margrethholm-1 well, at 1890–2007 m in the Höllviksnäs-1 well and at 1938–2082 m in the Ljunghusen-1 well (Table 3). The unit has a similar geophysical resistivity log response in the Margrethholm-1 and the Ljunghusen-1 wells (Fig. 7). The serrated geophysical log pattern combined with mud log data illustrate frequent changes in petrophysical properties, as well as rock types, where poorly sorted sub-arkose dominates (Fig. 7). In Skåne, this interval is defined as the Hammar and Flommen Formations, which are tentatively correlated with the Bunter Sandstone Formation in the Danish Basin and the corresponding Solling Formation in North Germany. The sandstone beds are often poorly consolidated and highly permeable (Erlström & Sivhed 2012).

So far the Hammar–Flommen interval is verified only in the southern and south-western parts of the Øresund Basin. To the north it becomes successively thinner and is absent on most parts of the Barsebäck Platform (Erlström & Sivhed 2012). It is unclear if the presumed equivalent, seismostratigraphically mapped, thick Triassic succession in the North Sjælland Half-graben includes strata of the same age and lithological properties as the Hammar–Flommen interval in the Höllviken Half-graben.

The Lower Triassic deposits in north-western Europe were primarily formed in a low relief landscape. Playa lakes (mudflats) and interfingering braided fluvial systems of ephemeral character dominated the depositional environment. Similar conditions prevailed in much of the North German Basin during the Early Triassic (Lepper & Röhling 1998). Similar depositional settings most likely occurred in the Øresund Basin, however, with a more pronounced influx of coarse clastic deposits from the Fennoscandian Shield. This highly variable depositional setting may lead to difficulties in assessing the hydraulic communication and the textural properties of this geothermally interesting interval. The present knowledge of the reservoir properties is mainly based on information from hydrological tests and production data from the Margrethholm-1 and -2 wells. Production data for this interval in Margrethholm-1 give an average permeability of 400 mD for a 92 m long, perforated section at a mid-point depth of 2550 m and 48 m net sand. The 73°C warm formation water from this depth has a chloride content of *c.* 130 g/l (Table 3).

The Keuper reservoir interval

In the Höllviken Half-graben the Keuper reservoir interval consists of the sandstone interval in the Vellinge

Formation and coarse-grained and conglomeratic beds of arkose in the overlying Fuglie and Kågeröd Formations. The Vellinge Formation is a 15–20 m thick sandstone interval overlying Ladinian to lowermost Carnian grey, micaceous, fine-grained beds of the Falsterbo Formation (Lindström *et al.* 2009; Lindström *et al.* 2017). The Vellinge Formation is interpreted as reflecting a change from relatively humid conditions, witnessed by a well-preserved and diverse palynoflora in the Falsterbo Formation, to more arid conditions with continental proximal deposition of variably sorted sandstone with numerous conglomerate beds (Lindström *et al.* 2009; Lindström *et al.* 2017). Part of the succession is composed of stratified fluvial sandstone beds with a grey overprint which indicates that there were still periods of more humid conditions. The sandstone beds of the Vellinge Formation have been tentatively correlated with the Hauptsandstein of the Erfurt Formation in the North German Basin (Erlström & Sivhed 2012).

The frequent presence of loose, permeable and poorly sorted sandstone beds with pedogenic-related features (nodules, dendritic calcite, rhizoliths and calcrete) and conglomerates results in very heterogeneous reservoir properties, with large variations both vertically and laterally within the interval. This renders an overall assessment of the Keuper reservoir interval difficult. Production tests in the FFC-1 well gave a productivity index of 2.9 m³/hr/bar for the Keuper interval. The 110 m of net sand over a 213 m long, perforated section with a mid-point at 1950 m depth gave an average permeability of 53 mD and a production temperature of 62.8°C (DONG 2003). Analyses on cores from individual sandstone beds in the FFC-1 and Höllviken-1 wells gave permeability values below 100 mD (Table 3).

Rhaetian–Lower Jurassic reservoir

In the late Triassic (Rhaetian), the structural pattern changed from local graben development to widespread subsidence of the Danish Basin. Eustatically controlled progressive overstepping of the Øresund Basin by the sea was accompanied by a change from seasonally arid to more humid climate with more widespread deposition (Bertelsen 1978; Norling & Bergström 1987; Ahlberg *et al.* 2003; Nielsen 2003). Thus, the texturally immature detrital sediments of the Carnian–Norian Kågeröd Formation were followed by Rhaetian–Hettangian chemically and texturally mature deposits (Ahlberg 1994). These comprise several repeatedly occurring similar successions of shallow marine and coastal depositional settings, including lagoonal, fluvial, estuarine, shoreline and marine facies associations (Norling *et al.* 1993; Ahlberg *et al.* 2003; Nielsen 2003). Most of the Rhaetian–Lower

Jurassic succession belongs to the 100–300 m thick Rhaetian to lowermost Sinemurian Gassum Formation, corresponding to the Höganäs Formation and the basal part of the Döshult Member in the Rya Formation in Skåne (Ahlberg *et al.* 2003; Nielsen 2003; Lindström *et al.* 2017).

In the Øresund Basin these strata are dominated by fine-grained shallow marine and shore face sandstones alternating with heterolites and clays deposited in coastal environments (Michelsen *et al.* 2003; Nielsen 2003). Six major lithofacies have been recognised, *i.e.* fine-grained quartz arenite, medium-grained arenite, silt- and clay-dominated heterolites, sand-dominated heterolites, claystone and coal (Bou Daher 2012).

In the central parts of the Danish Basin, the Lower Jurassic (Hettangian–lowermost Aalenian, post-Gassum Formation) succession consists predominantly of marine claystone and siltstone of the Fjerritslev Formation (Michelsen *et al.* 2003). The Stenlille-1, Lavø-1, Karlebo-1/1A, Margrethholm-1 and -2 wells in the eastern part of the Danish Basin encountered a 129–170 m thick post-Gassum Lower Jurassic succession with an eastward increasing amount of sandstone, interpreted as distal equivalents to the sandstone intervals in the Lower Jurassic of Skåne (Nielsen 2003; Hjuler *et al.* 2014).

The lower Sinemurian in Skåne is dominated by near-shore mature, coarse-grained arenite, forming the Döshult Member of the Rya Formation (Troedsson 1951; Norling & Bergström 1987; Norling *et al.* 1993; Erlström *et al.* 1999). Additional minor sandstone intervals are found in north-western Skåne in the overlying upper Sinemurian–lower Aalenian Katslösa and Rydebäck members (Sivhed 1984; Norling *et al.* 1993).

All in all, sandstone beds constitute as much as 40–60% of the Rhaetian–Lower Jurassic succession in Skåne. However, most of the sandstone beds are dominated by fine-grained micaceous quartz arenites with poor hydraulic properties. Analyses on cores show a permeability ranging from 50 mD for the fine-grained sandstone beds to 1500 mD for medium-grained varieties (Erlström & Sivhed 1997).

The petrography of the Rhaetian–Sinemurian sandstones is mainly known from studies by Ahlberg (1994), Ahlberg & Ohlsson (2001) and Hjuler *et al.* (2014). The composition and reservoir characteristics of the succession are relatively well constrained by these studies, as well as by hydraulic tests performed in the FFC-1 well. In the Malmö–Copenhagen and Helsingborg areas, the major part of this interval is composed of wavy- and flaser-bedded, fine-grained quartz arenites. The degree of cementation varies considerably. Poorly cemented beds, with interlocking grain-to-grain silica cementation, dominate. Coarser-grained sandstone beds are mainly found in the middle and

upper Rhaetian and uppermost Hettangian, *i.e.* the Bjuv Member, the Boserup beds and the Fleninge beds of the Höganäs Formation (Sivhed 1984). Medium- and coarse-grained units are also found in the Sinemurian Döshult Member of the Rya Formation (Norling *et al.* 1993). The overall dominance of fine-grained texture of the sandstone beds limits the reservoir properties with regard to the transmissivity. Pumping tests specifically targeting the Rhaetian–Lower Jurassic interval have not yet been performed. However, a pumping test in FFC-1 of the interval combined with the Lower Cretaceous interval gave a productivity index of 7.0 m³/hr/bar (Table 3). Nevertheless, judging from flow meter logging, not more than 20% of this was related to the Rhaetian–Lower Jurassic reservoir. Despite the indicated poor production capacity in the southern parts of the Øresund Basin, the general trend of increasing grain-size and amount of net sand to the north and north-east indicates increased potential for geothermal use of the Rhaetian–Lower Jurassic reservoir in this direction (Hjuler *et al.* 2014).

Lower Cretaceous including the Arnager Greensand reservoirs

In the Øresund Basin a 50–125 m thick Lower Cretaceous (Berriasian–Cenomanian) succession (Fig. 5) includes an up to 30 m thick sandstone overlying the base Middle Jurassic unconformity that truncates Lower Jurassic strata (Nielsen 2003; Lindström & Erlström 2011). The sandstone interval is overlain by variegated claystone layers with interbeds of sandstone, followed by the Arnager Greensand (Aptian–Cenomanian). The latter constitutes the top of the Lower Cretaceous mixed clastic succession formed in a marginal-marine and shallow shelf setting (Norling 1981; Gravesen *et al.* 1982; Packer & Hart 1994; Vajda-Santivanez & Solakius 1999; Larsson *et al.* 2000).

The lowermost part of the Lower Cretaceous succession in the FFC-1 well is represented by a 10 m thick bed composed of medium-grained quartz arenite showing excellent reservoir properties and a permeability in the range of several Darcy. Extensive hydraulic tests in FFC-1 have verified a regionally extensive reservoir with a transmissivity of 7.9×10^{-4} m²/s.

In the Margrethholm-1 well this sandstone unit is only represented by a few metres of net sand, while in the Lavø-1 and Karlebo-1/1A wells a 15–30 m thick sandstone-dominated interval has been identified. This indicates a trend of increasing thickness of the Berriasian–Barremian sandstone succession toward the north and north-east, in contrast to the Aptian–Cenomanian Arnager Greensand which thins to the north.

The Arnager Greensand is highly porous and permeable in the southern part of the Øresund Basin,

verified by results from core analyses from wells on the Falsterbo peninsula, where it has a permeability of several Darcy and a porosity of up to 35% (Erlström & Sivhed 1997). Analyses on sidewall cores from the Arnager Greensand in the FFC-1 well indicate significantly poorer reservoir properties. Here the permeability is <100 mD and the porosity in the range of 20%. These relatively low values are caused by a high amount of matrix, a fine-grained texture and carbonate cement, compared to the medium-grained, matrix-poor and uncemented, permeable varieties found in the wells to the south. The Arnager Greensand is up to 60 m thick in the southern part of the Øresund Basin, but thins considerably to the north accompanied by decreasing grain-size as well as poorer reservoir properties.

Lund Sandstone reservoir

This up to several hundred metres thick sandstone reservoir is found between 350 and 1100 m depth in

wells located along the Romeleåsen Fault Zone, e.g. in the Lund geothermal wells. Peak inversion and uplift of the STZ during the Santonian–Campanian resulted in formation of thick deltaic sand deposits at the north-eastern margin of the Øresund Basin, along the Romeleåsen Fault Zone (Erlström *et al.* 1997). Further basinward the sandstone is only a few metres thick and has significantly poorer reservoir properties (Erlström 1990). The sandstone unit shows good to excellent geothermal properties close to the Romeleåsen Fault Zone where it has a net sand thickness exceeding 100 m within a 7–15 km wide, undulating zone. Even though the formation temperature is low in comparison to the other potential reservoirs, the Lund Sandstone may be considered as a possible geothermal resource and aquifer for thermal energy storage. The permeability of the sandstone is commonly >1 Darcy and the porosity is 27–32% (Table 3). These geological conditions enable a production rate of up to 150 l/s of 21°C warm formation water in the Lund geothermal

Table 3. Summary of the main characteristics of the potential geothermal reservoirs in the Øresund Basin.

	Ljunghusen Sandstone	Hammar and Flommen Formations "Bunter Sandstone"	Keuper reservoir interval Vellinge, Fuglie and Kågeröd Formations	Rhaetian–Lower Jurassic reservoir Gassum, Höganäs and Rya Formations	Arnager Greensand and Lower Cretaceous	Lund Sandstone
Reservoir rock type	Medium- and coarse-grained, sandstone	Medium- and coarse-grained sub-arkose with interbeds of arenaceous claystone	Coarse-grained arkose and conglomerate	Fine- and medium-grained quartz arenite	Fine- and medium-grained glauconitic quartz arenite	Medium- and coarse-grained quartz arenite
Depositional setting	Arid, terrestrial, eolian	Arid–semi arid, ephemeral floodplain and playa-like	Arid red beds, alluvial fans, fluvial	Deltaic–marginal marine	Marginal marine–shallow shelf	Deltaic
Age	Early Triassic (Induan–Olenekian)	Early Triassic (Olenekian–Anisian)	Ladinian–Norian	Rhaetian–Pliensbachian	Berriasian–Cenomanian	Campanian
Net sand	20–60 m ¹⁾	80–120 m	20–50 m	60–100 m	20–50 m	200–350m
Depth below mean sea level	2010–2063 m ¹⁾ 2640–2658 m ²⁾ 2088–2150 m ⁵⁾	1890–2007 m ¹⁾ 2470–2660 m ²⁾ 1940–2088 m ³⁾	1498–1678 m ¹⁾ 2016–2230 m ²⁾ 1860–2075 m ³⁾	1288–1498 m ¹⁾ 1638–1965 m ²⁾ 1672–1820 m ³⁾	1190–1288 m ¹⁾ 1591–1638 m ²⁾ 1605–1672 m ³⁾	350–1100 ⁶⁾
Permeability	(High?)	400 mD ²⁾	<50 mD ⁴⁾ <100 mD ³⁾	50–1500 mD ^{3,6,7)}	10–4000 mD ^{1,3)}	>1 D ⁸⁾
Porosity	20–28% (logs) ¹⁾	23–25% (logs) ^{1,5)}	2–16% ⁴⁾	18–34% ^{1,3)}		27–32% ⁸⁾
Temperature	56–57° ¹⁾ 77° ²⁾	53–55° ¹⁾ 73° ²⁾	46–47° ¹⁾	36–38° ¹⁾ 52–54° ³⁾	36–38° ¹⁾ 44–45° ³⁾	20–25° ⁸⁾
Cl⁻ content	--	130 g/l ²⁾	120–190 g/l ^{1,3)}		100 g/l ⁸⁾	
Productivity index	--	5.6 m ³ /hr/bar ²⁾	2.9 m ³ /hr/bar ³⁾	7.0 m ³ /hr/bar ¹⁾		>10 m ³ /hr/bar ⁸⁾

¹⁾Höllviksnäs-1. ²⁾Margretheholm-1. ³⁾FFC-1. ⁴⁾Höllviken-2. ⁵⁾Ljunghusen-1. ⁶⁾Höllviken-1. ⁷⁾Svedala-1. ⁸⁾Lund wells.

wells, completed with up to 150 m long gravel-packed slotted screens. The maximum heat capacity of the Lund Geothermal system was 47 MW when it started in 1984 (Ottosson 2005). The effect has, however, after more than 30 years of operation decreased somewhat due to gradually lower temperatures in the production wells caused by influence from the 'colder' injection wells.

Discussion

Possible geothermal reservoirs in the North Sjælland Half-graben

In comparison to the southern parts of the Øresund Basin there is a greater uncertainty regarding occurrence and characteristics of the potential geothermal reservoirs in the North Sjælland Half-graben. Lower and Middle Triassic geothermal reservoirs are so far only verified in the Höllviken Half-graben. However, the interpreted seismic lines in the North Sjælland Half-graben indicate a similar Triassic succession (Fig. 4), which could be even thicker than that in the Höllviken Half-graben.

Seismic markers corresponding to the base of the Upper Cretaceous and the top pre-Rhaetian Triassic can be traced throughout the Øresund Basin and provide a reliable prediction on the presence of Rhaetian–Lower Jurassic and Lower Cretaceous geothermal reservoirs. The Rhaetian–Lower Jurassic reservoir is well known from the adjacent Helsingborg area in the eastern margin of the half-graben (Norling *et al.* 1993; Ahlberg *et al.* 2003; Bou Daher 2012; Hjuler *et al.* 2014). Uncertainty regarding the Gassum Formation is much reduced because of the comprehensive data set from Helsingborg, which clearly demonstrates the presence of laterally equivalent Rhaetian–Hettangian–lower Sinemurian strata, *i.e.* the Höganäs Formation and the Döshult Member of the Rya Formation (Fig. 3). Thus, a similar reservoir succession is expected to be present in North Sjælland. The interpreted larger overall grain-size and net sand content of the Rhaetian–Lower Jurassic in North Sjælland suggests somewhat better geothermal properties than for the southern parts of the Øresund Basin. Further, the interpreted seismic data suggest a relatively uniform thickness of about 100–170 msec TWT (Two Way Travel time) of the Gassum Formation, corresponding to 175–300 m assuming an interval velocity of 3500 m/s. The low end of this thickness span is in correspondence with the thickness of the Helsingborg composite succession, while the upper end corresponds well to the thickness of the Gassum Formation in the wells Hans-1 and Terne-1 located in the Kattegat sea area north of

Sjælland (Fig. 2; Michelsen & Nielsen 1991; Nielsen & Japsen 1991; Hjuler *et al.* 2014).

The interpretation of the seismic line presented in Fig. 4, profile 4, suggests a thickness of *c.* 400 m from the base Gassum Formation to the base Upper Cretaceous succession using velocity data from Margrethholm-1 well. The estimated thickness of 400 m is very small compared to the thickness of *c.* 1000 m estimated for the tilted Jurassic strata in the wells in the Øresund area, located in the flexure zone to the Romeleåsen Fault Zone (Larsen *et al.* 1968). However, the tilted strata between Helsingør and Helsingborg also include Middle Jurassic deposits. In north-western Skåne, the Middle Jurassic Vilhelmsfält Formation includes one potential geothermal reservoir, the Bathonian Glass Sand Member, which reflects high energy proximal coast environments such as delta front sands and beach–foreshore settings (Rolle *et al.* 1979). In the Danish Basin, the Middle Jurassic is represented by the Haldager Sand Formation which is primarily known from north Jylland, within the STZ, and in the Skagerrak and Kattegat areas (Fig. 2). It is uncertain whether any Middle Jurassic deposits and geothermal reservoirs occur in the northernmost parts of the Øresund Basin. However, on the basis on the observations between Helsingør and Helsingborg, it is possible that strata equivalent to the Vilhelmsfält Formation may be present (Larsen *et al.* 1968).

A Lower Cretaceous succession of claystone and sandstone beds was encountered in the Lavø-1, Karlebo-1/1A, Margrethholm-1 and Stenlille-1 wells. In the Lavø-1 and Karlebo-1/1A wells, the lower part of the Lower Cretaceous succession comprises a 15–30 m thick sandstone-dominated interval of similar composition as in south-west Skåne. The sandstone interval is a few metres thick in Stenlille-1 and Margrethholm-1, indicating a distinct trend of increasing thickness toward the north and north-east. An unpublished formation evaluation shows 21 m of net sand in the Karlebo-1/1A well, while the net sand value cannot be determined in Lavø-1 due to an incomplete log-suite. However, assuming a similar ratio between gross and net sand in the two wells, a net sand value of 10.5 m is estimated in Lavø-1. As hydraulic tests of the corresponding sandstone unit in FFC-1 have provided extremely good values (Table 3), it is expected that the Lower Cretaceous sandstone is also a potential geothermal reservoir in the North Sjælland Half-graben.

Formation fluids

In the Øresund Basin the formation fluids in the geothermal reservoirs are composed of brine formation water with only a few percent of dissolved gases. No hydrocarbons have been encountered. The chloride

content in the formation fluids in the described reservoirs varies between 100 and 190 g/l, mainly related to the depth of the reservoir (Table 3). These data indicate that the salinity increases almost linearly with depth, approaching saturation with respect to halite at 3000 m. This is interpreted to be caused by diffusion of salt from the extensive deposits of Permian–Triassic evaporites in the Danish Basin and entrapped residual brines in the formations (Laiet 2003). A few chloride concentrations in formation waters from various wells and reservoirs are presented in Table 3.

Compared to other geological formation waters, there are no explicit anomalies in those analysed from the FFC-1 well that could lead to problems with precipitates during geothermal heat production (Laiet 2003). However, an iron content of 40–70 mg/l will lead to significant precipitation of iron-oxyhydroxides under oxygenated conditions. Therefore, a closed and pressurised geothermal system without access to oxygen is required.

Gases are dominated by nitrogen and minor amounts of methane and noble gases such as he-

lium and argon. Analyses of two Keuper samples, from 1840 and 1860 m depth in the FFC-1 well, gave a solute gas content of 86 cm³ per litre of formation fluid, consisting of nitrogen with small admixtures of hydrocarbons (<2%), carbon dioxide (0.52%) and a relatively high share of helium (5.7%). Similar results were also obtained in the Lund geothermal field, where the 21°C warm formation water from the Lund Sandstone reservoir contains 2.5 litre of gas per 100 litre, composed primarily of nitrogen (92%), methane (3%) and helium (3%). The fluid has a pH of 6.8 and a salinity of *c.* 6‰. The content of total dissolved solids is *c.* 6 000 ppm (Bjelm & Alm 1995).

Porosities and permeabilities

Figure 8 illustrates a regional porosity–permeability trend for the Bunter and Gassum sandstones, based on porosity and permeability data for core samples from various wells in the Danish Basin (Mathiesen *et al.* 2009; Kristensen *et al.* 2016). This shows that the porosity of the Bunter sandstone in general varies between 5

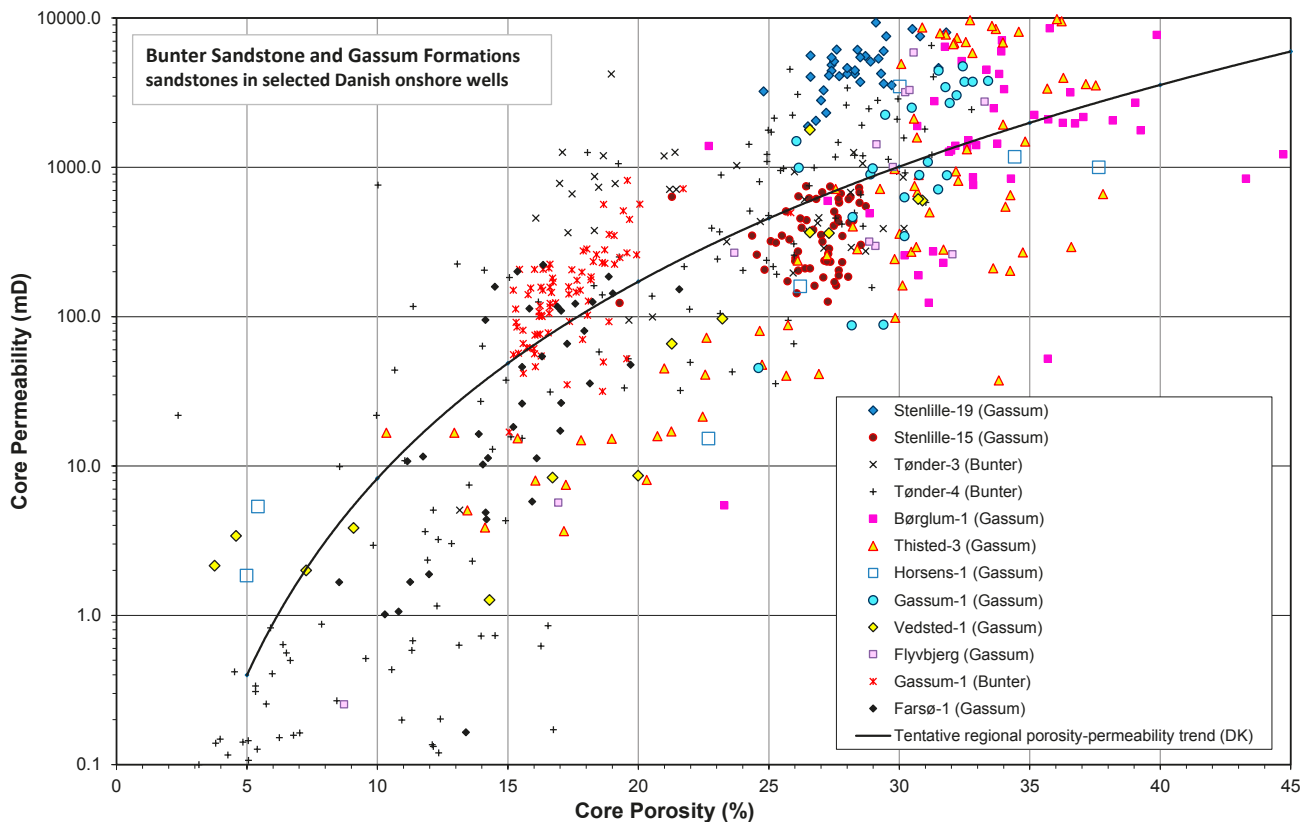


Fig. 8. Plot displaying the regional porosity–permeability relationship for the Bunter Sandstone and Gassum Formations in the Danish Basin onshore Denmark (Mathiesen *et al.* 2009). This compiled data set originates from core analysis reports provided by various core analysis laboratories during a period of *c.* 50 years (1950–2000). The core analysis reports are either company reports or in-house DGU and GEUS reports, and all reports are available from the GEUS Subsurface Archive. Data are fitted to a power function and the black line is a non-linear regression line.

and 25% while the Gassum sandstones show values that are commonly higher than 25%. There is also a corresponding decrease in permeability in the Bunter samples which rarely exhibit values above 500 mD, while the Gassum samples often show results above one Darcy. The plotted core data in Fig. 8 represent two geological formations and a wide range of depositional environments, resulting in a fairly scattered data set. Data from the two formations have been used in order to strengthen the definition of a regional correlation line. Analyses performed on cored intervals in wells from south-west Skåne have provided a less extensive data set on porosity and permeability values for the reservoirs in the Øresund Basin (Fig. 9; Erlström 1990; Springer 1997) In addition, a relatively new data set exists from analyses performed on cores of the Höganäs Formation in the Helsingborg area (Hjuler *et al.* 2014). The Helsingborg data are plotted in Fig. 8 which shows that these data fit into the various distributions of the porosity and permeability as presented in Fig. 9.

The porosity and permeability distributions for the Keuper as well as for the Lower Jurassic sandstones

in the Øresund Basin are more or less equivalent with the trend and ranges of values for the Bunter and Gassum sandstones in the Danish Basin shown in Fig. 8. Figure 10 shows a porosity–permeability plot solely of the Gassum and Höganäs sandstones, comprising data from selected Danish onshore wells as well as data from shallow wells drilled in the Helsingborg area (Hjuler *et al.* 2014). The Helsingborg dataset fits into the distributions of the porosity and permeability for the various geothermal reservoirs as presented in Fig. 9 and, moreover, the data contribute to establishing a tentative ‘North Sjælland–Helsingborg’ trend line (Fig. 10). Further drilling and coring in the North Sjælland area is needed in order to confirm (or reject) this relationship.

In Fig. 10, most of the Gassum Formation data from Thisted-3 and Stenlille-19 (location and well data in Fig. 2 and Table 1) are considered to signify elevated (or higher) permeability relative to the Gassum Formation sandstones found in the Øresund Basin, due to e.g. sedimentological differences, differences in grain size and different depositional environments. Figure

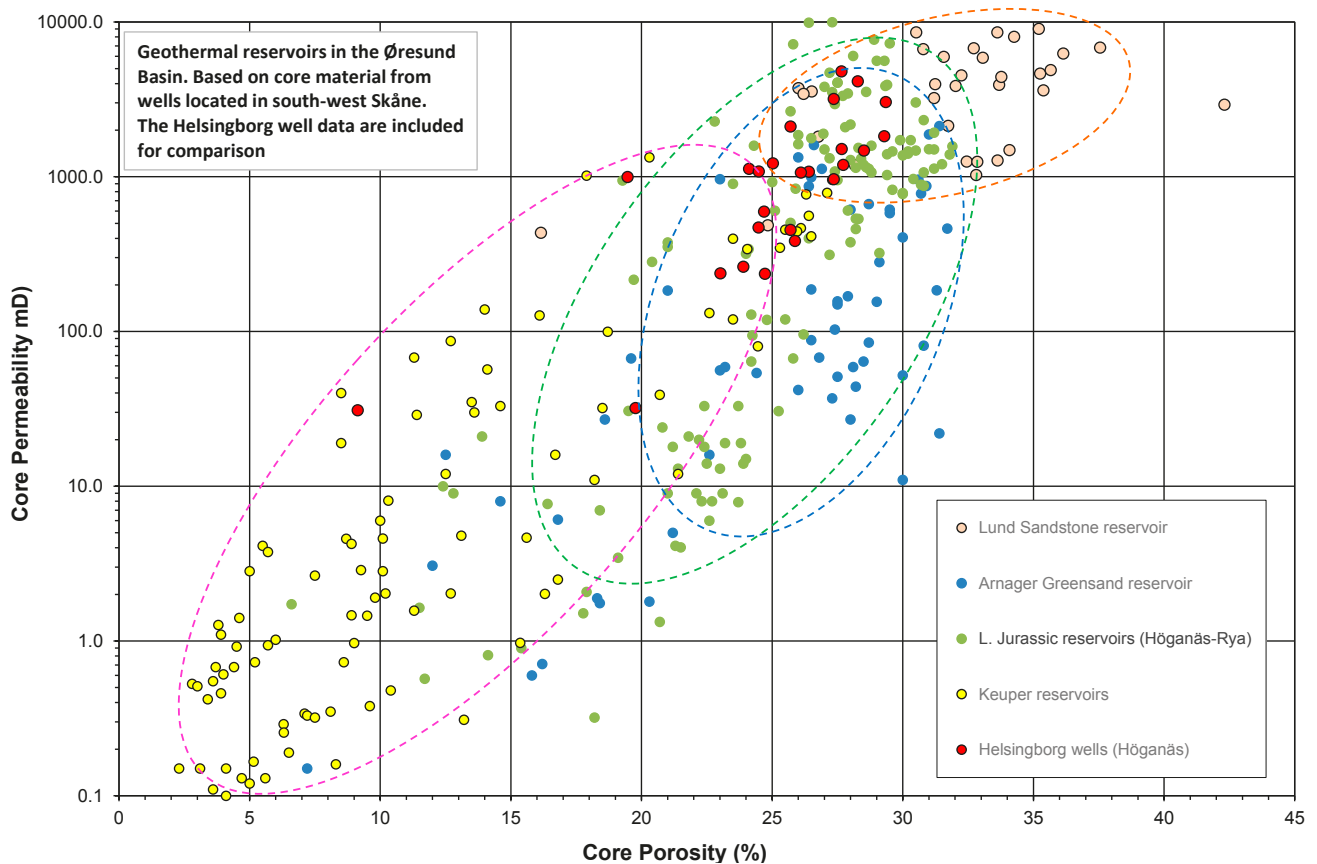


Fig. 9. Plot of the porosity–permeability relationship for different geothermal reservoirs in the Øresund Basin. The values are derived from analyses on core material from wells in south-west Skåne (Erlström 1990; Springer 1997). The dashed ellipses represent the assessed main distribution of the porosity and permeability of the various reservoirs. Porosity–permeability data from shallow wells drilled in the Helsingborg area are plotted for comparison (these data represent sandstones of the Höganäs Formation).

10 also includes data from the Gassum Formation in the Stenlille-15 well, and it is noteworthy that the data from the two Stenlille wells do not fit the suggested porosity–permeability trend line, which is based primarily on core analysis data from selected wells located in Jylland. Core analysis data from Jylland are largely measured on plug samples of medium-grained sandstones, while the Stenlille-15 samples primarily consist of fine-grained sandstones, suggesting that the depositional environment and the sandstone provenance are different. Conversely, the Stenlille-19 samples primarily consist mostly of coarse-grained and almost clay-free sandstones, resulting in elevated permeabilities. Hence, the Stenlille-15 and -19 data plot below and above the trend line, respectively.

The overall data set shows that the Triassic reservoir sandstones vary considerably with respect to porosity and permeability, reflecting their heterogeneous composition and texture. Well sorted, matrix-poor beds and beds with no or limited amounts of cement are subordinate in the Triassic succession. The highest permeability values are found in the Bunter Sandstone

Formation interval, where permeabilities between 100 and 1000 mD are recorded. The corresponding values for the Keuper interval are considerably lower (Table 3). There are unfortunately no core analyses or hydraulic test data for the lowermost Triassic Ljunghusen reservoir. However, the log response indicates a permeable, porous and up to 50 m thick homogeneous sandstone at the base of the Triassic succession.

Interpretation of log data from the reservoir sandstones in the pre-Rhaetian Triassic interval in the FFC-1 well, i.e. predominantly Keuper strata, gives an average porosity of 24–25% and a volume of shale matrix in the range of 20–22%. The corresponding interpretation of the Rhaetian–Lower Jurassic and Lower Cretaceous interval gives an average porosity of 21–23%, however with a significantly lower matrix content of 10–12%. The porosity and permeability values for the Lower Jurassic reservoirs are more consistent, reflecting the more homogeneous petrophysical properties compared to the Triassic reservoirs. However, the predominance of fine-grained sandstone beds generally results in poor permeability. In the FFC-1 well, an approximately 10

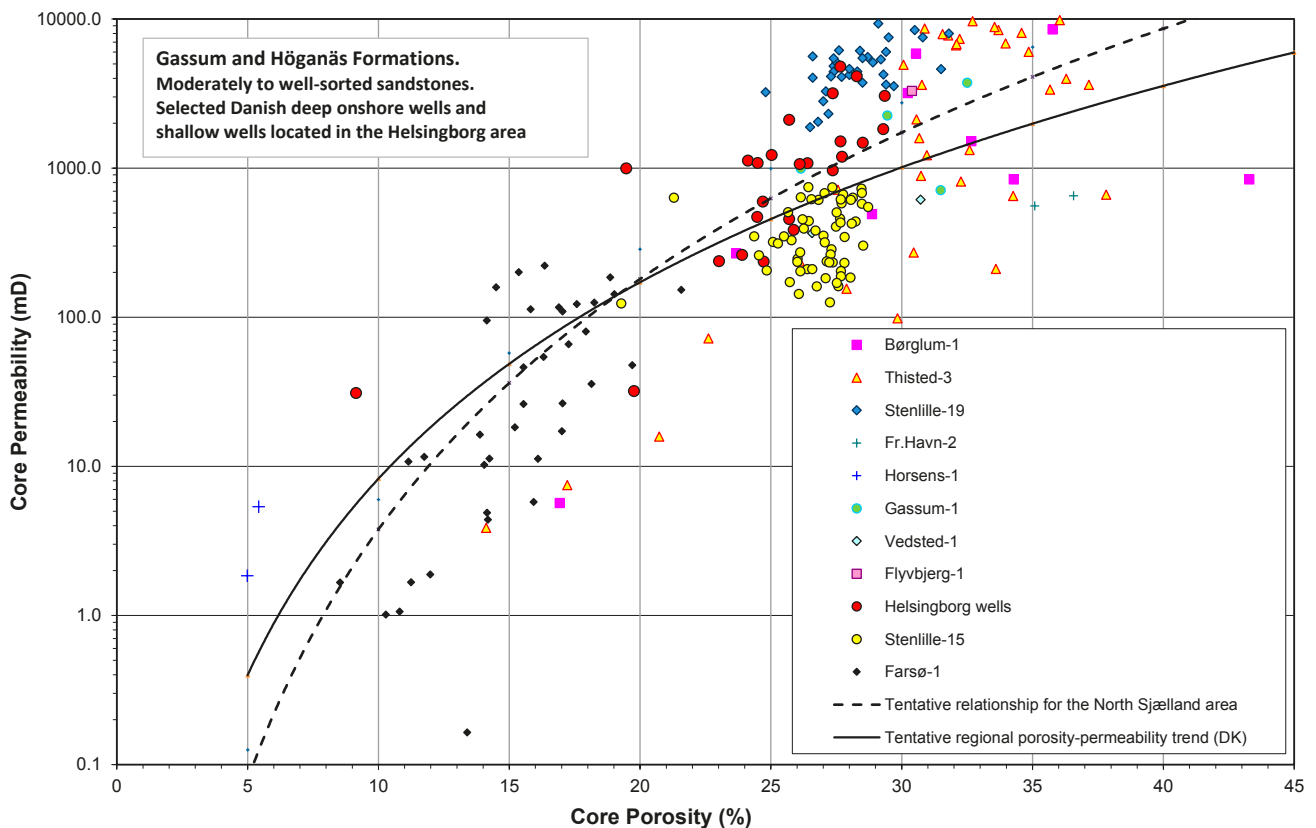


Fig. 10. Plot of the porosity–permeability relationship for moderately to well sorted sandstones in the Lower Jurassic Gassum and Höganäs Formations, from selected onshore wells in Denmark and shallow wells from Helsingborg (data from Hjuler *et al.* 2014). The regional porosity–permeability relationship for the Danish area (Fig. 8) is plotted for comparison. A tentative trend line for the North Sjælland and Helsingborg areas is suggested (dashed line).

m thick bed of medium-grained and highly permeable sandstone, i.e. the Lower Cretaceous sandstone on top of the Middle Jurassic unconformity, was found to contribute to as much as 80% of the water flow. The remaining 20% originate from an approximately 200 m thick Rhaetian–Lower Jurassic and Lower Cretaceous section between 1605 and 1818 m with a net sand thickness of 110 m. This signifies the important effect of grain-size on the permeability. The permeability of the fine-grained sandstone beds is generally less than 200 mD in the Höllviken Half-graben. The results from analyses on cores from the Lower Jurassic succession in Helsingborg indicate overall significantly higher permeabilities, commonly as high as 1–2 Darcy (Fig. 10). These high values are coupled to a predominance of medium-grained and highly porous sandstone. The high permeability values in the Helsingborg area could be speculated to be caused by Late Cretaceous uplift and pressure release, triggering chemical dissolution or mechanical disintegration of pre-existing cements in the rock, leading to elevated secondary porosities. However, no such processes have been verified (Ahlberg 1994; Hjuler et al. 2014). Based on the limited data set, it is assumed that the grain-size of the sandstones in the Rhaetian–Hettangian succession, i.e. the Gassum and Höganäs Formations, increases towards the north and north-west, which is also indicated from the Helsingborg area (Hjuler et al. 2014). The Lower Cretaceous reservoirs appear to show the same trend, as indicated by well data from the southern part of the Øresund Basin and the Karlebo-1/1A and Lavø-1 wells located on northern Sjælland.

Prediction models

Regarding prediction of the permeability and porosity of a potential geothermal reservoir in an area with poor data coverage, depth models for both the Gassum Formation and the Bunter Sandstone Formation in the Danish Basin were presented by Kristensen et al. (2016) and Weibel et al. (2017). A ‘best practice’ technique for predicting average porosity and permeability for these reservoirs was also presented by Kristensen et al. (2016), using primarily core analysis data and well-logs. The model by Weibel et al. (2017) also includes assessments of grain-size, detrital clay content and grain shape as well as diagenetic alterations, and shows that the porosity–permeability properties of the sandstone reservoirs in the Gassum Formation follow a steeper depth gradient than the Bunter Sandstone Formation due to higher degrees of mechanical compaction and diagenetic alterations. Further, there is a depth-related decrease in porosity for the Gassum Formation of 5%/1000 m in the Danish Basin. A similar situation may be assumed for the Øresund Basin, however with the consideration that the sandstone beds are likely to be

slightly more coarse-grained towards the Fennoscandian Border Zone to the north-east.

Temperature gradients

The available temperature data for the Øresund Basin are illustrated in Fig. 11. Most of the recorded temperatures are bottom hole temperatures (BHT) monitored during wire-line logging operations. The readings are likely to be affected by drilling operations, e.g. circulation of mud in the borehole before logging, which lead to relatively low measured temperatures. The temperature logging data for the FFC-1 and Ljunghusen-1 wells are corrected for the drilling operation and its effect on the recorded temperatures, but the BHT data from Skåne are not. Consequently, the scattered BHT values plot slightly to the left of the temperature profiles for FFC-1 and Ljunghusen-1 (Fig. 11).

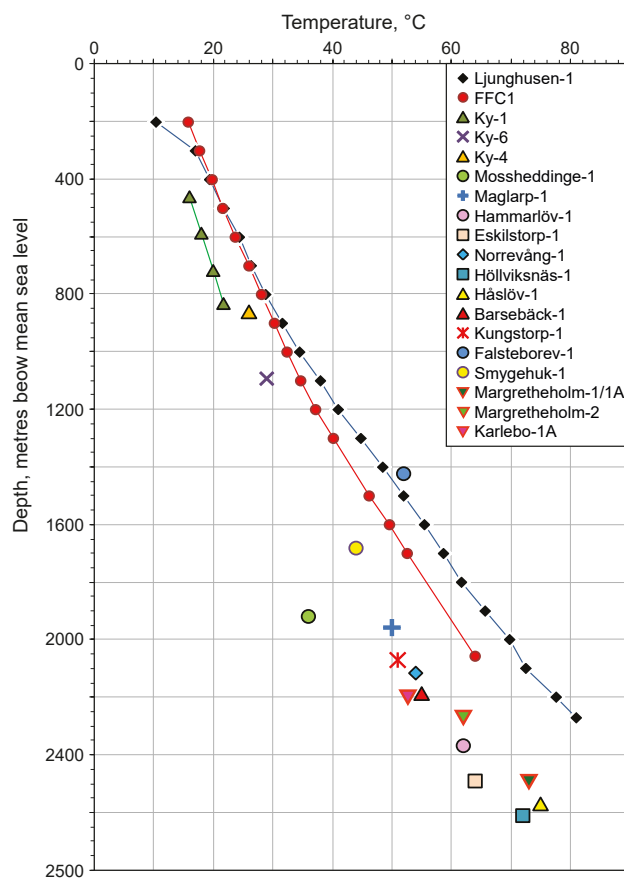


Fig. 11. Temperature data from deep wells in south-west Skåne and on Sjælland registered immediately after drilling, i.e. most of the data are bottom hole temperatures (BHT) values. The temperature profile in the FFC-1 and Ljunghusen-1 wells represent normalised conditions. The three Danish data represent updated estimates of equilibrium temperatures (Margretheholm-1/1A and -2) and BTH values (Karlebo-1). Danish values are from Poulsen *et al.* 2013).

The temperature gradient varies in the Ljunghusen-1 well between 27°C and 35°C/1000 m and is 29.5 °C in FFC-1, considering an average temperature of 10°C in the upper 200 m of the bedrock. Based on the data in Fig. 11 a formation temperature of 45–50°C at 1500 m, 60–70°C at 2000 m and 70–90°C at 2500 m depth may be expected for the reservoirs in the Øresund Basin.

Summarised assessment of the geothermal potential

The distribution, depth and petrophysical characteristics of the described geothermal reservoirs provide very variable geological conditions for utilising

geothermal energy in different parts of the Øresund Basin. A composite prognosis map regarding the geothermal potential in the Øresund Basin (Fig. 12) shows that the best conditions prevail along the western part of the basin in the Höllviken and North Sjælland half-grabens. There, multiple alternative reservoirs, in the Bunter Sandstone, Rhaetian–Lower Jurassic and Lower Cretaceous intervals, are interpreted to exist at depths ranging between 1500 and 4500 m. The corresponding reservoir temperatures for the same intervals are assessed to range between 45° and 85°C. In addition, the gross thickness of the Triassic to Lower Cretaceous interval with geothermal potential is at least 1000 m in those areas where the likelihood of finding Lower Triassic reservoirs with temperatures above 60°C is the greatest.

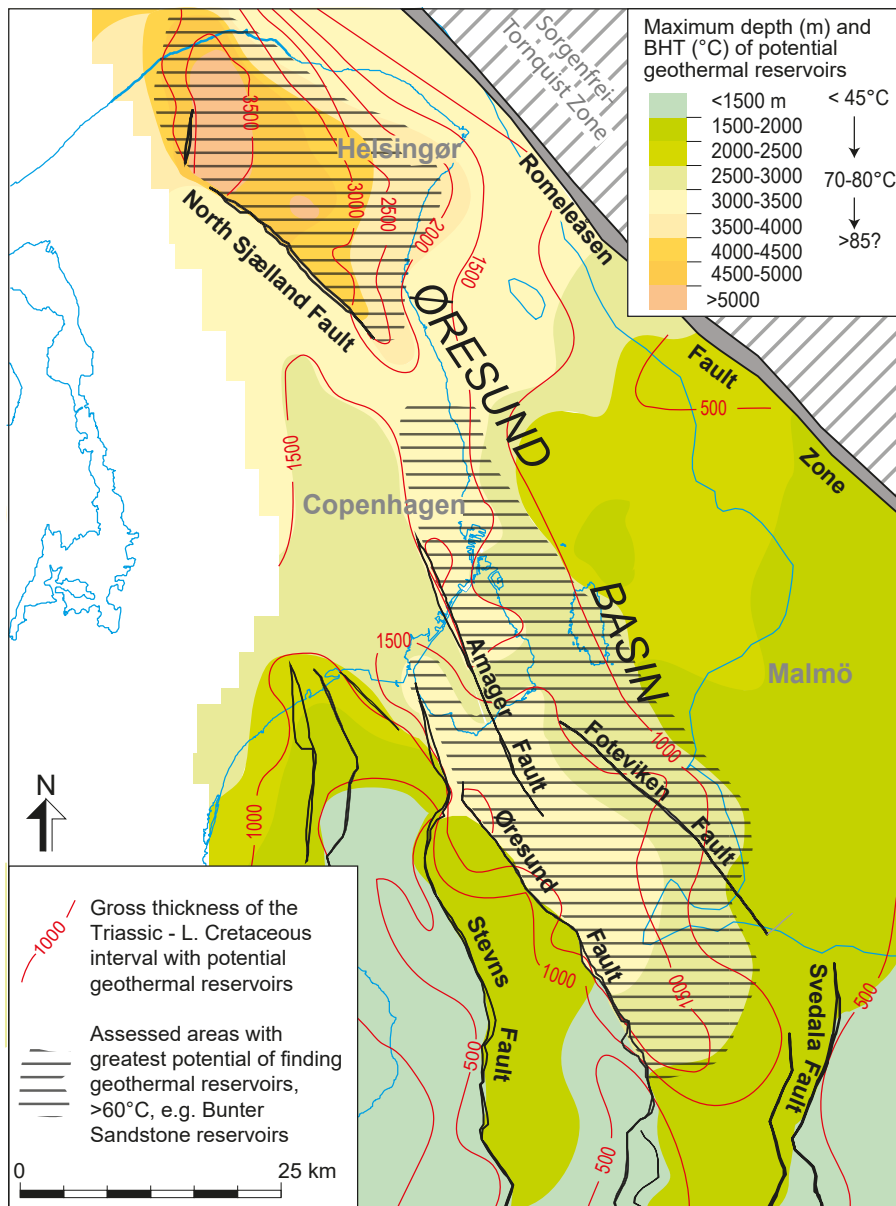


Fig. 12. Schematic prognosis map illustrating the maximum depth, gross thickness and the estimated corresponding maximum formation temperatures of the assessed, pre-Rhaetian Triassic, Rhaetian–Lower Jurassic and Lower Cretaceous geothermal reservoirs in the Øresund Basin. Areas of judged greatest potential for suitable geothermal reservoirs with a temperature >60°C are shown, mainly related to the occurrence of Bunter Sandstone reservoirs.

Pre-Rhaetian Triassic

The deepest reservoirs, i.e. the Bunter sandstones including the Ljunghusen Sandstone, and the Flommen and Hammar Formations, are located at 2200–2600 m depth adjacent to the Øresund and Amager faults. A similar succession with geothermal potential within the Triassic is indicated in the North Sjælland Half-graben. There, the depth of the Lower Triassic sandstone reservoirs is interpreted to be even greater than in the Höllviken Half-graben, which would result in higher temperatures. However, the porosity and permeability could suffer because of the greater burial depth.

In the Margrethholm-1 well, the temperature of the Lower–Middle Triassic succession is between 60° and 73°C. A productivity index of 5.6 m³/hr/bar is reached in a 75 m long perforated well section of the Flommen–Hammar interval. The reservoir has been in production since 2005. However, decreasing flow rates have been registered recently, possibly caused by migration of fine particles or precipitation of inorganic compounds, i.e. scales. Scales are formed by precipitation in geothermal water and may coat perforations, casing, valves, pumps and other technical equipment, thereby significantly reducing the production capacity of a well. Despite this, the Lower–Middle Triassic succession is still judged to have a considerable potential as geothermal reservoir, as it displays favourable formation temperatures and transmissivities, provided that there are technical solutions mitigating fines production from the commonly poorly sorted and argillaceous reservoir, and precipitation of scales. The heterogeneous reservoirs in the Keuper interval that exhibit smaller thicknesses and lower permeability are not considered suitable as geothermal reservoirs. However, they could be part of, and contribute to, a composite production interval in the Triassic, provided that mixing of formation fluids from different intervals does not cause scaling or give rise to precipitates (Laier 2003).

Rhaetian–Lower Jurassic

A succession encompassing the Rhaetian–Lower Jurassic sandstone reservoirs is present in all parts of the Øresund Basin. The succession is consequently evaluated to have the greatest geothermal potential, even if the individual reservoir properties vary within the basin. For instance, the Rhaetian–Hettangian reservoir sandstones are predominantly fine-grained and have a relatively low transmissivity in the south, whereas grain-size, net sand and transmissivity of the interval are interpreted to increase in the northern parts of the Øresund Basin. The medium-grained sandstone beds in the succession are highly permeable. However, it is difficult to map the distribution of these beds prior

to drilling of exploration wells. Detailed pre-drilling modelling and prediction of the geothermal potential of this interval is therefore uncertain for a specific site.

Cretaceous

The highly permeable Lower Cretaceous sandstone unit overlying the Middle Jurassic unconformity is distributed throughout the Øresund Basin. It is considered an alternative geothermal reservoir to the Bunter Sandstone and Rhaetian–Lower Jurassic reservoirs. The progressively increasing depth of the Lower Cretaceous reservoirs towards the Romeleåsen Fault Zone gives slightly higher relative temperatures of this interval in the north-east. In the Øresund Basin the top of this interval is found at depths between 1200 and 1700 m, corresponding to a temperature of 35–55°C.

The Lund Sandstone has the best overall reservoir properties, but has a limited geographical distribution and low formation temperatures between 20° and 25°C. This requires technical solutions involving compression heat pumps with input of preferably renewable electricity as the driving energy.

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