Geothermal reservoir rocks in Denmark

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An extended summary of a DGU/EEC research project is presented. The possibilities of low enthalphy energy sources in Denmark have been investigated. Particular emphasis has been placed on the reservoir characteristics with the intent, if possible, to produce synthetic reservoir assessments.

The investigations of the reservoirs have included the establishment of sedimentary environment, degree and type of diagenesis, temperature mapping, factors controlling formation brine salinity, the decrease of porosity with increased depth of burial, and the relationships between porosity and permeability.

Very simplified, the porosity of the reservoirs decrease from 30–40% at 500 m depth to 5–15% at about 3500 m depth. The significant decrease in permeability with increased depth is noted. Temperatures increase from about 55–75°C at 2000 m to 75–105°C at 3000 m depth. Temperatures of 100–150°C are reached in the central part of the sedimentary basins.

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Geological and geophysical investigations of geothermal possibilities prior to 1981 indicated that a more thorough analysis of the Danish reservoirs was needed (Michelsen et al. 1981).

In 1981 the EEC supported a two year continuation of the geothermal investigations. The study carried out by DGU/EEC 1981–82 and reported by Priisholm et al. 1982, has placed particular emphasis on the reservoir characteristics of clastic and orthochemic rocks with the intent of producing synthetic reservoir assessments. These are needed for analysing the potential of the low enthalphy geothermal reservoirs in Denmark.

The study was only possible through a joint research carried out by scientists and technicians as well as senior students. The following presentation is based on major contributions by:

N. Balling*	Temperature distribution
S. Fine	Bunter Sandstone, Tønder, and Skagerrak Formations – sedimentology, petrography, diagenesis, and compilation

N. Frandsen	Gassum Formation, Haldager Sand and Frederikshavn Member – sedimentology and compilation
H. Friis*	Petrography and diagenesis of Gassum Formation, Haldager Sand, and Frederikshavn Member. Heavy mineral analysis
L. Holm	Structural development
J. I. Kristiansen*	Temperature distribution
T. Laier	Geochemestry of formation water
O. Michelsen	Regional setting
E. Nygaard	Zechstein Formations
S. Priisholm	Porosity, permeability and reservoir evaluation

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The paper will first deal with the parametres governing the performance of the reservoir rocks such as the sedimentary environment, diagenesis, temperature distribution, salinity, porosity versus depth, and porosity versus permeability.

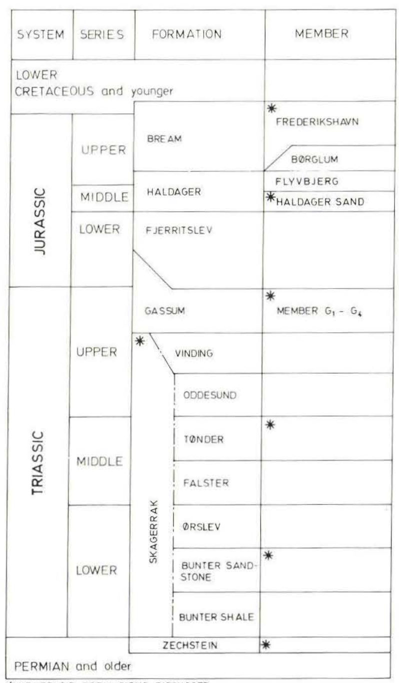

Fig. 1. Simplified stratigraphic subdivision of the Danish onshore area.

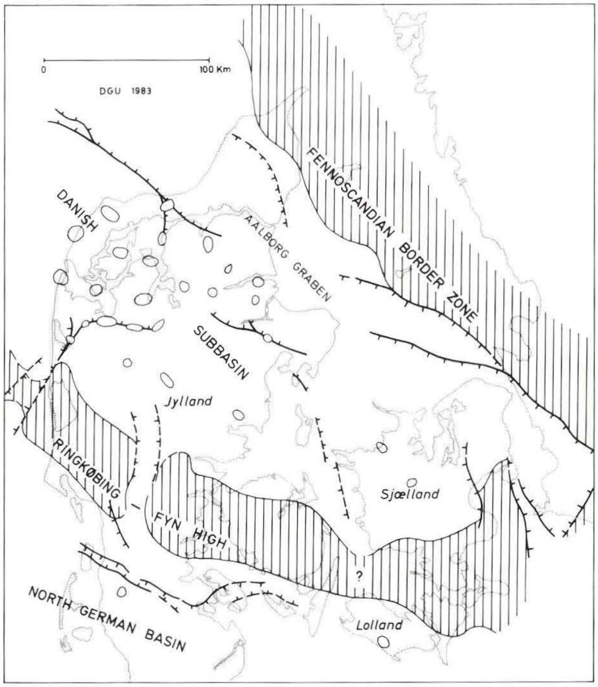

Fig. 2. Structural elements of Denmark. Pre-Upper Permian.

Legend to figures 2–8.

Abbreviation of formations:
Bu Bunter Sandstone Formation
Tø Tønder Formation
Sk Skagerrak Formation
Ga Gassum Formation
Ha Haldager Sand
Fr Frederikshavn Member

Major fault

Salt Structure

Positive area, reservoir thin or absent

— 0.5 — Contour. Depth or thickness in kilometres

Second, selected formations and members will be described with special reference to their geothermal reservoir possibility. Regional description of the rocks are previously published by Bertelsen (1978 and 1980), Larsen (1966), and Michelsen (1978 and 1981).

The possible reservoirs are the Zechstein carbonate deposits, the Lower Triassic Bunter Sandstone Formation, and the Middle Triassic Tønder Formation, all in the North German Basin, and the Lower to Upper Triassic

Skagerrak Formation, Upper Triassic Gassum Formation, the Middle Jurassic Haldager Sand, and the Upper Jurassic Frederikshavn Member, situated in the Danish Subbasin (fig. 1).

The structural elements of Denmark are presented in fig. 2 while the configuration of the Triassic formations is given by the general isopach map of the total Triassic (fig. 5), and the depth map to near top Triassic (fig. 6). General depth maps of the Gassum Formation, Haldager Sand, and Frederikshavn Member are presented on fig. 6–8.

Parametres

Sedimentary environment

In order to map the parameters of the sedimentary reservoir rocks, a classification into sedimentary environments has been carried out.

In general, the most high-energy environments, with the highest degree of reworking, have provided the most coarse-grained and well sorted sandstones.

The Haldager Sand and, to a lesser degree, the Skagerrak Formation, were both partly deposited in a braided river environment and are the most coarse-grained sediments of the investigated formations. This environment can provide sandstone bodies of considerable extension.

The Gassum Formation was deposited in a tidally influenced, shallow marine platform environment. The coarse-grained fraction of the Gassum Formation (fine- to medium-grained sand), is finer-grained than the abovementioned sediments and was deposited under intermediate energy conditions.

The Frederikshavn Member was probably deposited in an near-coast intermediate-energy environment also, but no obvious relationship between energy levels and grain size can be determined.

The lowest-energy environment of the discussed formations is the sabkha regime which is exemplified by the Bunter Sandstone and Tønder Formations and provides the most fine-grained sandstones.

Diagenesis

The degree of diagenesis has been evaluated with the aid of thin section, x-ray, SEM, and heavy mineral studies.

The Bunter Sandstone, Tønder and Skagerrak Formations have all suffered redbed diagenesis. The Skagerrak and Tønder Formations, when containing volcanic materials, have suffered especially strong diagenetic effects which resulted in lower porosity.

The "grey formations" all have different diagenetic histories. The Gassum Formation becomes increasingly cemented with increasing temperature (depth). Dissolution of feldspars at greater depths creates secondary porosity.

The Haldager Sand has no important early cementation and thus suffers great compaction (crushing of grains) at deep levels. The Frederikshavn Member has a very early glauconitic cement which, combined with the matrix, lowers the permeability considerably.

Temperature

Isotherm maps at depths of 2000 m and 3000 m and of each formation have been constructed.

Isolines generally follow the main tectonic units; the highest temperatures are predicted for the central Danish Subbasin with temperatures decreasing NE towards the Fennoscandian Border Zone and SE towards the Ringkøbing-Fyn High, above, and within which, the lowest temperatures are predicted. Temperatures range between 55°C and 75°C at 2000 m depth, and between 75°C and 105°C at 3000 m depth. In the deepest part of the Skagerrak Formation in the Danish Subbasin, temperatures may reach 100–150°C.

Salinity

The formation water data have been obtained from tests and from extraction of interstitial waters in cores.

The salinity of the post-Zechstein formation waters shows an almost linear increase in salinity with depth. The major solutes are sodium-, calcium-, magnesium-, and potassium chloride. The ions found in minor concentrations are bromide, strontium, sulfate and bicarbonate.

Analyses have shown an increase in the calcium to chloride ratio with depth, and a narrow range of the bromide to chloride ratios. This indicates a common origin of the post-Zechstein formation waters.

The salinity increase is interpreted as due to filtration of the interstitial waters through semipermeable membranes which allow only H_2O and some of the ions to pass through. As the compaction of the sediments proceed, the interstitial water will be progressively more concentrated.

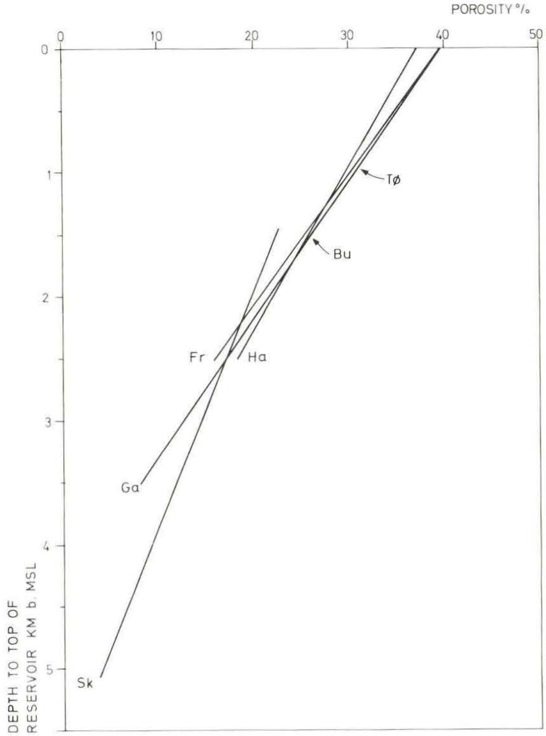

Fig. 3. Porosity gradients for geothermal reservoirs. The statistical calculated trend lines are based on log and core porosity data.

Depth versus porosity

The different depth/porosity trends of the geothermal reservoirs can be illustrated by the variations in porosity gradients which are 5.3% per 1000 m for the Skagerrak Formation, 9.0% per 1000 m for the Gassum Formation, 7.8% per 1000 m for the Haldager Sand and 9.4% per 1000 m for the Frederikshavn Member. No gradients are established for the Bunter Sandstone and Tønder Formations.

A comparison between the linear regression trends of the geothermal reservoirs shows that the Frederikshavn Member, Haldager Sand, and Gassum Formations have almost the same linear decrease of porosity with depth (fig. 3), from about 35% porosity at 500 m to 20–25% at 2000 m and 10–15% at 3000 m. The data from the Tønder and Bunter Sandstone Formations have no porosity/depth trend, but the data clouds of the formations fall within the stated trend; about 30% at 1000 m and 25% at 1500 m.

The linear trend and porosity gradient of the Skagerrak Formation indicates a less drastic decrease in porosity with depth compared to the abovementioned trend. The decrease is from about 20–25% porosity at 1500 m to 0–10% at 5000 m. Consequently, the porosity of the Skagerrak Formation is lower than for the other reservoirs at a given depth between 1500 and 2000 m, whereas the porosity of the Skagerrak Formation is higher below 2500 m. In the range 2000–2500 m, all reservoirs have porosities of 15–25%.

Porosity versus permeability

The porosity/air-permeability trends established for each geothermal reservoir are compared in fig. 4. They have almost the same linear trend from 40 mD permeability at 15–18% porosity down to 1 mD at 2–4% porosity. Above 40 mD at 15–18% porosity, the Skagerrak Formation and Haldager Sand have a common, "high permeability" trend with 2000 mD air-permea-

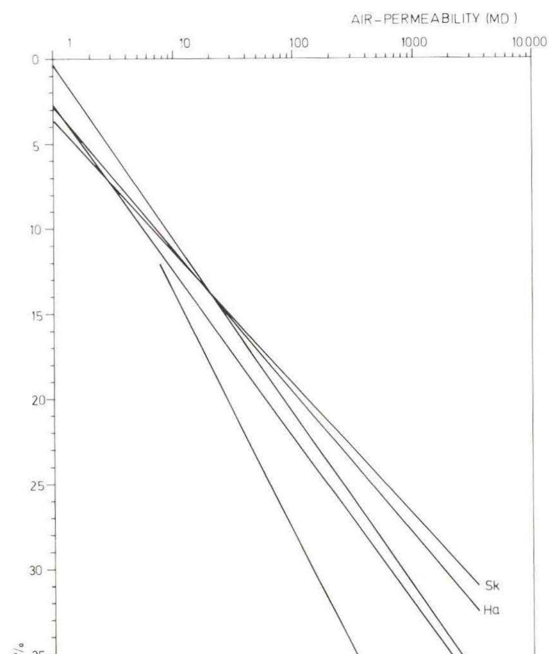

Fig. 4. Relationship between porosity and air-permeability for geothermal reservoirs. The lines of best fit are based on core data.

bility at 30% porosity, whereas the Gassum and Bunter Sandstone Formations have a trend predicting 2000 mD air-permeability at 35% porosity.

Using these trends together with the depth/porosity relations, a rough indication would be that 40 mD permeability is found at 2500 m depth and, for a given depth above 2500 m, the Haldager Sand and Skagerrak Formation will have higher air-permeability (almost a factor two higher) than will the Gassum and Bunter Sandstone Formations.

The reduction from air- to brine-permeability is found to about 50% around 100 mD air-permeability. This reduction is valid for the total permeability range of the Bunter Sandstone and Skagerrak Formations. At about 1000 mD air-permeability, the reduction is 30% for the Gassum Formation and about 25% for the Haldager Sand. Above 1000 mD, the decrease is negligible.

If the sedimentary environment, diagenesis, depth/porosity and porosity/permeability relationships are considered as a whole, it may be concluded that the relatively high-energy Haldager Sand and Skagerrak Formation, have similar porosity/high permeability trends although they differ in diagenetic history and, in certain localities, in lithology. This may cause the differences in porosity gradients where the Haldager Sand has high porosities at shallow depth of burial compared to the Skagerrak Formation. With a reduction of 25–35% from air- to brine-permeability for the Haldager Sand, compared to 50% for the Skagerrak Formation, the properties of the Haldager Sand are the most favourable of these two reservoirs. The Skagerrak Formation however, has a much greater net sand thickness but it also has a province of volcanic materials resulting in extensive diagenesis causing low reservoir quality.

Of the formations with moderate to low energy environments, a porosity gradient can only be established for the Gassum Formation. However, the data of the Bunter Sandstone and Tønder Formations appear to cluster around the same gradient. The porosity/air-permeability trends for the Gassum and Bunter Sandstone Formations are similar but a difference is noted in air- to brine-permeability reduction with better reservoir properties in the Gassum Formation.

Although the porosity gradient of the Frederikshavn Member follows the general trend as shown in fig. 3, the very early cementation with glauconite causes severe damage to the reservoir as indicated by the porosity/low permeability trend.

Despite the great differences in sedimentary environments, diagenesis, and porosity/permeability values of the reservoirs, and bearing in mind the limitation in data on which the gradients and trends are based, the geothermal reservoirs in Denmark, as known today, have characteristics which fall within broad bands with a common decrease in porosity with depth. The porosity band is from 30–40% porosity at abcut 500 m depth to 5–15% at about 3500 m depth, and the brine-permeability is in the range 300–3000 mD at about 30% porosity decreasing to 10–30 mD at 15% porosity. Most likely, the reservoirs will fall, within these broad trends. The analyses presented for each reservoir indicate that the reservoir potential at depths below 2500 m is low.

Formations

Zechstein Formations

The Zechstein carbonates only have a small geothermal potential which is considered to be highest where reservoir rocks are found in combination with fracturing. This may occur along the margins of the basement blocks along the southern flank of the Ringkøbing-Fyn High. A limiting factor for the geothermal potential is the risk that poisonous hydrogen sulphide and highly corrosive, acidic pore fluids, may be present.

Bunter Sandstone Formation

In the southern and southwestern part of southern Jylland, transmissivities are probably in the range of 2.5 to 25 Darcymetres. In the troughs, the formation is thicker and the transmissivity high. The reservoir bodies may be sheets. The temperatures are 50–70°C. On Lolland-Falster, the temperatures are lower (about 40°C) because of a more elevated position of the formation. The northern boundary of North German Basin, as defined by the Ringkøbing-Fyn High, may be a reservoir area because of the increasing sandy content with approach to the Skagerrak Formation further to the north. Temperatures north of the Ringkøbing-Fyn High on Sjælland are 50–70°C.

Tønder Formation

In Jylland, around the Ringkøbing-Fyn High and southwards to the central part of southern Jylland, transmissivities are 5–10 Darcymetres. Temperatures are 30–50°C. The small amount of data however, makes the transmissivity estimates rather uncertain.

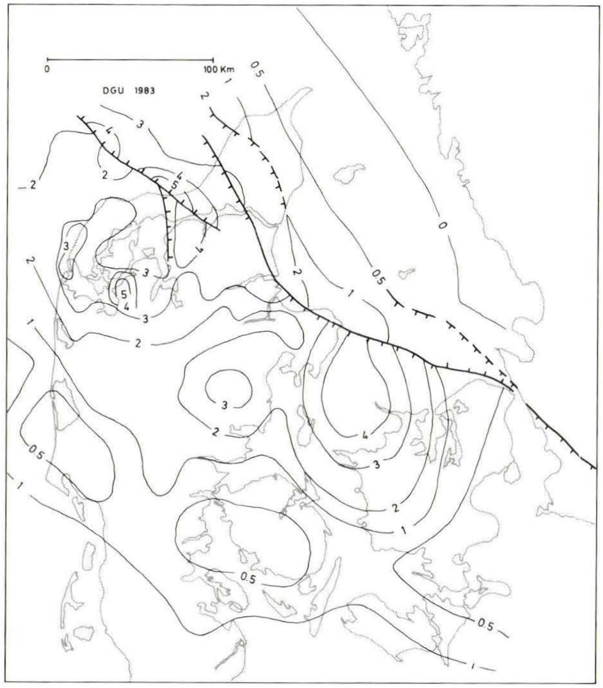

Fig. 5. Generalized isopach map of the Triassic sequence. Thickness in kilometres.

Skagerrak Formation

In areas where the formation is situated above 2000–2500 m depth, and where the depositional environment is the braided river regime, transmissivities may be in the order of 20 Darcymetres.

In the central part of the Danish Subbasin, the formation is situated more deeply and thus has a lower permeability, except above salt structures where the transmissivity may be high. Further, positive temperature anomalies can be present above the salt structures. A westerly province with the volcanic materials will have reduced transmissivities.

In the Fennoscandian Border Zone, the depositional environment is dominated by poorly sorted alluvial fan deposits and thus the permeability will be lower. Sand body extension is probably relatively small.

In general, the estimates of the Skagerrak Formation are questionable because of few data.

Gassum Formation (fig. 6)

In areas where the formation is situated shallower than 2000 m depth, and where net sand is relatively thick, transmissivities may be greater than 5 Darcymetres. In most of the Ålborg Graben and in parts of Mid-Sjælland, these conditions should be fulfilled. The temperatures are 40–70°C here. In addition, areas above salt structures in the central part of the Danish Subbasin may have similar, or even considerably better, reservoir properties.

In the deeper part of the Danish Subbasin, down to 3000 m, transmissivities are 0.5–5 Darcymetres and temperatures are 60–100°C. The sandy platform environment should be present in most of the above-mentioned areas and thus relatively extensive sand bodies are expected.

On Lolland-Falster, net sand thicknesses of 50–70 m are found. The depth to the formation is 500–700 m here, and the temperatures are 20–30°C. An estimate of other reservoir properties can not be given for this region at the present time.

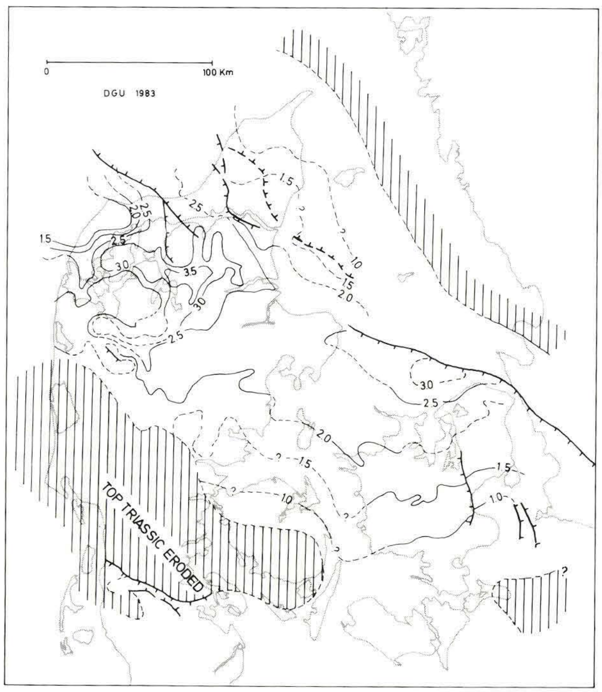

Fig. 6. Generalized depth map to top of Gassum Formation/near top Triassic. Depth in kilometres.

Haldager Sand (fig. 7)

In areas where the member is deposited as relatively extensive sand bodies in a braided river environment and where it is situated at depths less than 2000 m, transmissivities of 10–20 Darcymetres may be present. The net sand thickness is, however, expected to vary locally. The above-mentioned conditions are probably present in the Ålborg Graben, especially in the southern part where the braided river environment dominates. Further, in relation to salt structures in the central part of the Danish Subbasin, transmissivities may be high. The transmissivity elsewhere in the area is possibly around 1–5 Darcymetres. Temperatures in the Ålborg Graben are 40–60°C, and 60–80°C in the central part of the Danish Subbasin.

Frederikshavn Member (fig. 8)

In the Fennoscandian Border Zone in Jylland, in the Ålborg Graben and in the easternmost part of Jylland, transmissivities may be in the order of 10–20 Darcymetres. The lateral extension of the sand bodies may be relatively

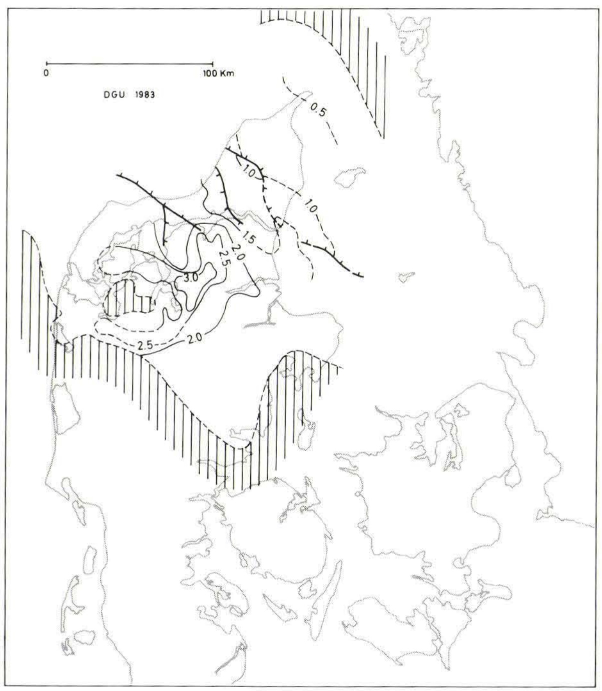

Fig. 7. Generalized depth map to top Haldager Sand. Depth in kilometres.

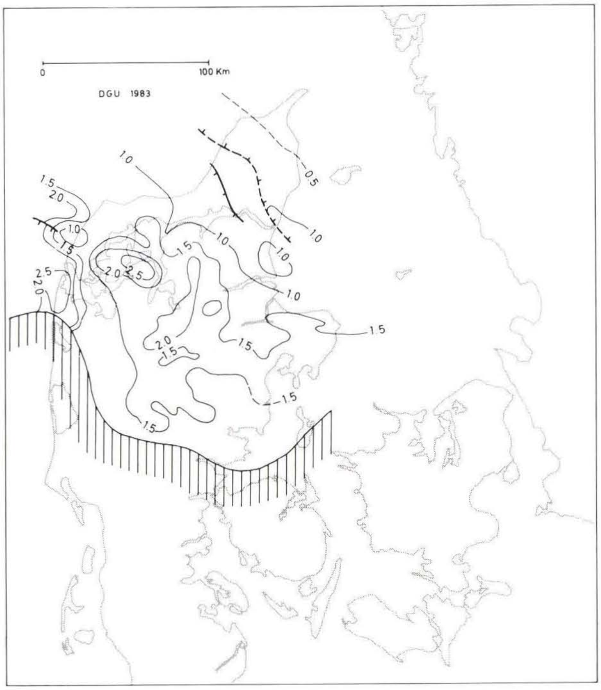

Fig. 8. Generalized depth map to top of Frederikshavn Member. Depth in kilometres.

large. Temperatures of the member are 20–40°C in northern Jylland and 50°C in the eastern part of Jylland. Due to the poor quality of the material however, the estimates of the transmissivity are uncertain and the postulated values may be too high.

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