Assessment of Geothermal Resources and Reserves in Denmark

A contribution to the geothermal resource and reserve estimate of the European Community

DGU
Geological Survey of Denmark

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A DGU – EC project

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INTRODUCTION

Project framework and objective

In 1979 the European Community (EC) Directorate-General for Research and Development invited the member states to look into the aspects of geothermal resource and reserve evaluation and practical implimentation of the assessment exercise within the EC.

From fall 1979 to fall 1981 a working group, in which Denmark was represented by E. Gosk, set up guidelines for a discription, classification, and evaluation of geothermal resources and reserves. The guidelines are basically those outlined by Muffler and Cataldi (1978), USGS Circ 790, and applied by Cataldi et al. (1978).

Contractors working on geothermal energy within the EC were from 1982 involved in the assessment of geothermal resources and reserves. From Denmark the company Danish Oil and Natural Gas A/S (D.O.N.G. A/S) and the Geological Survey of Denmark (DGU) were invited to participate in the assessment. D.O.N.G. A/S was involved as the company had the concession on geothermal energy in Denmark and was making exploration drilling. DGU was involved as the survey up to that date had made the regional mapping of the reservoirs (Michelsen et al. 1981) and was involved in contract work for the EC.

The contract (no. EG-B-3-005-DK(G)) between EC and DGU, 1981-1982, had the goal of investigating the reservoir proporties of possible geothermal reservoir rocks. The study was terminated with the report "Geothermal Reservoirs in Denmark" (Priisholm et al. 1982).

The above mentioned contract was by a First Supplementary Agreement extended to cover 1983 with the aim of making an assessment of the geothermal resources and reserves in Denmark. The work is terminated with this final report.

The report is based on the general geological knowledge of the reservoir proporties which are available at the survey from the previous studies and on data made available through the exploration activities of D.O.N.G. A/S. The evaluation of assessments has been carried out as a joint work where D.G.U. has contributed with the geology and reservoir data while Tage Sørensen A/S made the resource and reserve assessments.

Contributors

S. Priisholm: Geology and reservoir data.

S. Christensen: Resource and reserve assessment.

The geological part has been reviewed by L. Holm and suggestions to the resource and reserve assessment as well as major contributions to the appendicies I & II has been made by G. Iversen (D.O.N.G. A/S). F. Larsen performed the planimetry of the areas.

Drafting was carried out by Kirsten Andersen, Eva Melskens and coordinated by Uli Jørgensen.

The typing was performed by Dorthe Plougmann.

RESERVOIR DATA FOR ASSESSMENT

The guidelines for the assessment of geothermal resources and reserves are given by EC, DG XII, in working documents of 31 March 1980 and January 26th 1982. The documents are based on work by Muffler and Cataldi (1978).

The reservoir assessment require data and maps which gives

I Lateral extend of each aquifer.

II Isotherm map of each aquifer.

III Net pay, porosity, permeability, transmissivity.

These and other relevant data are presented in the report by Priisholm et al. (1982) and the DONG A/S reports: "Undersøgelse af geologi, marked, teknik og økonomi for potentielle geotermiske anlæg i Midt- og Nordjylland". (July 1980) and "Undersøgelse af geologi, marked og økonomi for potentielle geotermiske anlæg i Sønderjylland og på Sjælland". (Febr. 1982).

Data and maps used for calculations are presented on figs. 1-10 and in tables 1-10 in this report.

A brief outline of parametre origin and trends as well as of the individual reservoirs are summarized in the following. Details are given in Priisholm et al. (1982).

Definition and origin of parametres Table 1-5

Reservoirs

The reservoirs drawn into consideration are the Bunter Sandstone Formation, Skagerrak Formation, Gassum Formation, Haldager Sand, and Frederikshavn Member (Fig. 3).

Depth intervals

It has been convenient in the analysis to divide the reservoirs in 0,5 km thick sequences, as most reservoir parametres are depth dependent.
The individual depth sequences has been chosen from the maps shown on fig. 4-8.

Regions

Within the 0,5 km thick depth sequences some of the reservoir parametres show lateral variation. Where this is the case the reservoirs have been divided into regions in order to limit these variations.

Areas

The area of the regions has been measured using planimetry.

Temperature

Temperature data are based on tabulations and maps presented in reports by Balling et al. (1981), Priisholm et al. (1982), and Saxov (1978).
These data have been interpolated using model A temperatures to give the average temperature at mean depth of the reservoir interval of a given region.
The determination of reserves does not alter with

moderate temperature variations, and hence only an average value is sufficient.

Porosity

By using the porosity versus depth plot of each reservoir (Fig. 9) and well data from a specific region the average porosity at mean depth of the reservoir interval has been calculated.

Moderate porosity variations does not alter the resource and reserve estimates, and hence an average value used.

Brine-permeability

Average, as well as minimum and maximum brine-permeability values for a certain reservoir interval are determined by using the correlation charts between porosity and depth, porosity and air-permeability (Fig. 10), and air- versus brine-permeability. Well data, including test results, and reservoir configuration has been taken into consideration.

The permeability parametre is critical in reserve analyses. Therefore and because the parametre is difficult to establish with certainty average as well as minimum and maximum values have been used.

Net reservoir thickness

Net thickness includes the sandstone layers which are considered to have reservoir quality and which could produce.

Transmissivity

The productivity of the reservoir, the transmissivity, is the brine-permeability multiplied by net reservoir thickness.

The tranmissivity is a very difficult value to measure or to calculate with certainty. The average, minimum, and maximums transmissivity has been estimated by using the brine-permeability, and the net sand thickness values as well as the knowledge from tests and sedimentological facies analyses.

Outline of parametre trends

Parametres governing the reservoir characteristics and the performance of the reservoir rocks are the sedimentary environment, diagenesis, temperature-distribution, salinity, porosity,and permeability trends with increased depth.

Sedimentary environment

In order to map the parametres of the sedimentary reservoir rocks, a classification into sedimentary environments has been carried out. In the interpretation this classification is important because the lateral reservoir extension, the net sand, porosity, and permeability are related to the type of sedimentary environment.

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 above-mentioned sediments and was deposited under intermediate energy conditions.

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

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

Diagenesis

The degree of diagenesis of the reservoir is important to know in order evaluate the porosity and permeability. It has been evaluated with the aid of thin sections, x-ray, SEM, and heavy mineral studies.

The Bunter Sandstone and Skagerrak Formations have suffered redbed diagenesis with the formation of hematite, authigenic feldspar, and carbonates. The Skagerrak Formation, when containing easily dissoluble volcanic material, have especially strong diagenetic effects which resulted in lower porosity.

The Gassum Formation becomes increasingly cemented with increasing temperature (depth). Dissolution of felspars 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 of each formation and at depth of 2000 m and 3000 m 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 degree C and 75 degree C at 2000 m depth, and between 75 degree C and 105 degree C at 3000 m depth. In the deepest part of the Skagerrak Formation in the Danish Subbasin, temperatures may reach 100-150 degree C.

Salinity

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

The salinity of the formations-waters in question 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.

Depth, porosity, and permeability

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 about 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 reservoir values will fall, within these broad trends. The analyses presented for each reservoir indicate that the reservoir potential at depths below 2500 m is low.

Depth versus porosity Fig. 9

The different depth versus porosity trends of the geothermal reservoirs can be illustrated by the variations in porosity gradients which are 5% per 1000 m for the Skagerrak Formation, 9% per 1000 m for the Gassum Formation, 8% per 1000 m for the Haldager Sand and 9% per 1000 m for the Frederikshavn Member. No gradients are established for the Bunter Sandstone Formation.

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. 9), from about 35% porosity at 500 m to 10-15% at 3000 m. The data from the Bunter Sandstone Formation have no porosity/depth trend, but the data clouds of the formation fall within the stated trends; 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 above-mentioned trend. The decrease is from about 20-25% porosity at 1500 m to 0-10% at 5000 m. The lower gradient of the Skagerrak Formation cause the trend line of this formation to cross the other trend lines at 2000-2500 m depth. Consequently, the porosity of the Skagerrak Formation is lower than for the other reservoirs at a given depth above 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 Fig. 10

The porosity/air-permeability trends established for each geothermal reservoir are compared in fig. 10. 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-permeability 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 the Gassum and Bunter Sandstone Formations. In the Bunter Sandstone and Skagerrak Formations the analysis of the reduction going from air- to brine-permeability is found to be in the range of 50%.

For the Gassum Formation and the Haldager Sand the decrease from air- to brine-permaebility is negligible above 1000 mD. At 1000 mD air-permeability the reduction is 30% for the Gassum Formation and 25% for the Haldager Sand. Near 100 mD the reduction is 50% for both reservoirs.

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 (Fig. 10). 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 favorable 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 deposited in moderate to low energy environments, a porosity gradient can only be established for the Gassum Formation. A similar trend could be expected for the Bunter Sandstone Formation. 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. 9, the very early cementation is indicated by the porosity/low permeability trend.

General outline of geothermal reservoirs

Based on the report "Geothermal Reservoirs in Denmark" a general outline of the geothermal reservoirs in Denmark can be given.

Regional description of the rocks are previously published by Bertelsen (1978 and 1980), Larsen (1966), and Michelsen (1978 and 1981).

The possible reservoirs considered here are the Lower Triassic Bunter Sandstone Formation 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 to Lower Cretaceous Frederikshavn Member, situated in the Danish Subbasin (Fig. 3).

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 in fig. 6-8 .

Bunter Sandstone Formation

In the southern and southwestern part of southern Jylland, transmissivities are probably in the range of 5 to 25 Darcymetres. In the troughs, the formation is thicker and the transmissivity is hence expected to be high. The reservoir bodies may be characterized as sheet with a possible great areal extension, measured in kilometres of width. The temperatures are 50-70 degrees C. On Lolland-Falster, the temperatures are lower (about 40 degrees C) because of a more elevated shallow 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 Skagerrak Formation further to the north. Temperatures north of the Ringkøbing-Fyn High on Sjælland are 50-70 degrees C.

Skagerrak Formation

In areas where the formation is situated above 2000-2500 m depth, and where the depositional environment is the braided river regime with extensive sand bodies, 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 pillows 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 North and Middle Jylland transmissivities may reach the order of 25-50 Darcymetres and at shallow depth, 1000-1500 m, in North Jylland 50-75 Darcymetres can be encountered locally.

In the Fennoscandian Border Zone (North Jylland), the depositional environment is dominated by alluvial fan deposits which generaly are poorly sorted and thus the permeability will be lower. Sand body extension is probably relatively small measured in hundreds of metres.

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 in the order of 10-20 Darcymetres or even higher. In most of the Ålborg Graben and in parts of Mid-Sjælland, these conditions should be fulfilled. The temperatures are 40-70 degress C here. In addition, areas above salt structures in the central part of the Danish Subbasin may have similar reservoir properties (e.g. Thisted structure, more than 100 Darcymetres).

In the deeper part of the Danish Subbasin, down to 3000 m, transmissivities are 0.5-5 Darcymetres and temperatures are 60-100 degrees C. The depositional environment is the shallow marine platform, in which the sandstone bodies most commen will have an extent within houndreds of metres but they may coalesce to form bodies of greater extent.

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 degrees C. An estimate of other reservoir properties can not be given for this region at the present time because of lack of sufficient data, but high transmissivities, in the order of 50 Darcymetres may be expected.

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 may be in the order of 10-20 Darcymetres. 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 5 Darcymetres. Temperatures in the Ålborg Graben are 40-60 degrees C, and 60-80 degrees 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 large. Temperatures of the member are 20-40 degrees C in northern Jylland and 50 degrees 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.

RESOURCE AND RESERVE ASSESSMENT

The guidelines for the assessment of geothermal resources and reserves are given by EC, DG XII, in working documents of March 31st 1980 and January 26th 1982. The documents are based on work by Muffler and Cataldi (1978).

As only low-enthalpy geothermal resources are found in the Danish sedimentary basins, the evaluation procedure is reduced to what is outlined in fig. 11. Corresponding definitions, formulae and nomenclature are found below (see also Fig. 12).

Definitions and formulae

The following definitions and formulae are those valid for low-enthalpy geothermal reservoirs.

Accessible Resource Base (ARB)

(ARB) is the heat stored in rocks and fluids below a specific area down to a depth (7 km) accessible by current drilling technology and practice and measured as the temperature rise from mean (annual) ground temperature to actual temperature at depth. Per unit area ARB is expressed as:

(1) $$ARB = \int_o^h C_t(h) x (T(h)-T(h=o)) x \, dh.$$

where $C_t(h)$ is the total heat capacity in the reservoir at depth h.

$T_D(h)$ is the temperature at depth h.

T(h=o) is the local mean annual ground temperature.

A detailed description is given in appendix II.

The total heat capacity of the reservoir (rocks and fluids) is found as:

(2) $C_t(h)=\emptyset(h) \times C_W(h) + (1-\emptyset(h))\ C_r(h)$

where $\emptyset(h)$ is the reservoir effective porosity at depth h.

$C_W(h)$ is the fluid heat capacity at depth h.

$C_r(h)$ is the rock heat capacity at depth h.

For more detailed analyses please refer to appendix I.

Geothermal Resource (GRSCE)

GRSCE is the heat or/and energy in place stored in a reservoir volume characterized by exploration evidence and which could be produced at some future time. All actual reservoirs can be characterized as low enthalpy Hot Wet Rocks (HWR) (low enthalpy reservoirs are hot water reservoirs with a temperature below 150 degrees C). According to this fact, the HWR resources in the actual case only consists of Heat in Place (HIP).

Heat in Place (HIP)

Per unit reservoir volume HIP is equal to the sum of heat stored in the host rock and in the fluid, assuming thermal equilibrium and measured from the mean annual ground temperature, e.g.:

$$(3)\ HIP = C_t \times (\bar{T} - T_O)$$

where C_t is the total heat capacity in the reservoir.

$\bar{T}$ is the mean temperature in the reservoir.

T_o is the local mean annual ground temperature.

Identified Resources (IR)

IR represents that part of the geothermal resources economically and legally produceable at some specified time in the future. For a low enthalpy hot water system IR can be written (permit volume)

(4) IR = RHW MAX x HIP where

RHW MAX (Max. Recovery Factor) gives the ratio of the entire amount of energy in a reservoir (HIP) which is practically extractable (IR). For a doublet practical experience in France has shown, that RHW MAX can be calculated as (see Lavigne 1978):

$$(5)\ RHW\ MAX = 0.33 \times \frac{\bar{T} - 25°C}{\bar{T} - 8°C}$$

See also formula (7).

Identified Reserves (IRSVE)

IRSVE is the gain in energy when exploiting the identified, geothermal resources. This is expressed by a recovery factor RHW, which is difficult to determine. The factor depends on the site specified geological conditions as well as on the costs of installation and operation of heating plant and distribution system. According to the calculations made by Wurtz in Michelsen et al. 1980 RHW is roughly estimated to be 50%. IRSVE is then found to

(6) IRSVE = 0.5 x IR

IRSVE (or parts of it) is characterized as either proven, probable or possible reserves.

Proven Reserves represents that part of IRSVE which is supported by geological and drilling evidence (e.g. direct assessment) at the time of determination.

Probable Reserves represents that part of IRSVE which is based on geological, geophysical and/or geochemical (but not local drilling) evidence at the time of determination.

Possible Reserves represents that part of IRSVE which is based only on geological evidence at the time of determination.

Discussion of parametres

Accessible Resource Base (ARB)

ARB is a theoretical estimate of the geothermal heat, that could be available with the current drilling technology. Despite ARB represents the heat stored down to a depth of 7 km, it is today only technically and economically feasible to exploit the part stored above 3 km depth. According to calculations in Appendix II this forms a 25% of the total ARB.

The pratical relevance of the determination of ARB is moderate compared with the relevance of the determination of the identified geothermal reserves, that today or in the near future can be exploited. For that reason ARB is only calculated for a typical, geological profile from the central part of the Danish Subbasin. The variation in relevant parametres above a depth of 7 km, is limited and the calculated order of magnitude of ARB is considered as typical for the entire Danish area. The value therefore can be used to compare the future possibilities of geothermal energy exploitation in Denmark and other European countries.

Calculating ARB it is assumed, that the temperature gradient from the surface to a depth of 3150 m is constantly 0.028 degrees C/m. Below this depth the temperature gradient is assumed to be 0.020 degrees C/m. This simplification introduces an uncertainty on ARB, that is considered less than 10%. That the sensitivity of ARB to temperature variations is moderate, is illustrated by a calculation with a constant temperature gradient of 0.024 degrees C/m. The difference between the two results is less that 6%.

In Appendix I the uncertainty of the total heat capacity is found to be lower than 10%. The total uncertainity in the ARB calculation is therefore considered to be lower than 20%.

Heat in Place (HIP)

Contrary to ARB, HIP is reservoir specific and gives the stored heat in the reservoir. The determination of HIP is based on exploration, confirming that the resources is technically exploitable. HIP is found to some extent in the previously described fairly permeable formations.

The basis for calculations is improved according to the explorations compared with the basis for determination of ARB. Uncertainty in the HIP determination therefore is considered to be less, probably around 10-15%.

Identified Resources (IR)

IR represents that part of the geothermal resource being economically and legally produceable as district heat energy. The temperature conversion between the geothermal and district heating water takes place by means of a heat pump plant. The detailed description of the method appears in Michelsen et al. 1980.

From experience, the economic drilling depth is about 3 km, the minimum mean reservoir temperature about 40 degrees C, and the minimum transmissivity about 5-10 Darcymetres, (see Koppe et al. 1983). These limits though may change in the future.

It is not considered, whether or not there are consumers of the produced heat within an economically acceptable distance from the geothermal heating plant.

Determing IR, the geothermal heating plants are assumed to be single doublet systems (i.e. one extraction and one injection well). If another design is chosen, IR as mentioned below can be changed essentially.

According to the uncertainties in the determination of HIP and RHW MAX, the uncertainty in the determination of IR is considered to be approximately 35-40%.

<u>Max. Recovery Factor (RHW MAX)</u>
The magnitude of RHW MAX is dependable on design and operation of the geothermal heating plant. For instance Gringarten (1978) shows, that production with reinjection of heat depleted water will increase the heat recovery by several orders of magnitude. Further greater lifetime and heat recovery factors are obtained by alternating injection and production wells. This is illustrated in Michelsen et al. 1980. For four Danish geothermal reservoirs it is shown, that, depending on the number and placing of extration and injection wells, RHW MAX might vary within a range from 0 to 75%. Assuming an ideal well configuration a single doublet, a two doublet and a (theoretical) infinite lattice of doublets was found to have 25%, 40% and 75% max. recovery factors. The calculations are made as given by Gringarten (1978).

It is assumed that the geothermal resources are exploited in single doublet plants. The detailed description of the method appears in Michelsen et al. (1980).

RHW MAX is calculated as:

$$(7)\ \text{RHW MAX} = \frac{S_c}{S_d} \times \frac{\bar{T} - T_i}{\bar{T} - T_o}$$

where S_c is theoretical area cooled by a single doublet exploitation.

S_d is the area influenced by a geothermal doublet.

$\bar{T}$ is the mean reservoir temperature.

T_i is the injection temperature of the heat depleted water.

T_o is the mean annual temperature.

In France practical experience has shown, that the area ratio is about 0.33, see Lagivne (1978). The mean annual ground temperature in Denmark is about 8 degrees C, while the injection temperature is assumed to be 25 degrees C. Using these values in (7), (5) is found. The uncertainty on RHW MAX is considered to be up to 25%.

Identified Reserves (IRSVE)

In this report it has only been possible to estimate the Identified geothermal Reserves in Denmark roughly as 50% of the Identified Resources. However, because of uncertainty in most of the significant parametres and lack of practical experience in geothermal energy exploitation in Denmark there will always be great uncertainty about such an estimate. The uncertainty on the reserve determination is with the used method considered to be about 50%.

Still all identified reserves in Denmark is to be characterized as possible reserves grading towards the classification probable. However, soon the first practical experiences with geothermal heat exploitation will be made. During the last 3 years exploration and establishment of a single doublet pilot plant has been going on in Thisted and since the summer 1984 the plant has been in operation. Reference is made to Magtensgaard (1983).

Results (Table 6-10 and figs. 13-17)

Accessible Resource Base

For at typical, geological profile in the Danish Subbasin the accessible resources base is found to be

1450×10^3 TJ/km^2

(see Appendix II). This corresponds with the energy content in about 35 million tons of oil or the double of the yearly energy consumption in Denmark.

The calculated order of magnitude can be considèred for the entire Danish area, and the total accessible, geothermal resource is estimated to about

60×10^9 TJ.

However, only a small ratio of this energy, the part stored in porous, geothermal reservoirs, can be exploited at the present time (compare with IR and IRSVE found below).

Resources and Reserves

Heat in Place (HIP), Identified Resources (IR) and Identified possible Reserves (IRSVE) are determined for the porous geothermal reservoirs in the Bunter Sandstone, the Skagerrak, and the Gassum Formations and in the Haldager Sand and the Frederikshavn Member. The results and parametres making the basis for the determination are shown in table 6-10 and figs. 13-17. The following should be noticed:

The total value of HIP, IR and IRSVE in Denmartk is calculated to

770.1 x 10^6 TJ, 206.4 x 10^6 TJ, and 103.2 x 10^6 TJ respectively.

(See Appendix II).

Only about 25% (IR) of the geothermal heat stored in the reservoirs (HIP) can be exploited with the used method. Because of the cost of design and operation of the heat plant the gain in energy (IRSVE) is only about 13% of the stored heat.

The distribution of the total resources and reserves is about 3% in the Bunter Sandstone Formation, 70% in the Skagerrak Formation, 20% in the Gassum Formation, 3% in the Haldager Sand and 4% in the Frederikshavn Member.

If the economical minimum limits for mean reservoir temperature (40 degrees C) and transmissivity (10 Darcymetres) given by Koppe et. al. (1983) is considered, the results for HIP, IR and IRSVE has to be reduced with 35%. Practically all geothermal energy stored in the Bunter Sandstone, Haldager Sand, Frederikshavn Member, and more than 80% of the energy stored in the Gassum Formation has to be left out of consideration. However, it is not known whether the limits given by Koppe is valid for geothermal heat exploitation (with the actual method) in Denmark. Further these limits might change in the future.

Conclusion and postscript

It has been shown, that geothermal reservoirs of interest are present in Denmark. The reservoirs are analysed in the depth intervals between 500 m and 3000 m below ground level. The geothermal heat stored in the reservoirs is determined to be

7.7×10^8 TJ.

Assuming an exploitation with single doublets and heat pump plants, the possible gain in energy is about

1.0×10^8 TJ.

To throw this in relief the total heat demand in Denmark is about

1.66×10^5 TJ.

per year (see Appendix III). The demand distribution is illustrated in fig. 19.

Comparing the heat demand distribution in fig. 19 with the determined possible geothermal reserves in tables 6-10 and figs. 13-17 it immediately seems possible to supply most of the heat demand in Denmark from geothermal heat plants. To exploit the geothermal resources in a certain area economically it is still a condition, that a relatively high and concentrated heat demand (e.g. a high district heating demand) is present nearby the plant, see Michelsen (1980). As shown in Dansk Olie & Naturgas A/S et. al (1980) & (1982) only a number of such areas can be found in Denmark, situated outside larger cities, where coproduction of electricity and district heating takes place. Therefore it is only realistic, that a smaller part of the heat demand can be supplied from geothermal heat plants, although the possible reserves can supply the yearly demand several times.

The results presented in this report have been based on data and conclusions from wells drilled up to the year 1983. Since then further reservoir studies have been carried out as well as new wells have been drilled to test the Haldager and Gassum Formation (Thisted) and the Bunter Sandstone (Tønder).

In both areas the reservoirs are at depths above 2000 metres. The reservoir rocks are unconsolidated to slightly consolidated sands, which have proven to have marked better reservoir proporties than encountered and predicted up to then in more consolidated and deeper reservoirs. This new approach of drilling reservoirs in the depth range of 500-1500 metres may prove very rewarding for future geothermal exploration.

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Appendix I. Uncertainty about total heat capacity

The total heat capacity in a reservoir is determined as:

$$C_t = \emptyset \times C_W + (1 - \emptyset) \times C_r$$

where $\emptyset$ is the reservoir porosity

C_W is the heat capacity of the fluid (permit volume)

C_r is the heat capacity of the rock (permit volume)

The uncertainty about C_t depends on the three significant parametres:

Heat capacity of the fluid (C_W)

C_W depends on temperature and salinity. The temperature depth relation is simplified as:

$$T = 10 + 0.030 \times d \quad (°C)$$

where T = is the temperature (°C)

d is depth (m)

The salinity is estimated to 10% at 1000 m, 18% at 2000 m, and 26% beyond 3000 m. From these relations C_W is determined in table I. 1. The uncertainty about C_W introduced by the simplified temperature and salinity relations is assessed to be less than +/- 5%.

Table I.1. Calculations of C_W based on simplified depth relations of temperature and salinity.

Depth m	Temp. °C	Salinity %wt.	C.avg.heat Kj/kg°C*)	P, density Kg/m³ *)	C_W Mj/m³ °C
1000	40	10	3.70	1060	3.92
2000	70	18	3.41	1035	3.70
3000	100	26	3.23	1120	3.62
4000	130	26	3.23	1105	3.57
5000	160	26	3.25	1090	3.54

*) Values from L. Berkeley Lab.: Aqueous Sol. Database to High. Temp. and Press. NaCl Solutions.

Heat capacity of the rock (C_r)

C_r is about 2.2 MJ/(m³ x C). The uncertainty about this value is +/- 5%.

Porosity (Ø)

The variation in Ø is given in table I.2 at different depths to the Skagerrak and Gassum Formations and the Haldager Sand. C_t is calculated from the above given values of C_W and C_r and the porosities given in table I.2. This gives the distribution shown in fig. 18. It is seen that for all formations the variations in C_T is less than +/- 5%.

Total uncertainty about C_t

From the evaluations shown above the total uncertainty about C_t is estimated to be less than 10%.

Table I.2. Porosity variations of the Skagerrak Formation, Gassum Formation and Haldager Sand.

depth m b.MSL	porosity avr.	min.	max.
Skagerrak Formation			
2000	20	15	25
3000	15	10	20
4000	9	5	13
5000	5	2	8
Gassum Formation			
1000	30	23	40
2000	21	14	28
3000	12	9	16
Haldager Sand			
1000	30	23	37
2000	22	16	27

Appendix II. Calculation of ARB

The accessible resource base (ARB) is found by integration as:

$$(1)\ ARB = \int_{o}^{h} C_t(h) \times (T(h = O)) \times dh$$

where $C_t(h)$ is the total heat capacity at depth h

$T(h)$ is the temperature at depth h

h is the depth below ground level

The ARB calculation is based on the knowledge about the stratigraphic profile in the Danish Subbasin. This is illustrated in table II.1., where the units are characterized by lithology, porosity and vertical extension of the layers. The profile during the calculation is separated in (N) intervals, where C_t is approximately constant. (1) then can be rewriten to

$$(2)\ ARB = \sum_{i=1}^{N} \int_{h_{i-1}}^{h_i} C_{ti}\ (T(h) - T(h=o))\ dh$$

According to table II.1. the intervals are separated at the following depths:

100, 1750, 2400, 2450, 3150, 3300, 4400, 6500 and 7000 metres below ground level.

The rise in temperature is assumed constant 0.028°C/m from the ground level through the first five layers (O-3150). Below this is assumed a temperature rise of 0.020°C/m.:

$$(3)\ T(h)=T(h=O) + 0.028 \times h; \quad O \leq h \leq 3150\ m$$

$$T(h)=T(h=3150) + 0.020 \times (h-3150); \quad 3150\ m \quad h \leq 7000\ m$$

(2) and (3) gives:

$$(4)\quad ARB = \sum_{i=1}^{5} \int_{h_{i-1}}^{h_i} \left\{ C_{ti} \; (0.028 \times h) \; dh \right\} + \sum_{i=6}^{9} \int_{h_{i-1}}^{h_i} C_{ti} \; (T(3150) - T(o) + 0.020(h-3150))dh \Big\}$$

which integrated gives:

$$(5)\quad ARB = \tfrac{1}{2} \times 0.028 \sum_{i=1}^{5} \left\{ C_{ti}(h_i^2 - h_{i-1}^2) \right\} + 0.020 \sum_{i=6}^{9} \left\{ C_{ti}(\tfrac{1}{2} h_i^2 - 3150 \; h_i \div \tfrac{1}{2} \; h_{i-1}^2 + 3150 \; h_{i-1}) \right\} + (T(3150) - T(o)) \sum_{i=6}^{9} \left\{ C_{ti}(h_i - h_{i-1}) \right\}$$

As the heat capacity of sandstone is used 2.2 MJ/(m^3 x °C). In lack of better information the same value is used for clay- and limestone, while the heat capacity of rock salt is about 2.0 MJ/(m^3 x °C). The variation in fluid heat capacity is calculated as shown in APP.I (the same variation in salinity is used). The calculation of total heat capacity is shown in table II.2.

In table II.2. the calculation of ARB is shown. The total accessible resouce base is estimated to 1.45 x 10^6 TJ/km^2. It is worth noticing, that only about 25% of ARB is found above a depth of 3150 m.

Table II.1. Simplified stratigraphic column of the Danish Subbasin

Period	m b.MSL	Lithology	Porosity % avg.	min	max
Quarternary	0-100	claystone	49	42	55
U.Cretaceous	100-1750	limestone	23	10	29
-	100-350	-	28	26	29
-	350-650	-	25	22	28
-	650-800	-	27	25	28
-	800-1000	-	23	20	27
-	1000-1100	-	20	15	25
-	1100-1750	-	14	10	18
L.Cretaceous	1750-2150	claystone	30	28	32
U.Jurassic	2150-2350	-	20	18	25
-	2350-2400	-	27	24	30
M.Jurassic	2400-2450	sandstone	22	20	27
L.Jurassic	2450-3150	claystone	18	15	21
L.Jurassic/ U.Triassic	3150-3300	sandstone	12	9	17
Triassic	3300-4400	claystone/salt	15	12	18
-	4400-6500	sandstone/clayst.	5	0	10
Zechstein	6500-7000	salt	0	-	-

Table II.2. Calculation of Accessible Resource Base

Interval i	Depth h m	Temp. $\overline{T}$ °C	Salinity %wt	Fluid heat capacity C_w MJ/(m³ x°C)	Rock heat capacity C_r MJ/(m³ x°C)	Porosity Ø %	Total heat capacity C_t MJ/(m³ x°C)	Acc.Resource Base ARB 10^9 MJ/km³
1	0-100	9	0	4.19	2.2	49	3.2	0.4
2	100-1750	34	9	3.95	2.2	23	2.6	111.1
3	1750-2400	66	18	3.71	2.2	25	2.6	98.2
4	2400-2450	76	22	3.68	2.2	22	2.5	8.5
5	2450-3150	86	24	3.66	2.2	18	2.5	137.2
6	3150-3300	98	26	3.63	2.2	12	2.4	32.2
7	3300-4400	110	26	3.61	$\frac{2.2+2.0}{2}$	15	2.3	258.1
8	4400-6500	142	26	3.56	2.2	5	2.3	647.2
9	6500-7000	168	26	3.54	2.0	0	2.0	160.0
							Total ARB:	1452.9

Assumptions: T(o) = 8°C

Appendix III. Netto heat demand

The netto heat demand of Denmark is tabulated in table III.1 and illustrated on fig. 19.
The data are based on a preliminary summary prepated by The Danish Energy Agency, 1983. The data are collected by DEA from the counties and other local authorities.

Table III.1 Netto heat demand according to counties and heating type, TJ/year, status.

County	District heating	Block heating	Gas heating	Central heating	Electrical heating	Unspecified	Total
Metropolitan area	10761	2511	1358	17413	562	5987	38591
Frederiksborg	1345	371	78	6628	1015	902	10339
Roskilde	828	64	4	3901	569	283	5648
Westsjælland	1430	488	66	6628	756	2101	11469
Storstrøm	1256	52	1	6004	654	1057	9024
Bornholm	-	-	-	-	-	-	1500
Fyn	6324	124	32	8794	221	584	15478
Southjylland	2286	547	3	5741	500	476	9552
Ribe	3640	115	0	3534	188	198	7675
Vejle	3334	249	6	7632	259	424	11904
Ringkøbing	3389	45	-	4400	129	278	8241
Århus	6162	44	-	6993	245	122	13568
Viborg	1670	13	2	3741	113	381	5919
Northjylland	6761	381	20	8497	330	710	16699
Total							165607

Table 1

Basic data tabulation

BUNTER SANDSTONE FORMATION

Region	S. Jylland	Loll.-Falster	S. Sjælland	Fyn
Depth interval, km	1.4-2.1	1.0-1.5	1.5-2.0	1.0-1.5
Temp. % mean depth	60	48	58	45
Porosity % mean	28	27	25	30
Brine-permeab. mD average	250	200	100	400
Brine-permeab. mD max.	1100	1100	400	800
Brine-permeab. mD min.	30	35	35	100
Netresou. thickness m average	35	30	50	5
Netresou. thickness m max.	60	50	75	15
Netresou. thickness m min.	5	20	20	0
Transmiss. Dm average	9	6	5	2
Transmiss. Dm max.	15	10	7.5	7.5
Transmiss. Dm min.	1.5	0.5	2	0
Area km^2	2500	2300	2000	2500

Table

Basic data tabulation

SKAGERRAK FORMATION

Region		Vendsyssel	Vendsyssel	Vendsyssel	Himmerland	Thy-Himmerl.	Thy
Depth interval, km		0.5-1.0	1.0-1.5	1.5-2.0	1.5-2.0	2.5-3.0	1.0-1.5
Temp. % mean depth		40	55	65	75	93	50
Porosity % mean		26	24	24	24	16	24
Brine-permeab. mD	average	250	180	180	180	45	280
	max.		1000	1000	1000	100	
	min.					10	
Netresou. thickness m	average	40	50	50	50	200	270
	max.	55					
	min.	25					
Transmis. Dm	average	10	10	10	10	9	75
	max.	14				20	
	min.	6				2	
Area km²		500	1090	200	100	2000	320

Region		Central	Jylland	NW Jylland
Depth interval, km		2.0-2.5	2.5-3.0	>3
Temp. % mean depth		71	85	115
Porosity % mean		18	16	12
Brine-permeab. mD	average	120	45	8
	max.		100	45
	min.		10	3
Netresou. thickness m	average	100	250	500
	max.		450	1000
	min.		100	
Transmis. Dm	average	12	11	4
	max.		20	8
	min.		5	
Area km²		3000	3500	3500

Region		S.-M. Sjælland	M.-N. Sjælland	N.-M. Sjælland	Sjælland
Depth interval, km		1.5-2.0	2.0-2.5	2.0-2.5	2.5-3.0
Temp. % mean depth		63	70	75	88
Porosity % mean		21	18	18	16
Brine-permeab. mD	average	200	120	120	45
	max.				100
	min.				10
Netresou. thickness m	average	50	200	250	250
	max.	75		450	
	min.	20		100	
Transmis. Dm	average	10	24	30	11
	max.	15		50	
	min.	4		10	
Area km²		1950	2800	550	1250

Basic data tabulation

GASSUM FORMATION

Table 3

Region		Vendsyssel	Vendsyssel	Vendsyssel	Vendsys.-Himml.	Himml.-Thy
Depth interval, km		0.5-1.0	1.0-1.5	1.5-2.0	2.0-2.5	2.5-3.0
Temp. % mean depth		40	55	70	80	95
Porosity % mean		33	30	24	19	15
Brine-permeab. mD	average	200	350	300	50	35
	max.	400	1400		70	
	min.	100	100		5	
Netresou. thickness m	average	15	50	50	60	60
	max.	25	75	75	90	90
	min.	5	25	25	30	30
Transmis. Dm	average	3	18	15	3	2
	max.	10	40	23	4.5	3.5
	min.	1	3	8	1.5	1
Area km^2		850	910	660	1110	1100

Region		E.Middle Jyll.	E.Jylland	Central	Jylland	Central	Jylland
Depth interval, km		1.0-1.5	1.5-2.0	2.5-3.0	>3	1.5-2.0	2.0-2.5
Temp. % mean depth		50	65	85	110	60	75
Porosity % mean		28	24	15	<13	24	19
Brine-permeab. mD	average	200	300	35	8	80	20
	max.	1400	450			450	100
	min.	45	15			15	5
Netresou. thickness m	average	25	50	50	80	20	25
	max.	50	75	70	110	30	70
	min.	10	25	30	50	10	15
Transmis. Dm	average	5	15	1.5	0.6	2	0.5
	max.	25	22	3		3	1.5
	min.	1	7.5	0.5		1	0.3
Area km^2		900	890	2000	1100	2910	4380

Region		S.Denmark	M.-S.Sjælland	Sjælland		Fyn
Depth interval, km		0.5-1.0	1.0-1.5	1.5-2.0	2.0-2.5	1.0-1.5
Temp. % mean depth		35	50	60	70	47
Porosity % mean		33	28	24	19	28
Brine-permeab. mD	average	1000	200	150	100	200
	max.	1400	1400	450	200	1400
	min.	100	45	15	10	45
Netresou. thickness m	average	50	70	90	80	60
	max.	75	100	130	100	90
	min.	10	40	50	60	30
Transmis. Dm	average	50	14	12	8	12
	max.	75	50	25	10	45
	min.	2	2	6	6	2
Area km^2		500	1950	2810	1340	320

Basic data tabulation

HALDAGER SAND

Table

Region	Vendsyssel	Vendsyssel	East Jylland	NW Jylland	NW Jylland	NW Jylland
Depth interval, km	0.5-1.0	1.0-1.5	1.0-1.5	1.5-2.0	2.0-2.5	>3
Temp. % mean depth	35	45	55	65	75	95
Porosity % mean	31	28	28	24	20	15
Brine-permeab. mD average	2000	800	800	200	90	15
Brine-permeab. mD max.	7500	3000			180	
Brine-permeab. mD min.	350	200				
Netresou. thickness m average	15	45	5	10	20	20
Netresou. thickness m max.	40	90		20	45	
Netresou. thickness m min.	5	10		5	5	
Transmiss. Dm average	30	36	4	2	9	0.3
Transmiss. Dm max.	80	135		10	15	
Transmiss. Dm min.	10	9				
Area km^2	1450	1730	770	3430	3000	500

Region	Himmerland	Central N.Jylland
Depth interval, km	2.5-3.0	2.5-3.0
Temp. % mean depth	85	75
Porosity % mean	16	16
Brine-permeab. mD average	20	20
Brine-permeab. mD max.	90	
Brine-permeab. mD min.		
Netresou. thickness m average	25	10
Netresou. thickness m max.	40	
Netresou. thickness m min.	10	
Transmiss. Dm average	0.5	0.2
Transmiss. Dm max.	3.5	
Transmiss. Dm min.		
Area km^2	300	650

Bacis data tabulation

FREDERIKSHAVN MEMBER

Table 5

Region		N.Vendsyssel	S. Vendsyssel Himmerland	NW Jylland	NW Jylland	NW Jylland	NW Jylland
Depth interval, km		0.5-1.0	0.5-1.0	0.1-1.5	1.5-2.0	2.0-2.5	2.5-3.0
Temp. % mean depth		27	32	45	55	70	70
Porosity % mean		32	32	27	23	18	13
Brine-permeab. mD	average	250	250	150	100	40	20
	max.						
	min.						
Netresou. thickness m	average	70	20	30	20	15	20
	max.	100	30	40	40	20	
	min.	40	10	10	0	0	
Transmiss. Dm	average	18	5	4.5	2	0.6	0.4
	max.	25	7.5	6	4	1	
	min.	10	2.5	1	0	0	
Area km^2		2380	1590	7600	7000	1170	360

Resource and Reserve Calculations

BUNTER SANDSTONE FORMATION

Table 6

Region		S. Jylland	Lolland-Falster	S. Sjælland	Fyn	Total
Depth b. MSL	(m)	1.4-2.1	1.0-1.5	1.5-2.0	1.0-1.5	
Mean temperature	(°C)	60	48	58	45	
Porosity	(%)	28	27	25	30	
Tot. Heat. Cap.	(MJ/m^3 °C)	2.50	2.50	2.45	2.55	
Res. thickness	(m)	35	30	50	5	
Transmissivity	(Dm)	9*	6*	5*	2*	
Area	(km^2)	2500	2300	2000	2500	
Heat in Place	(10^6 TJ)	11.4	6.9	12.3	1.2	31.8
Max. Recov. Fact.	(-)	0.22	0.19	0.22	0.18	
Ident. Resources	(10^6 TJ)	2.5	1.3	2.7	0.2	6.7
Possible Reserves	(10^6 TJ)	1.3	0.6	1.4	0.1	3.4
	(TJ/km^2)	520.0	260.7	700.0	40.0	

Please refere to the text for the derival and uncertainty of the above mentioned values.

* Values below 40° C or 10 Dm, the limit for economical plants given by Koppe et. al. (1983).

Resources and Reserves Calculations

SKAGERRAK FORMATION

Table 7

Region		Vendsyssel	Vendsyssel	Vendsyssel	Himmerland	Thy-Himml.	Thy	Central Jylland	Central Jylland
Depth b. MSL	(m)	0.5-1.9	1.0-1.5	1.5-2.0	1.5-2.0	2.5-3.0	1.0-1.5	2.0-2.5	2.5-3.0
Mean temperature	(°C)	40	55	65	75	93	50	71	85
Porosity	(%)	26	24	24	24	16	24	18	16
Tot. Heat. Cap.	(MJ/m^3 °C)	2.65	2.60	2.57	2.54	2.43	2.60	2.47	2.43
Res. thickness	(m)	40	50	50	50	200	270	100	250
Transmissivity	(Dm)	10	10	10	10	9*	75	12	11
Area	(km^2)	500	1090	200	100	2000	320	3000	3500
Heat in Place	(10^6 TJ)	1.7	6.7	1.5	0.9	82.6	9.4	46.7	163
Max. Recov. Fact.	(-)	0.15	0.21	0.23	0.25	0.26	0.20	0.24	0.26
Ident. Resources	(10^6 TJ)	0.3	1.4	0.3	0.2	21.5	1.9	11.2	42.6
Possible Reserves	(10^6 TJ)	0.2	0.7	0.2	0.1	10.7	1.0	5.6	21.3
	TJ/km^2	400.0	642.2	1000.0	1000.0	5350.0	3125.0	1866.7	6085.7

Region		S.-M. Sjælland	M.-N. Sjælland	N.-M. Sjælland	Sjælland	Total
Depth b. MSL	(m)	1.5-2.0	2.0-2.5	2.0-2.5	2.5-3.0	
Mean temperature	(°C)	63	70	75	88	
Porosity	(%)	21	18	18	16	
Tot. Heat. Cap.	(MJ/m^3 °C)	2.53	2.47	2.46	2.43	
Res. thickness	(m)	50	200	250	250	
Transmissivity	(Dm)	10	24	30	11	
Area	(km^2)	1950	2800	550	1250	
Heat in Place	(10^6 TJ)	13.6	85.6	22.7	60.8	495.9
Max. Recov. Fact.	(-)	0.23	0.24	0.25	0.26	
Ident. Resources	(10^6 TJ)	3.1	42.8	5.7	15.8	146.8
Possible Reserves	(10^6 TJ)	1.5	21.4	2.8	7.9	73.4
	TJ/km^2	769.2	7642.9	5090.9	6320.0	

Please refere to the text for the derival and uncertainty of the above mentioned values.

* Values below 40° C or 10 Dm, the limit for economical plants given by Koppe et.al. (1983).

Table 8

Resources and Reserve Calculations

GASSUM FORMATION

Region		Vendsyssel	Vendsyssel	Vendsyssel	Vendsyssel-Himmerland	Himmerland-Thy	E.-M. Jylland	E.-Jylland
Depth b. MSL	(m)	0.5-1.0	1.0-1.5	1.5-2.0	2.0-2.5	2.5-3.0	1.0-1.5	1.5-2.0
Mean temperature	(°C)	40	55	70	80	95	50	65
Porosity	(%)	33	30	24	19	15	28	24
Tot. Heat. Cap.	(MJ/m³ °C)	2.78	2.68	2.56	2.48	2.41	2.66	2.57
Res. thickness	(m)	15	50	50	60	60	25	50
Transmissivity	(Dm)	3*	18	15	3*	2*	5*	15
Area	(km²)	850	910	660	1110	1110	900	890
Heat in Place	(10^6 TJ)	1.1	5.7	5.2	11.9	14.0	2.5	6.5
Max. Recov. Fact.	(-)	0.15	0.21	0.24	0.25	0.27	0.20	0.23
Ident. Resources	(10^6 TJ)	0.2	1.2	1.3	3.0	3.8	0.5	1.5
Possible Reserves	(10^6 TJ)	0.1	0.6	0.7	1.5	1.4	0.3	0.7
	(TJ/km²)	117.6	659.3	1060.6	1351.4	1261.3	333.3	786.5

Region		Central Jylland	Central Jylland	Central Jylland	Fyn	S.-Denmark	M.-S.-Sjælland	Sjælland	Sjælland	Tota
Depth b. MSL	(m)	1.5-2.0	2.0-2.5	2.5-3.0	1.0-1.5	0.5-1.0	1.0-1.5	1.5-2.0	2.0-2.5	
Mean temperature	(°C)	60	75	85	47	35*	50	60	70	
Porosity	(%)	24	19	15	28	33	28	24	19	
Tot. Heat. Cap.	(MJ/m³ °C)	2.57	2.48	2.42	2.66	2.80	2.66	2.57	2.48	
Res. thickness	(m)	20	25	50	60	50	70	90	80	
Transmissivity	(Dm)	2*	0.5*	1.5*	12	50	14	9*	8*	
Area	(km²)	2910	4380	2000	320	500	1950	2810	1340	
Heat in Place	(10^6 TJ)	7.8	18.2	18.6	2.0	1.9	15.2	33.8	16.5	160.
Max. Recov. Fact.	(-)	0.22	0.25	0.26	0.19	0.12	0.20	0.22	0.24	
Ident. Resources	(10^6 TJ)	1.7	4.5	4.8	0.4	0.2	3.0	7.4	4.0	37.
Possible Reserves	(10^6 TJ)	0.9	2.3	2.4	0.2	0.1	1.5	3.7	2.0	18.
	(TJ/km²)	309.3	525.1	1200.0	625.0	200.0	769.2	1316.7	1492.5	

Please refere to the text for the derival and uncertainty of the above mentioned values.

* Values below 40° C or 10 Dm, the limit for economical plants given by Koppe et.al. (1983)

Resources and Reserve Calculation

Table 9

HALDAGER SAND

Region		Vendsyssel	Vendsyssel	N.-W. Jylland	N.-W. Jylland	Himmer-land	Central N.Jylland	E.-Jylland	Total
Depth b. MSL	(m)	0.5-1.0	1.0-1.5	1.5-2.0	2.0-2.5	2.5-3.0	2.5-3.0	1.0-1.5	
Mean temperature	(°C)	35*	45	65	75	85	75	55	
Porosity	(%)	31	28	24	20	16	16	28	
Tot. Heat. Cap.	(MJ/m^3 °C)	2.76	2.67	2.57	2.50	2.43	2.44	2.66	
Res. thickness	(m)	15	45	10	20	25	10	5	
Transmissivity	(Dm)	30	36	2*	9*	0.5*	0.2*	4*	
Area	(km^2)	1450	1730	3430	3000	300	650	770	
Heat in Place	(10^6 TJ)	1.6	7.7	5.0	10.1	1.4	1.1	0.5	27.4
Max. Recov. Fact.	(-)	0.12	0.18	0.23	0.25	0.26	0.25	0.21	
Ident. Resources	(10^6 TJ)	0.2	1.4	1.2	2.5	0.4	0.3	0.1	6.1
Possible Reserves	(10^6 TJ)	0.1	0.7	0.6	1.2	0.2	0.2	0.1	3.1
	(TJ/km^2)	69.0	404.6	174.9	400.0	666.7	307.7	129.9	

FREDERIKSHAVN MEMBER

Table 10

Region		N.-Vendsyssel	S.-Vendsys. Himmerland	N.W. Jylland	N.W. Jylland	N.W. Jylland	N.W. Jylland	Total
Depth b. MSL	(m)	0.5-1.0	0.5-1.0	1.0-1.5	1.5-2.0	2.0-2.5	2.5-3.0	
Mean temperature	(°C)	27*	32*	45	55	70	70	
Porosity	(%)	32	32	27	23	18	13	
Tot. Heat. Cap.	(MJ/m^3 °C)	2.80	2.79	2.65	2.57	2.47	2.39	
Res. thickness	(m)	70	20	30	20	15	20	
Transmissivity	(Dm)	18	5*	4.5*	2.0*	0.6*	0.4*	
Area	(km^2)	2380	1590	7600	7000	1170	360	
Heat in Place	(10^6 TJ)	8.9	2.1	22.4	16.9	2.7	1.1	54.1
Max. Recov. Fact.	(-)	0.03	0.10	0.18	0.21	0.24	0.24	
Ident. Resources	(10^6 TJ)	0.3	0.2	4.0	3.6	0.6	0.3	9.0
Possible Reserves	(10^6 TJ)	0.1	0.1	2.0	1.8	0.3	0.2	4.5
	(TJ/km^2)	42.0	62.9	263.2	257.1	256.4	555.6	

Please refere to the text for the derival and uncertainty of the above mentioned values.

* Values below 40° C or 10 Dm, the limit for economical plants given by Koppe et.al. (1983).

F I G U R E S

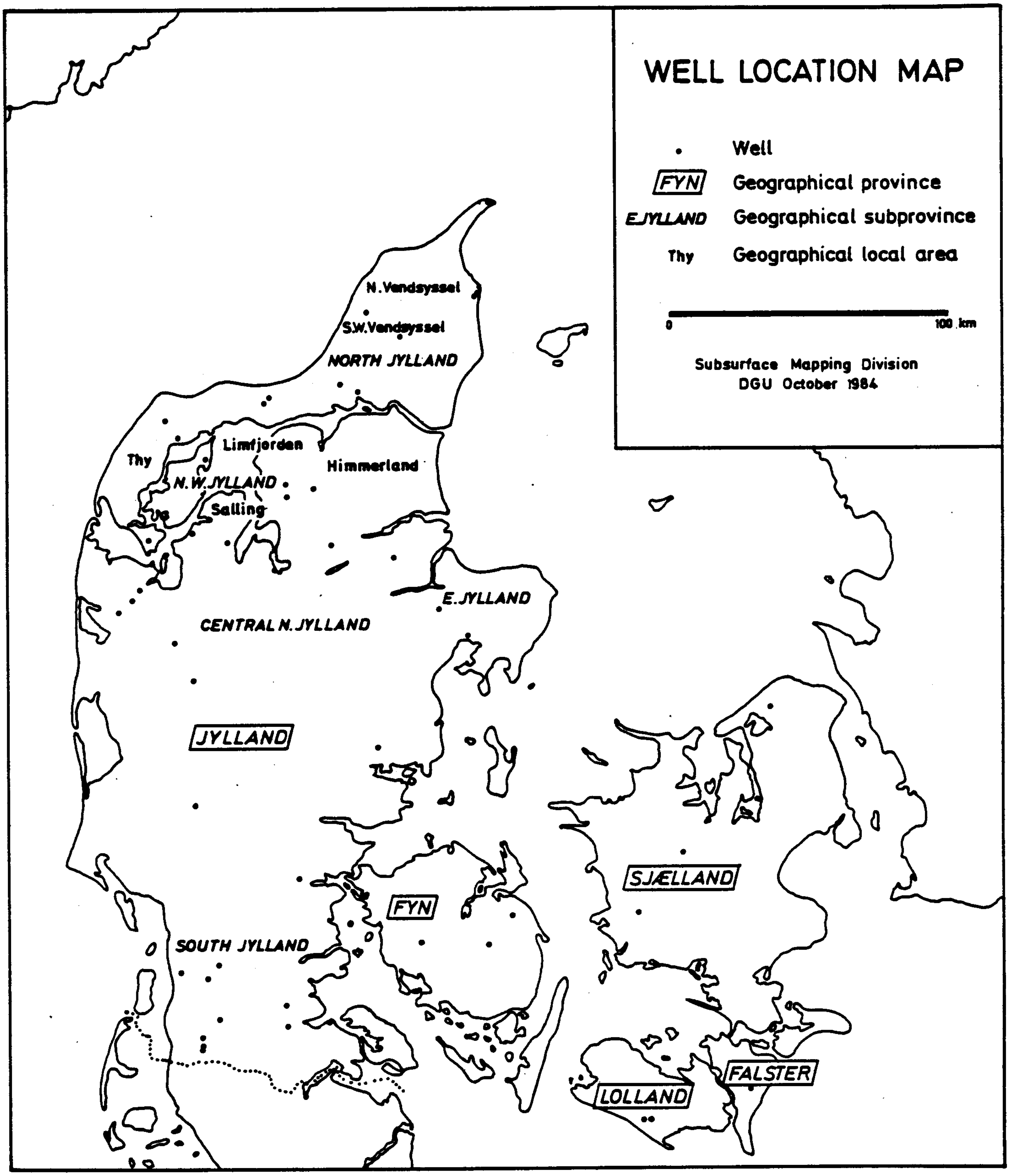

WELL LOCATION MAP
Well
FYN
Geographical province
E.JYLLAND
Geographical subprovince
Thy
Geographical local area
0
100 km
Subsurface Mapping Division
DGU October 1984
N.Vendsyssel
S.W.Vendsyssel
NORTH JYLLAND
Limfjorden
Thy
Himmerland
N.W.JYLLAND
Salling
E.JYLLAND
CENTRAL N.JYLLAND
JYLLAND
SJÆLLAND
FYN
SOUTH JYLLAND
FALSTER
LOLLAND

Fig.1

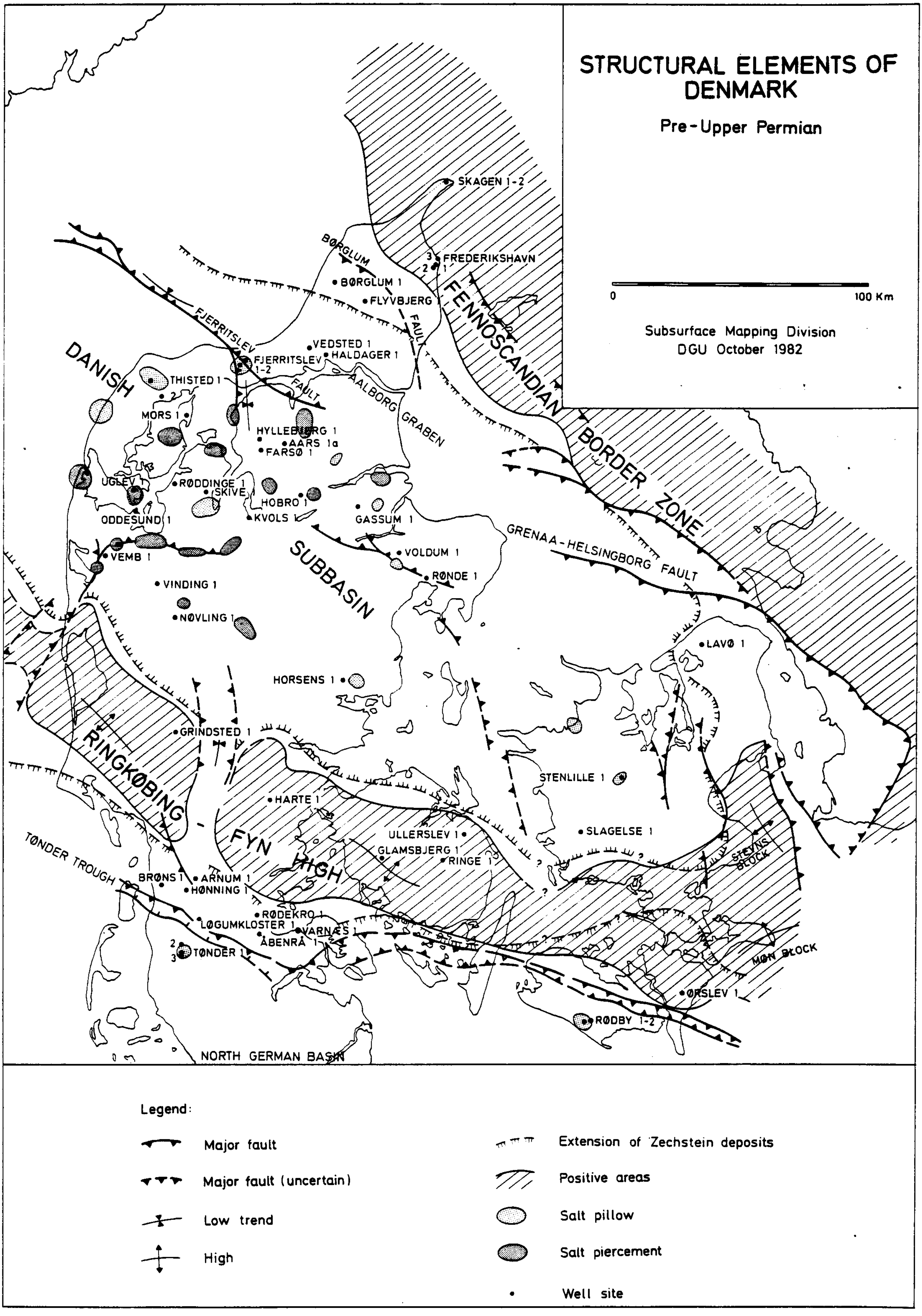

STRUCTURAL ELEMENTS OF DENMARK
Pre-Upper Permian
0
100 Km
Subsurface Mapping Division
DGU October 1982
SKAGEN 1-2
FREDERIKSHAVN
BØRGLUM
BØRGLUM 1
FLYVBJERG
FAULT
FENNOSCANDIAN BORDER ZONE
FJERRITSLEV
FJERRITSLEV 1-2
VEDSTED 1
HALDAGER 1
FAULT
AALBORG GRABEN
DANISH
THISTED 1
MORS 1
HYLLEBJERG 1
AARS 1a
FARSØ 1
UGLEV
RØDDINGE 1
SKIVE
HOBRO 1
KVOLS 1
ODDESUND 1
GASSUM 1
GRENAA-HELSINGBORG FAULT
VEMB 1
VOLDUM 1
SUBBASIN
RØNDE 1
VINDING 1
NØVLING 1
LAVØ 1
HORSENS 1
GRINDSTED 1
RINGKØBING - FYN HIGH
STENLILLE 1
HARTE 1
SLAGELSE 1
ULLERSLEV 1
GLAMSBJERG 1
RINGE 1
TØNDER TROUGH
BRØNS 1
ARNUM 1
HØNNING 1
STEVNS BLOCK
RØDEKRO 1
LØGUMKLOSTER 1
VARNÆS 1
ÅBENRÅ 1
TØNDER 1
MØN BLOCK
ØRSLEV 1
RØDBY 1-2
NORTH GERMAN BASIN
Legend:
Major fault
Major fault (uncertain)
Low trend
High
Extension of Zechstein deposits
Positive areas
Salt pillow
Salt piercement
Well site

Fig.2

STRATIGRAPHIC SUBDIVISION
OF
THE DANISH ONSHORE AREA

SYSTEM	SERIES	STAGE	GROUP	FORMATION	MEMBER
TERTIARY and younger					
CRETACEOUS	UPPER		CHALK GROUP		
CRETACEOUS	LOWER	ALBIAN		RØDBY FORMATION	
		APTIAN BARREMIAN HAUTERIAN VALANGINIAN		VEDSTED FORMATION	
		BERRIASIAN		BREAM FORMATION	* FREDERIKSHAVN MEMBER (C, B, A)
JURASSIC	UPPER	PORTLANDIAN			
		KIMMERIDGIAN			BØRGLUM MEMBER
		OXFORDIAN		HALDAGER FORMATION	FLYVBJERG MEMBER
	MIDDLE	CALLOVIAN BATHONIAN BAJOCIAN			* HALDAGER SAND
	LOWER	AALENIAN TOARCIAN		FJERRITSLEV FORMATION	MEMBER F-IV
		U. PLIENSBACHIAN			MEMBER F-III
		L. PLIENSBACHIAN			MEMBER F-II (c, b, a)
		U. SINEMURIAN			MEMBER F-I (b, a)
		L. SIN.-HETTANGIAN			
TRIASSIC	UPPER	RHAETIAN	RHAETIC: MORS GROUP	GASSUM FORMATION	* MEMBER G_1 - G_4
		NORIAN		* SKAGERRAK FORMATION / VINDING FORMATION	
		CARNIAN	KEUPER: JYLLAND GROUP	ODDESUND FORMATION	MEMBER O_3 MEMBER O_2 MEMBER O_1
	MIDDLE	LADINIAN		TØNDER FORMATION	
		ANISIAN	MUSCHELKALK: LOLLAND GROUP	FALSTER FORMATION	
	LOWER	OLENIKIAN	BUNTSANDSTEIN, Röt: LOLLAND GROUP	ØRSLEV FORMATION	
		JAKUTIAN	BUNTSANDSTEIN: BACTON GROUP	BUNTER SANDSTONE FORMATION	*
		BRAHMANIAN		BUNTER SHALE FORMATION	
PERMIAN and older				ZECHSTEIN	

* RESERVOIR FORMATIONS DISCUSSED IN THIS REPORT

DGU 1984

Fig.3

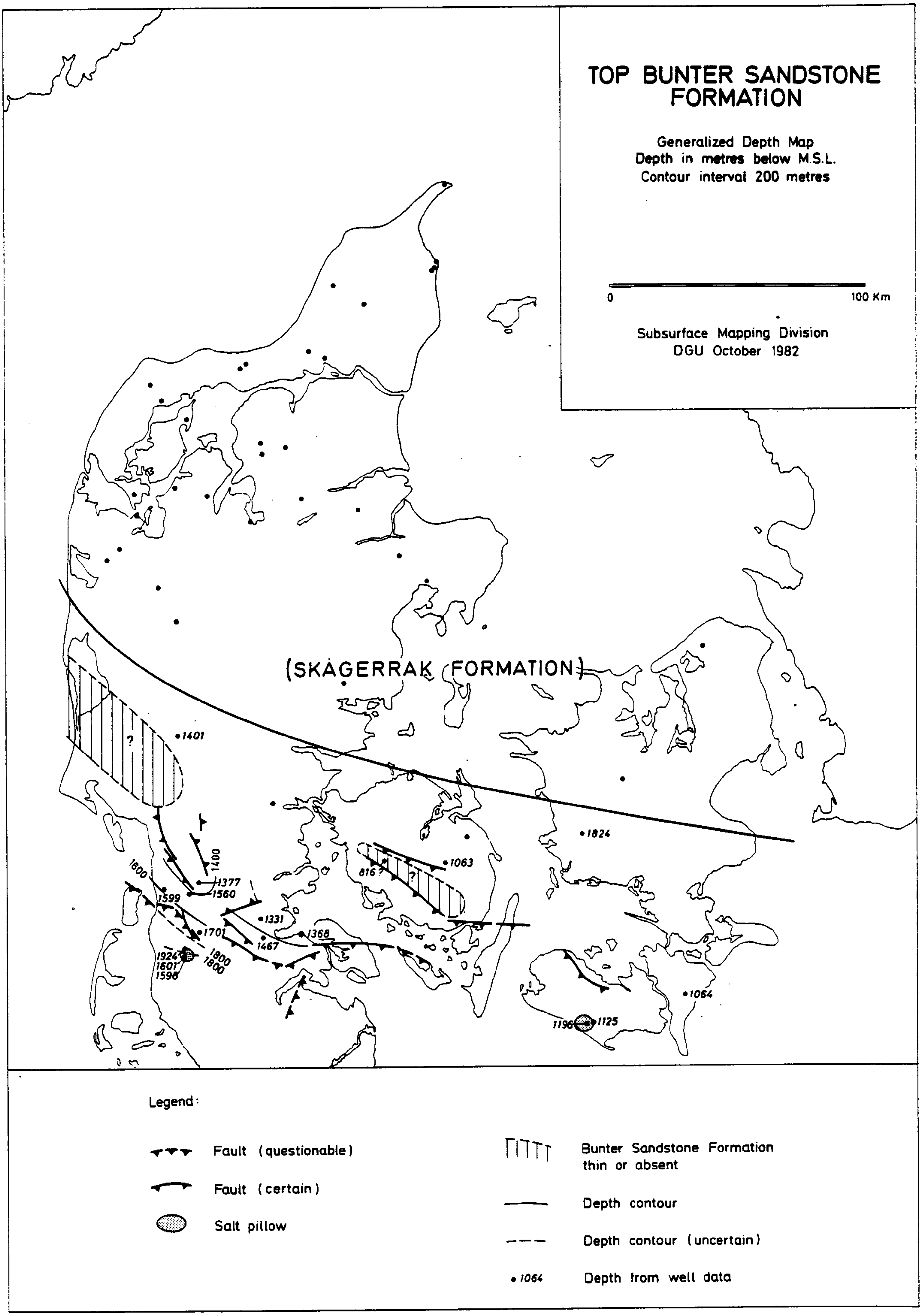

TOP BUNTER SANDSTONE FORMATION
Generalized Depth Map
Depth in metres below M.S.L.
Contour interval 200 metres
0
100 Km
Subsurface Mapping Division
DGU October 1982
(SKAGERRAK FORMATION)
1401
1824
1063
816
1400
1377
1560
1800
1599
1331
1368
1701
1467
1800
1800
1924
1601
1596
1064
1196
1125
Legend:
Fault (questionable)
Fault (certain)
Salt pillow
Bunter Sandstone Formation thin or absent
Depth contour
Depth contour (uncertain)
1064
Depth from well data

Fig.4

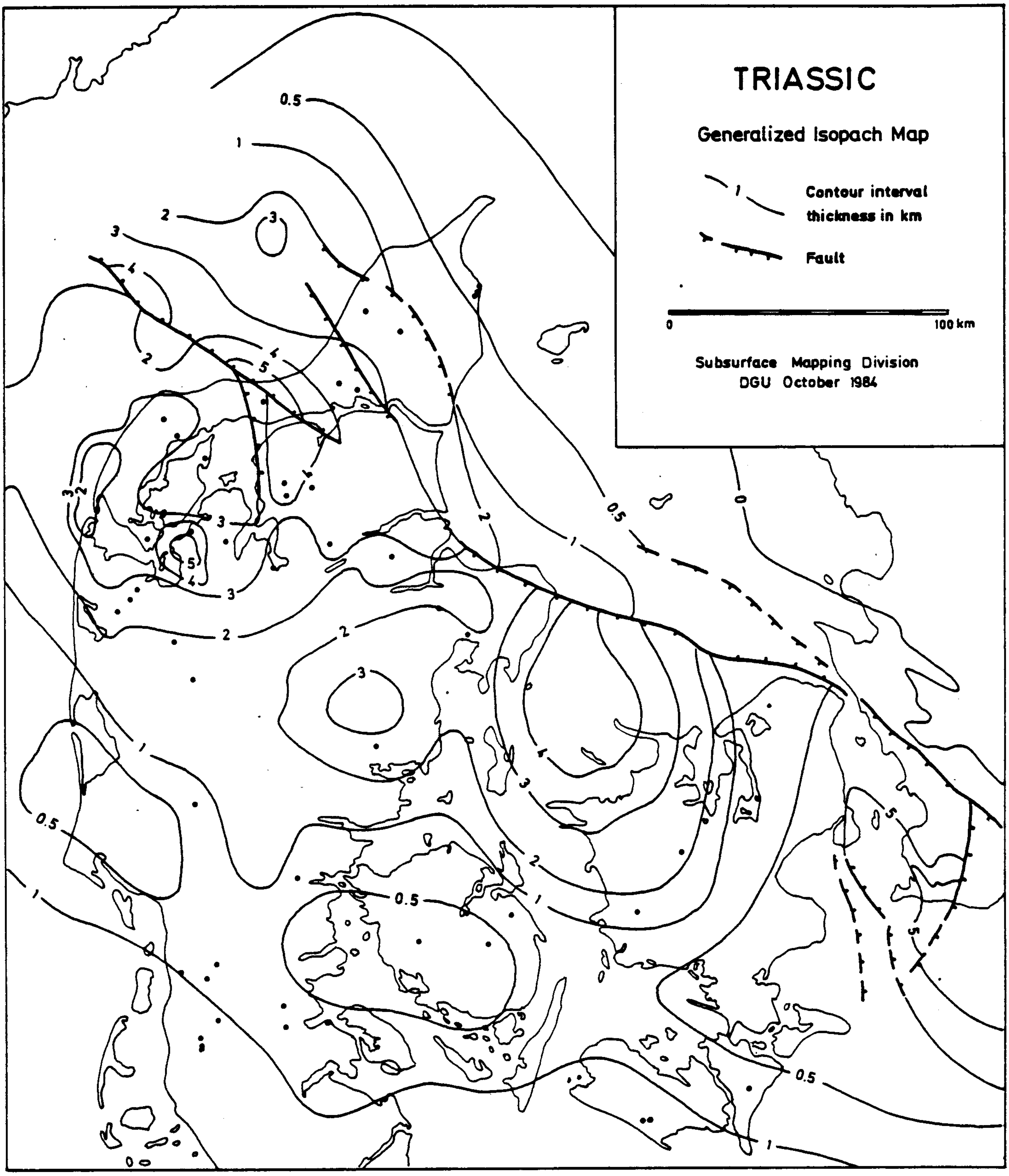

TRIASSIC
Generalized Isopach Map
Contour interval thickness in km
Fault
0
100 km
Subsurface Mapping Division
DGU October 1984
0.5
1
2
3
4
5

Fig.5

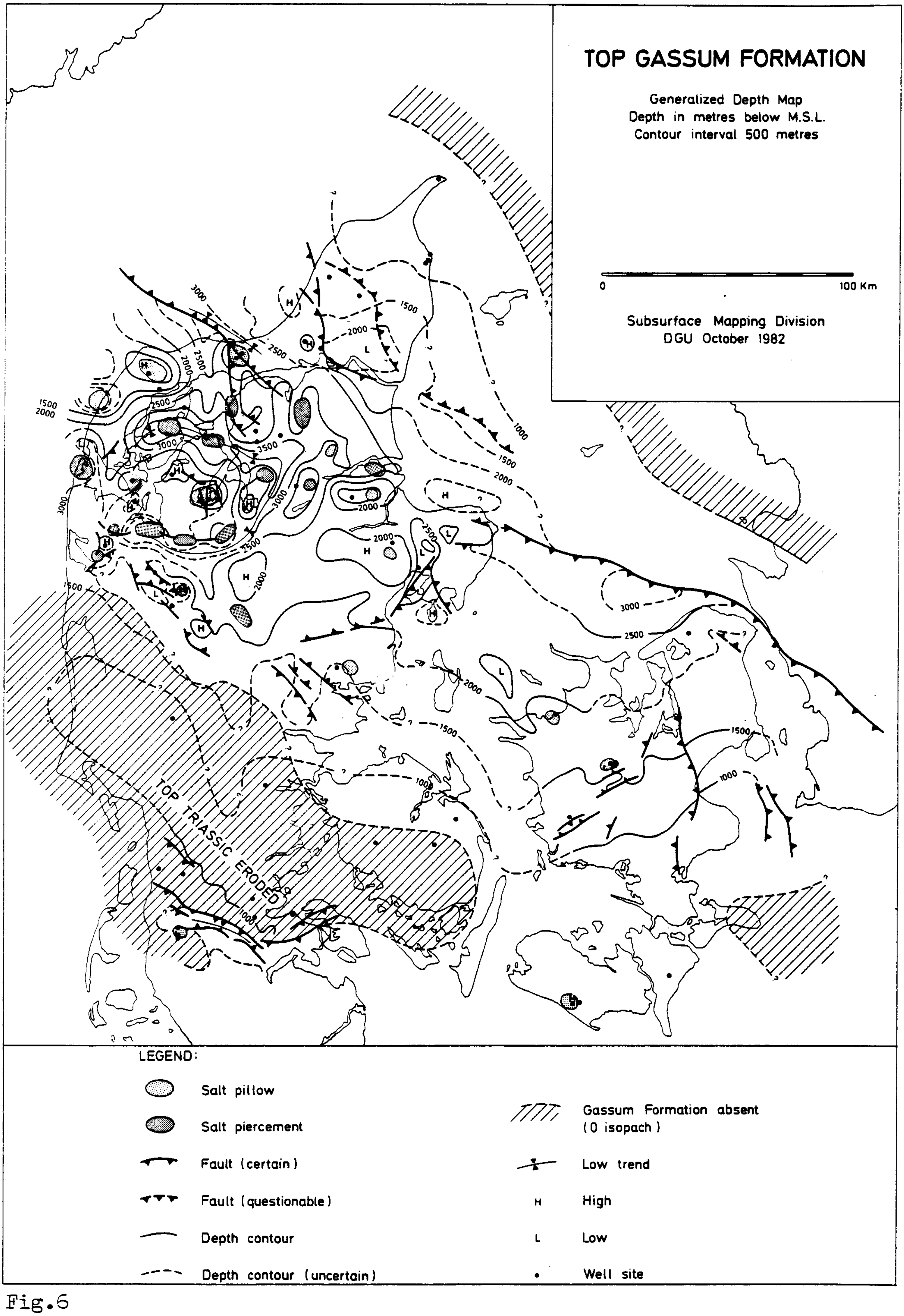
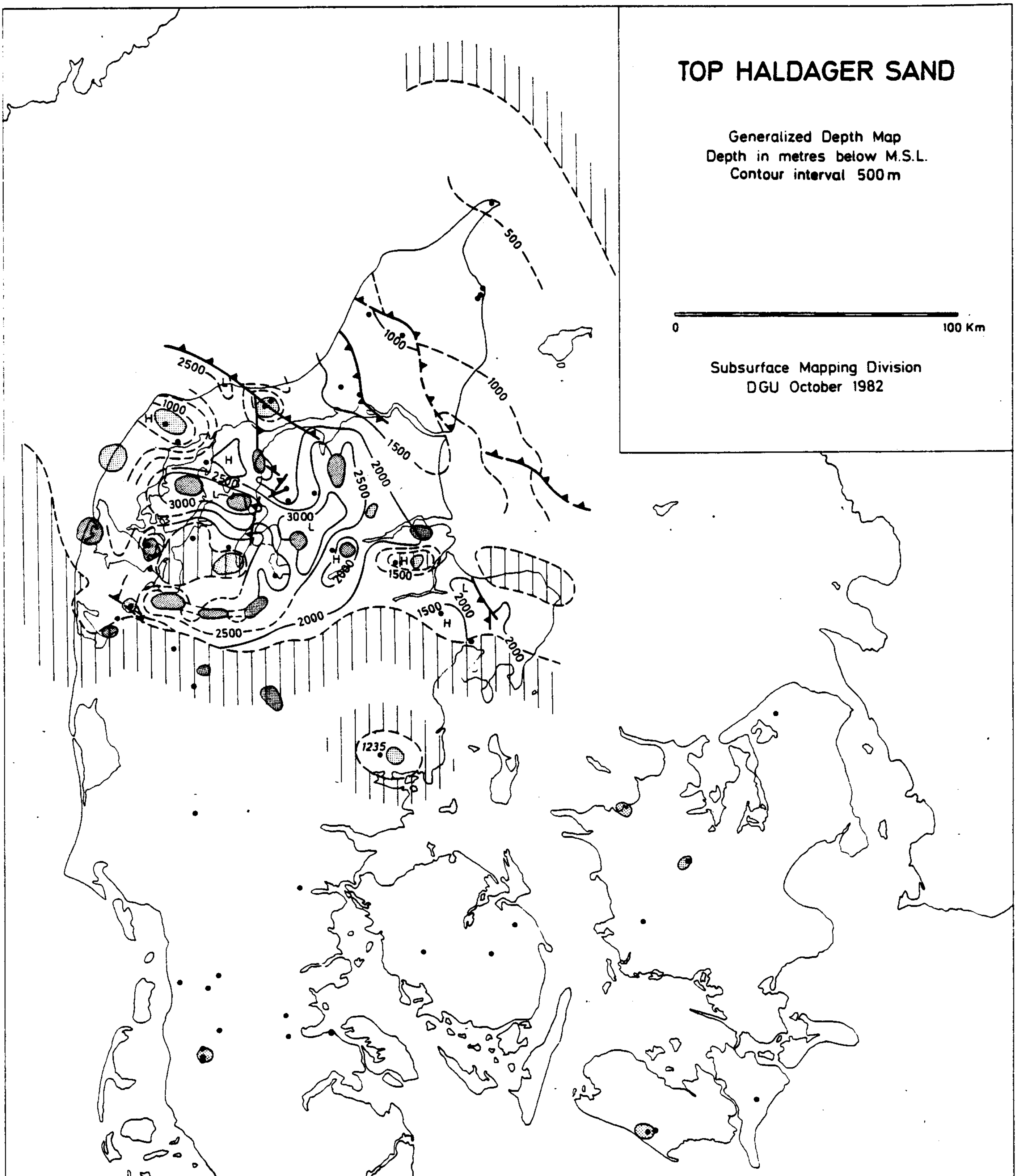

TOP GASSUM FORMATION
Generalized Depth Map
Depth in metres below M.S.L.
Contour interval 500 metres
0
100 Km
Subsurface Mapping Division
DGU October 1982
TOP TRIASSIC ERODED
3000
2500
2000
1500
1000
3500
H
L
LEGEND:
Salt pillow
Salt piercement
Fault (certain)
Fault (questionable)
Depth contour
Depth contour (uncertain)
Gassum Formation absent
(0 isopach)
Low trend
High
Low
Well site

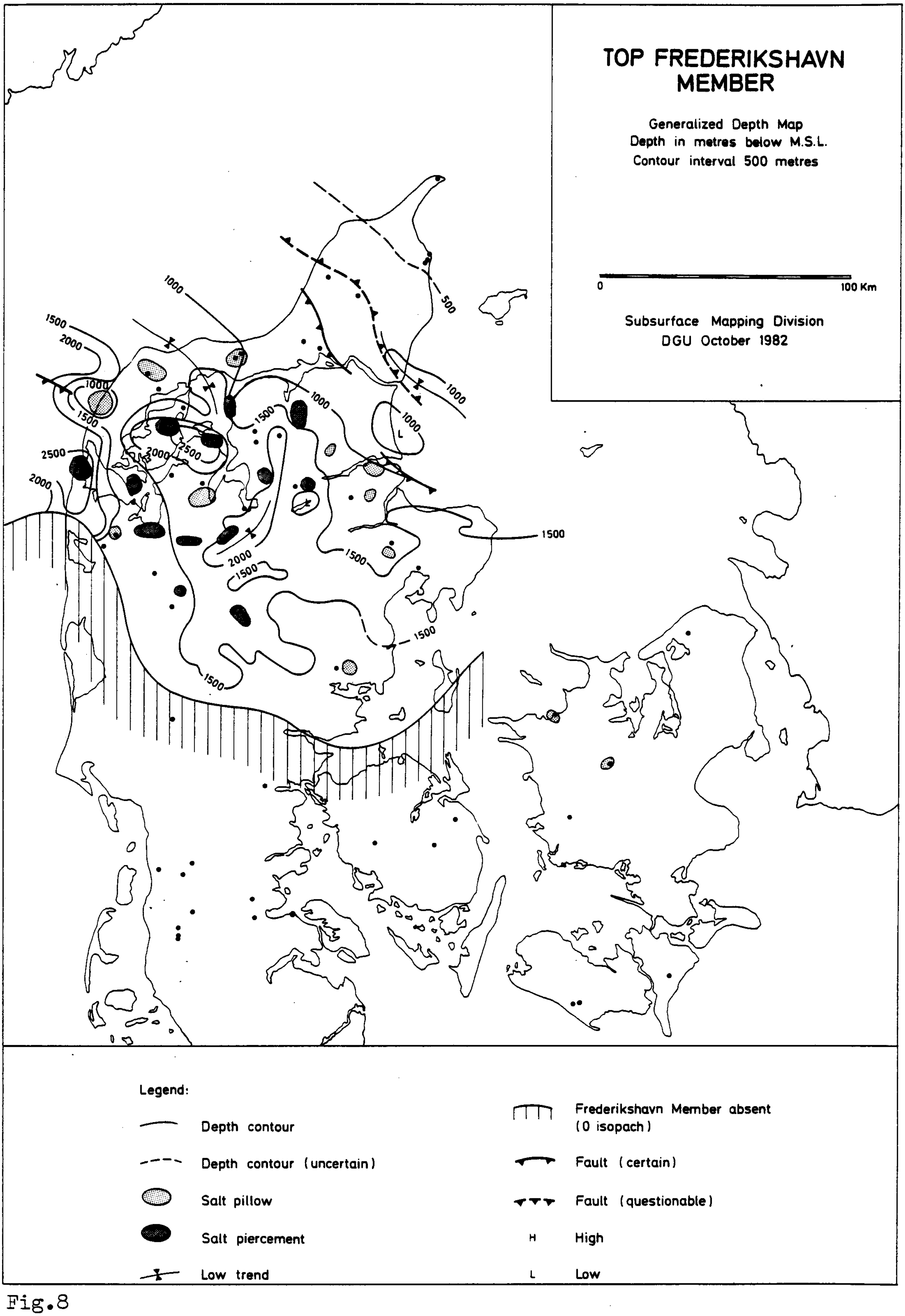
Fig.6



Legend:

Salt pillow		• 1235	Depth from well data
Salt piercement			Depth contour
Fault (certain)			Depth contour (uncertain)
Fault (questionable)		H	High
TTTT	Haldager Sand thin or absent	L	Low

Fig.7



TOP FREDERIKSHAVN MEMBER
Generalized Depth Map
Depth in metres below M.S.L.
Contour interval 500 metres
0
100 Km
Subsurface Mapping Division
DGU October 1982
500
1000
1500
2000
2500
L
Legend:
Depth contour
Depth contour (uncertain)
Salt pillow
Salt piercement
Low trend
Frederikshavn Member absent
(0 isopach)
Fault (certain)
Fault (questionable)
H
High
L
Low

Fig.8

POROSITY GRADIENTS FOR
CLASTIC RESERVOIRS
DGU NOVEMBER 1982

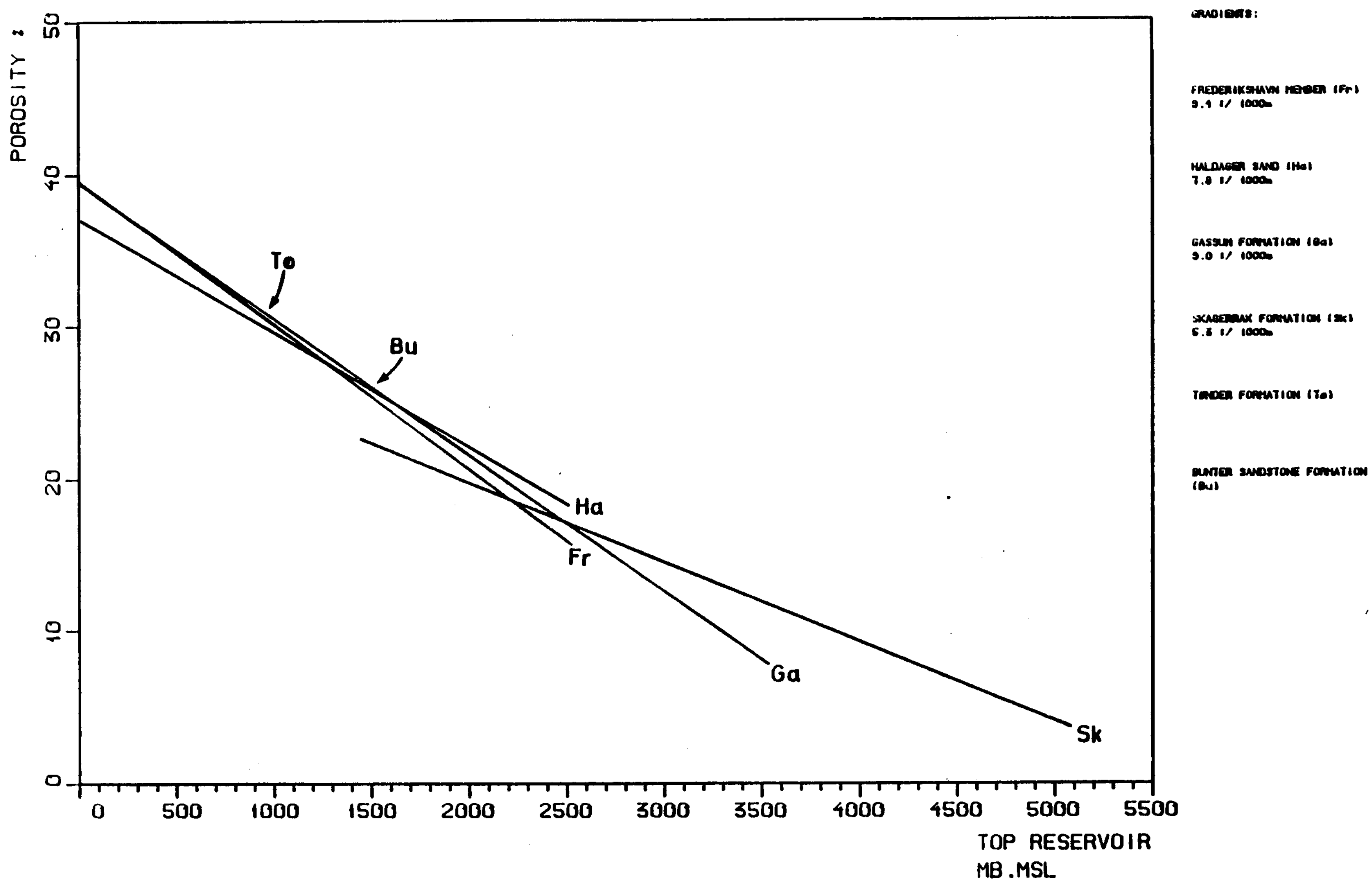
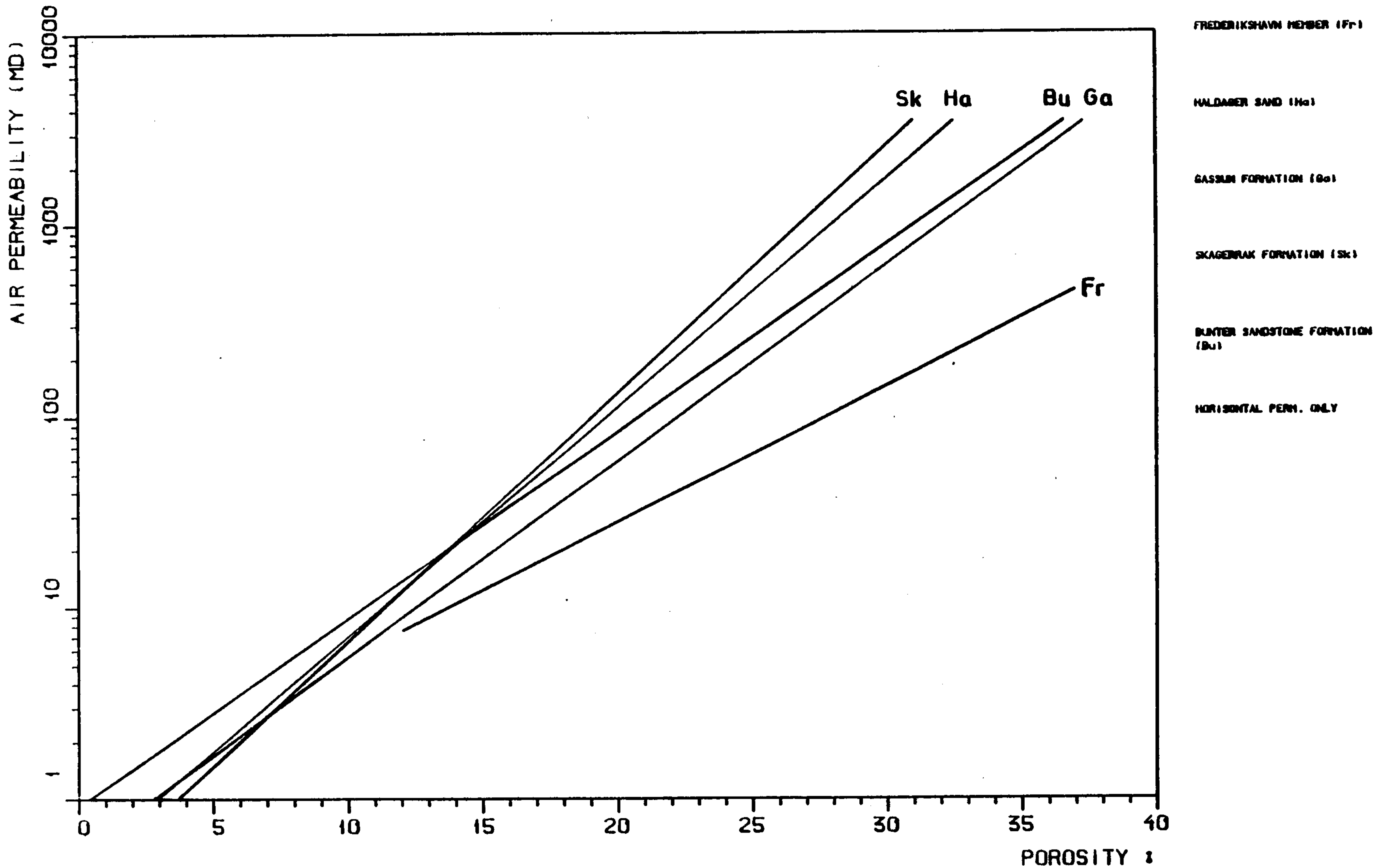
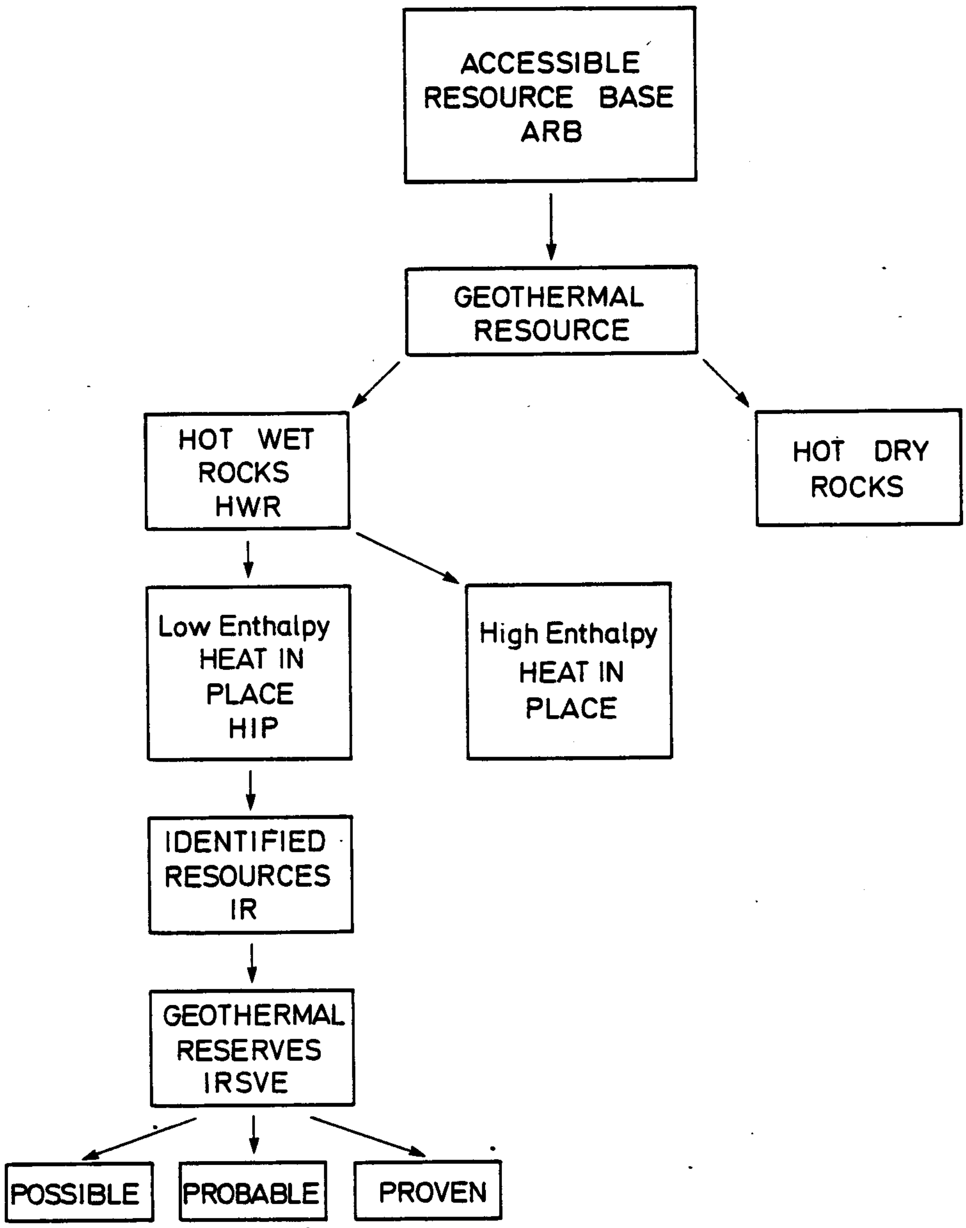


Fig.9

Fig.10

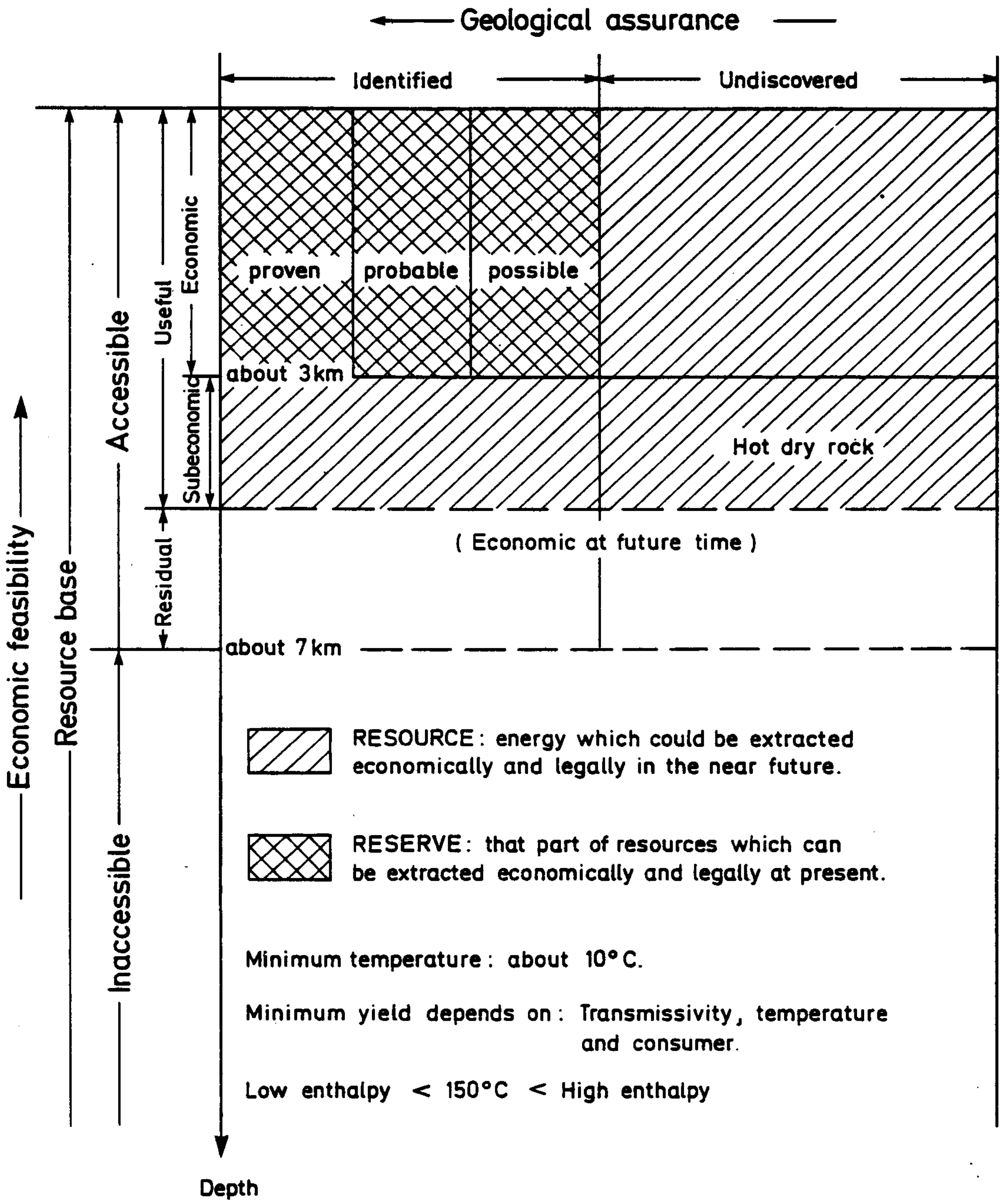
RELATIONSHIP BETWEEN POROSITY AND AIR PERMEABILITY
FOR CLASTIC RESERVOIRS
DGU NOVEMBER 1982





The evaluation procedure for resource and reserve assessment in the Danish sedimentary basins.

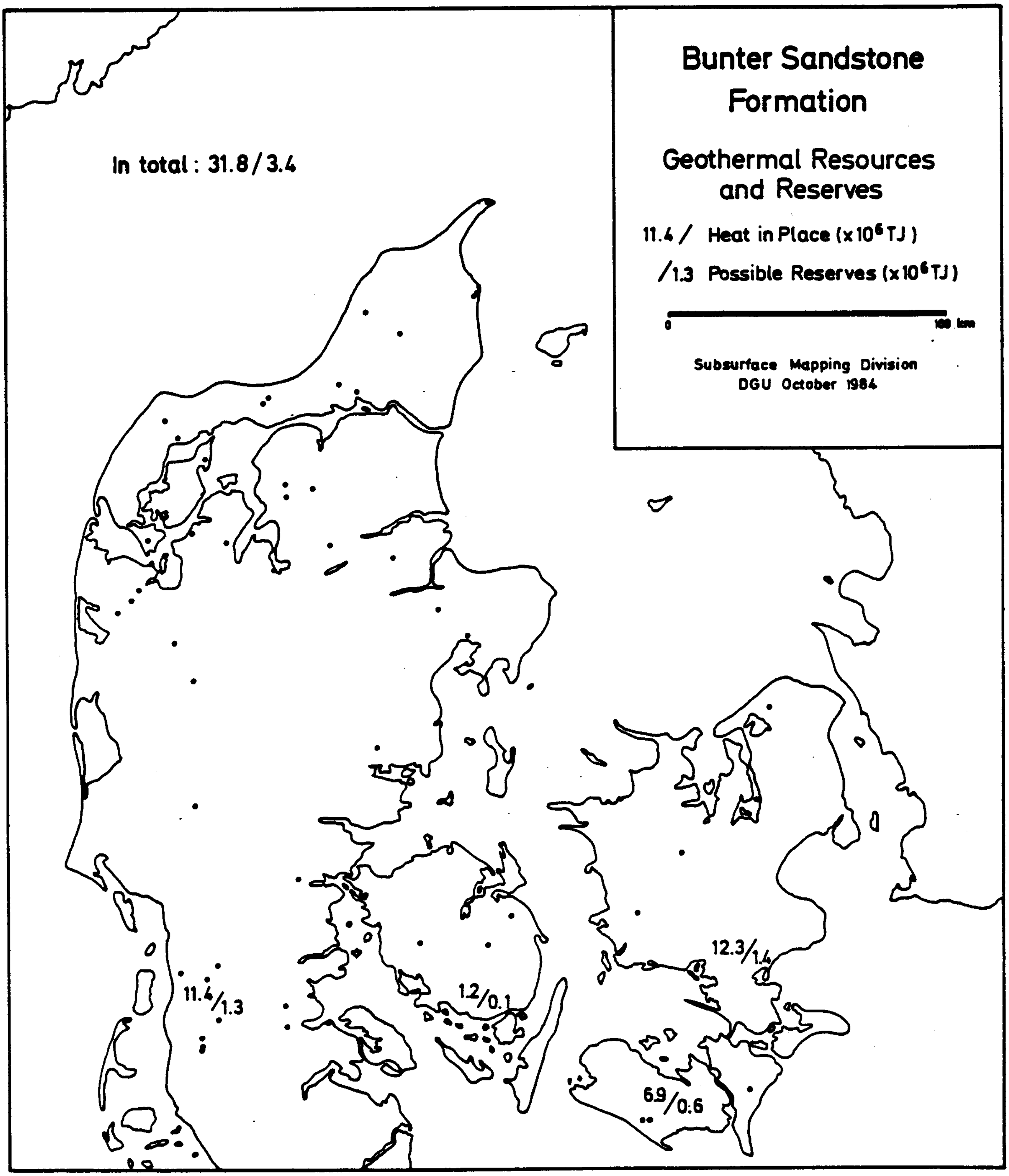
Fig.11



McKelvey diagram, revised version for geothermal energy

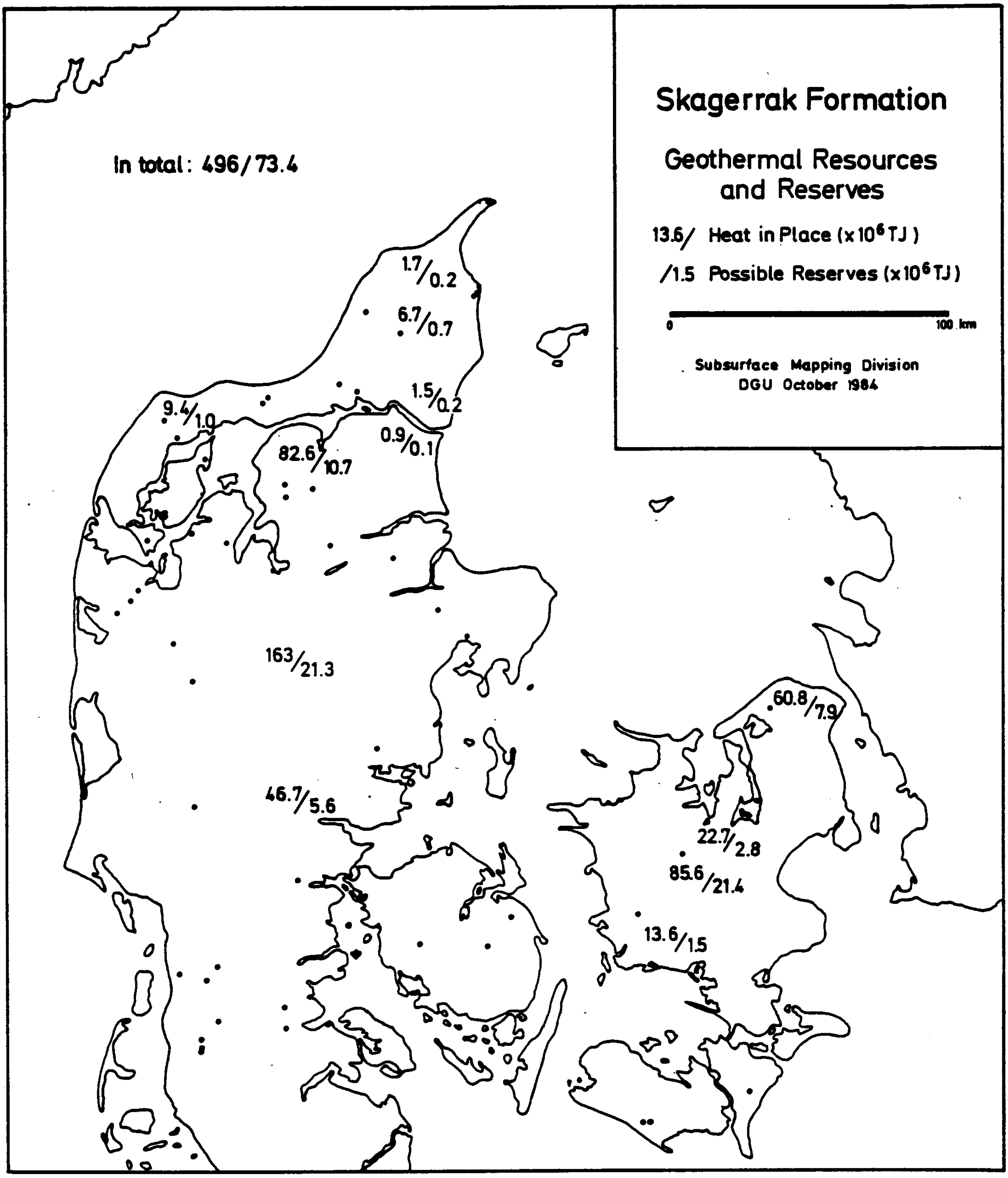
Modified after Muffler, L.J.P., and Marianne Guffanti, 1979. Assessment of geothermal resources of the United States 1978. - U.S. Geological Survey Circular 790, p. 1-7.

Fig.12



Bunter Sandstone Formation
Geothermal Resources and Reserves
11.4 / Heat in Place (x10⁶ TJ)
/1.3 Possible Reserves (x10⁶ TJ)
0
100 km
Subsurface Mapping Division
DGU October 1984
In total : 31.8 / 3.4
11.4/1.3
1.2/0.1
12.3/1.4
6.9/0.6

Fig.13



Skagerrak Formation
Geothermal Resources and Reserves
13.6/ Heat in Place (x10⁶ TJ)
/1.5 Possible Reserves (x10⁶ TJ)
0
100 km
Subsurface Mapping Division
DGU October 1984
In total: 496/73.4
1.7/0.2
6.7/0.7
1.5/0.2
9.4/1.0
0.9/0.1
82.6/10.7
163/21.3
46.7/5.6
60.8/7.9
22.7/2.8
85.6/21.4
13.6/1.5

Fig.14

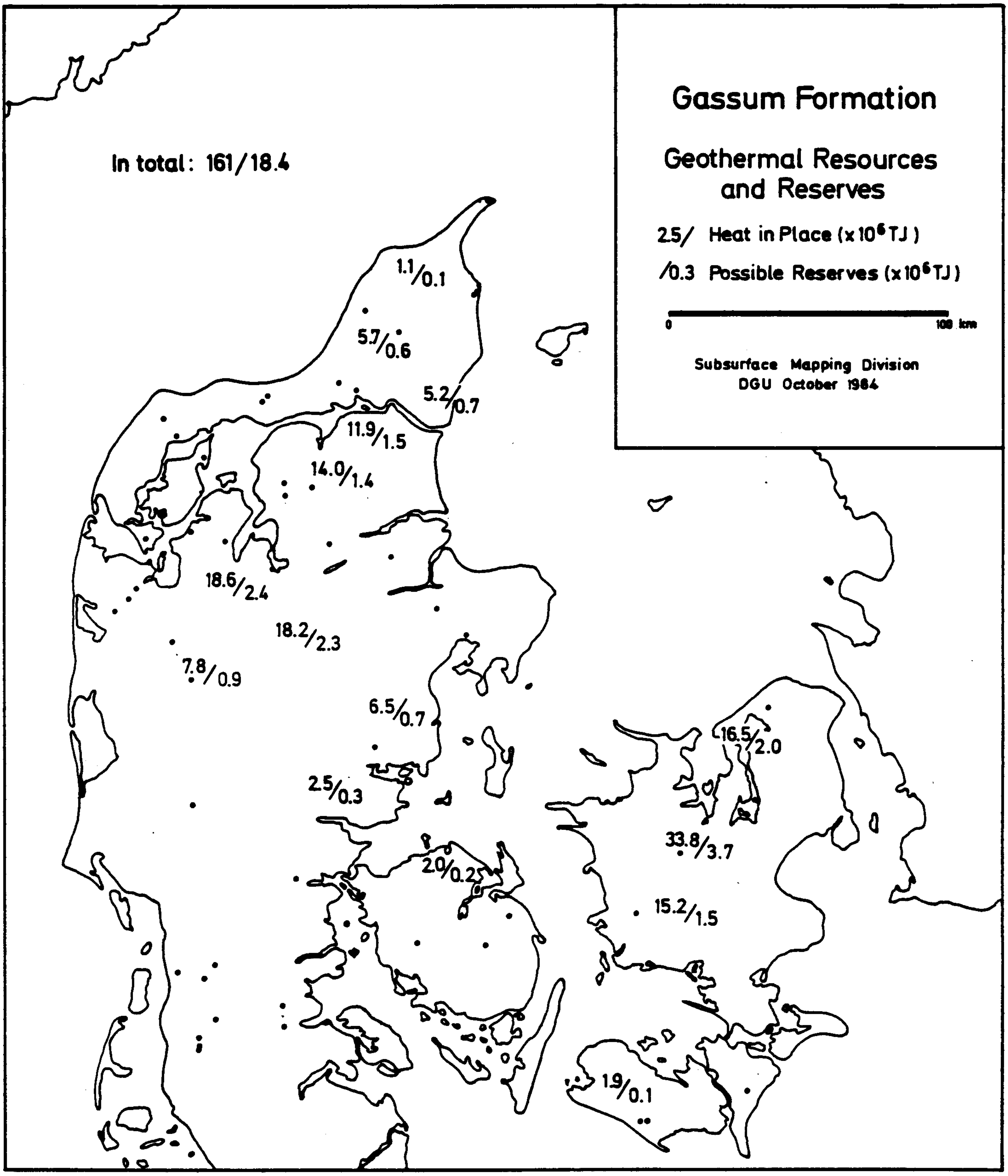

Gassum Formation
Geothermal Resources and Reserves
2.5/ Heat in Place (x10⁶ TJ)
/0.3 Possible Reserves (x10⁶ TJ)
0
100 km
Subsurface Mapping Division
DGU October 1984
In total: 161/18.4
1.1/0.1
5.7/0.6
5.2/0.7
11.9/1.5
14.0/1.4
18.6/2.4
18.2/2.3
7.8/0.9
6.5/0.7
2.5/0.3
2.0/0.2
16.5/2.0
33.8/3.7
15.2/1.5
1.9/0.1

Fig.15

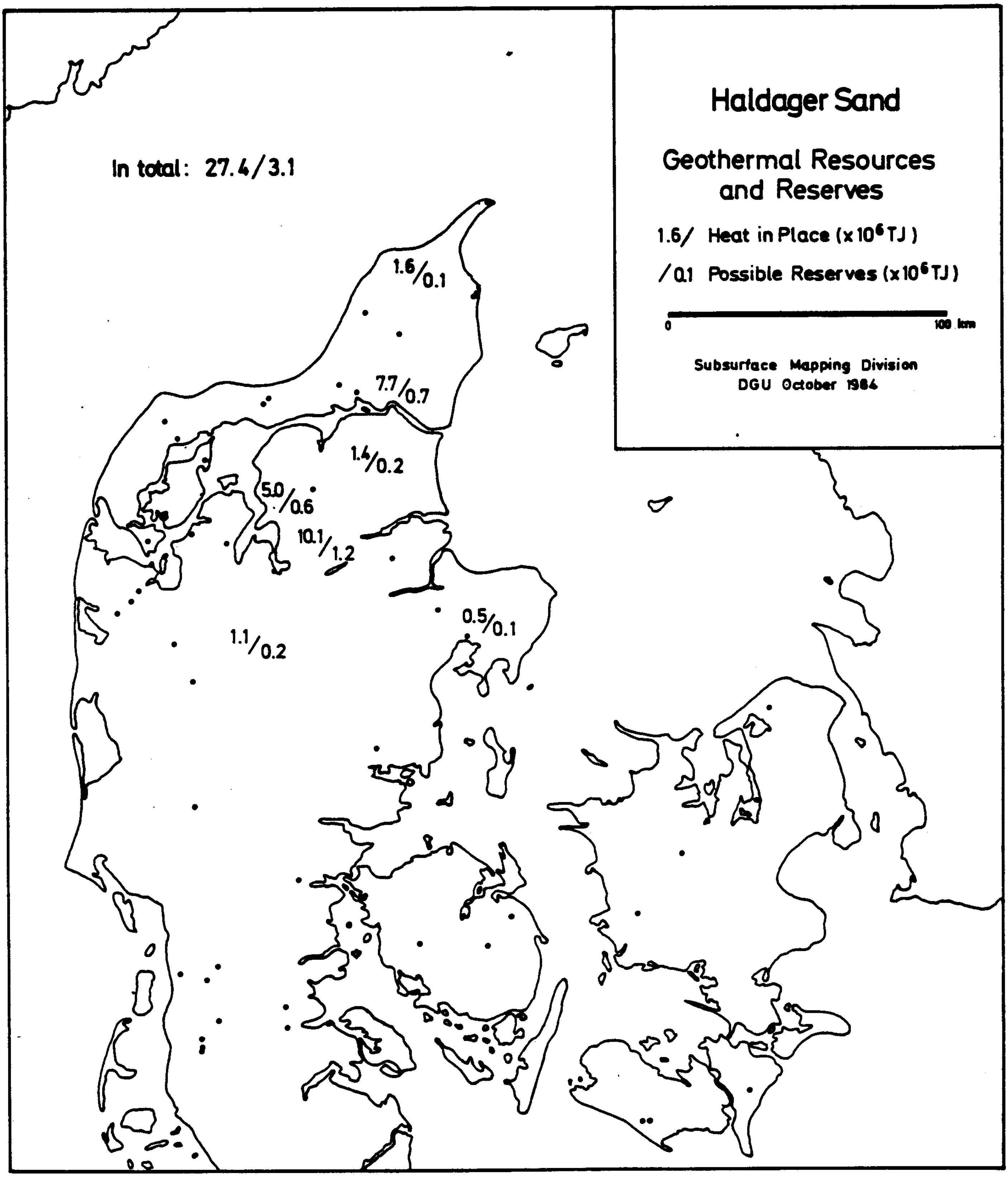

Haldager Sand
Geothermal Resources and Reserves
1.6/ Heat in Place (x 10⁶ TJ)
/0.1 Possible Reserves (x 10⁶ TJ)
0
100 km
Subsurface Mapping Division
DGU October 1984
In total: 27.4/3.1
1.6/0.1
7.7/0.7
1.4/0.2
5.0/0.6
10.1/1.2
0.5/0.1
1.1/0.2

Fig.16

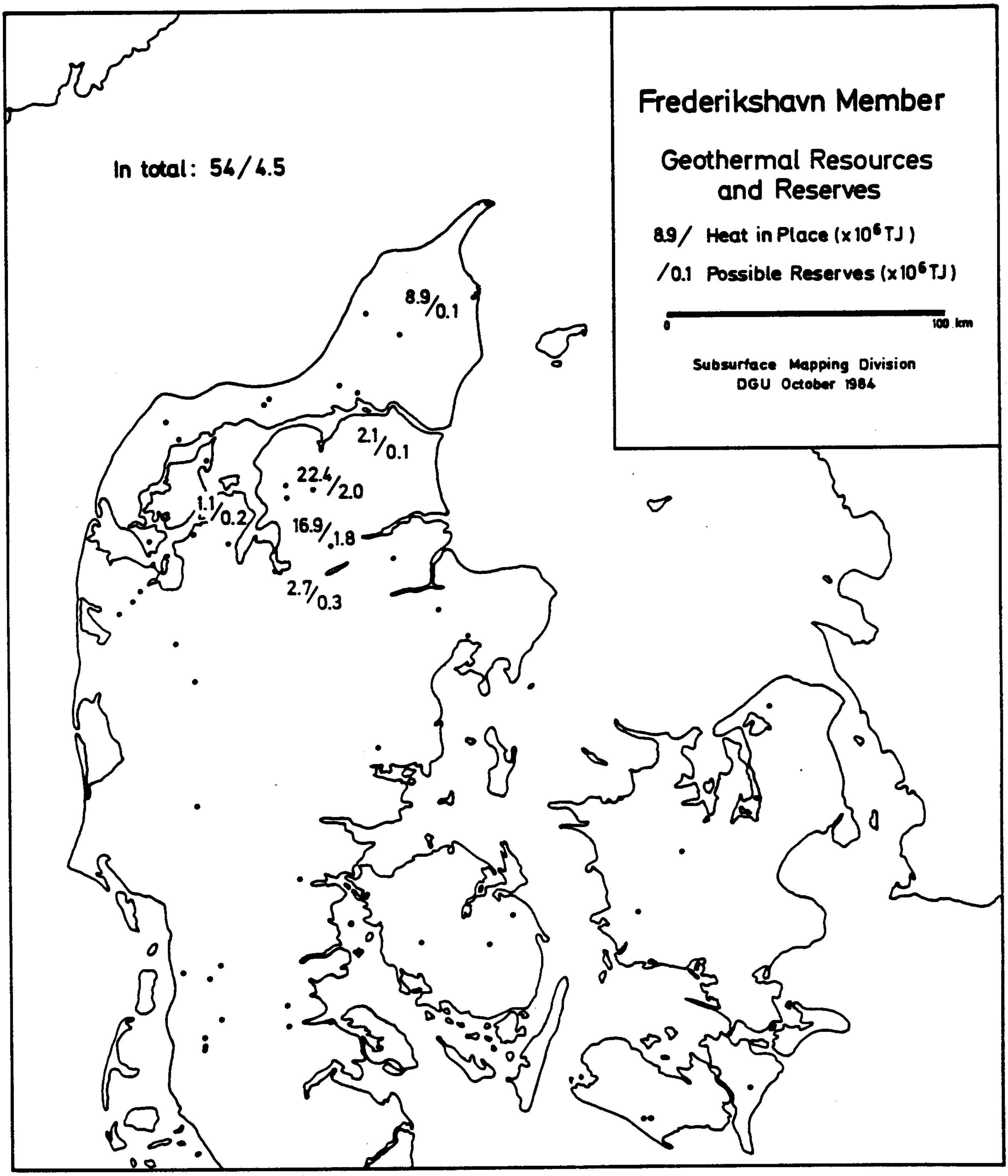
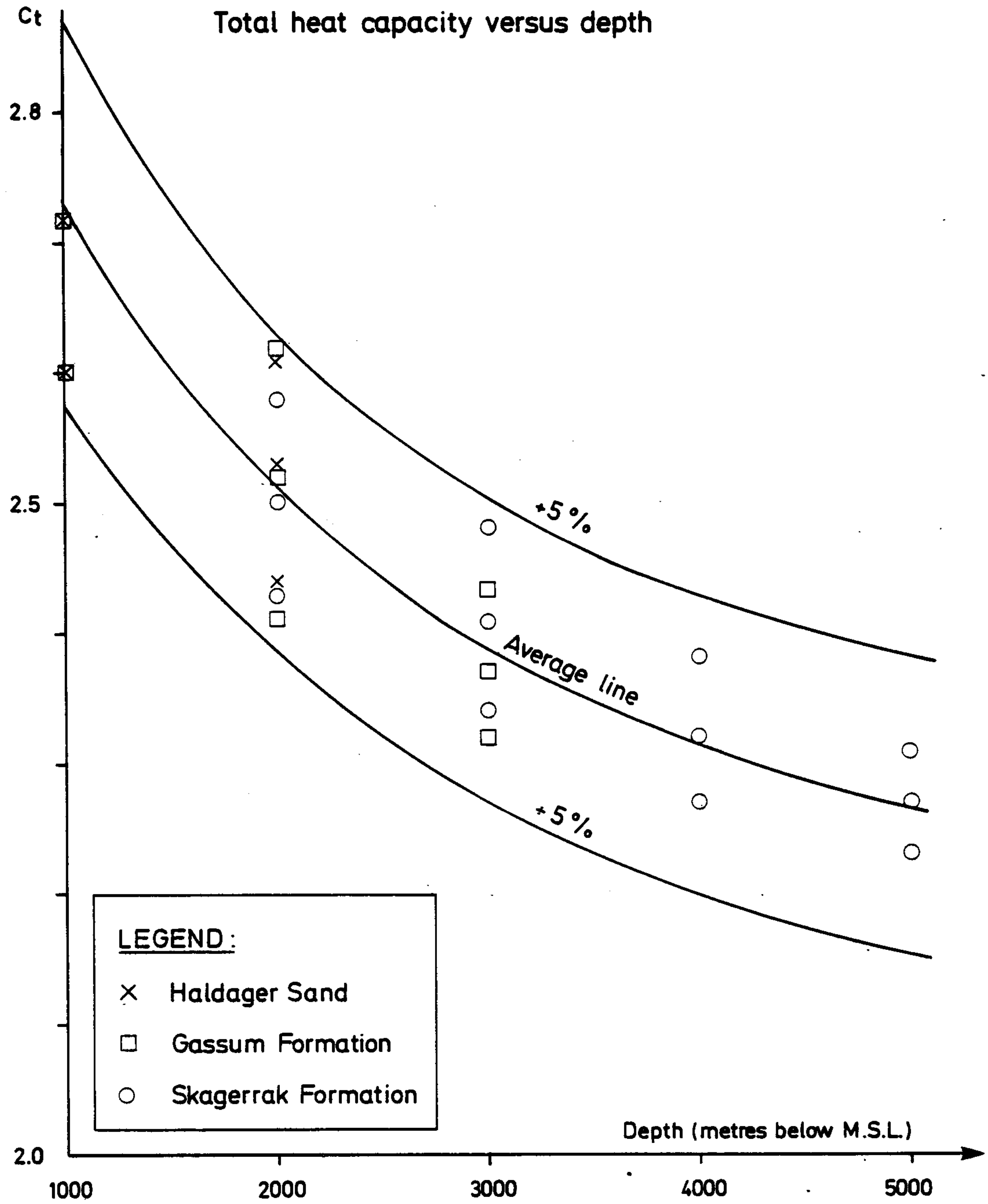
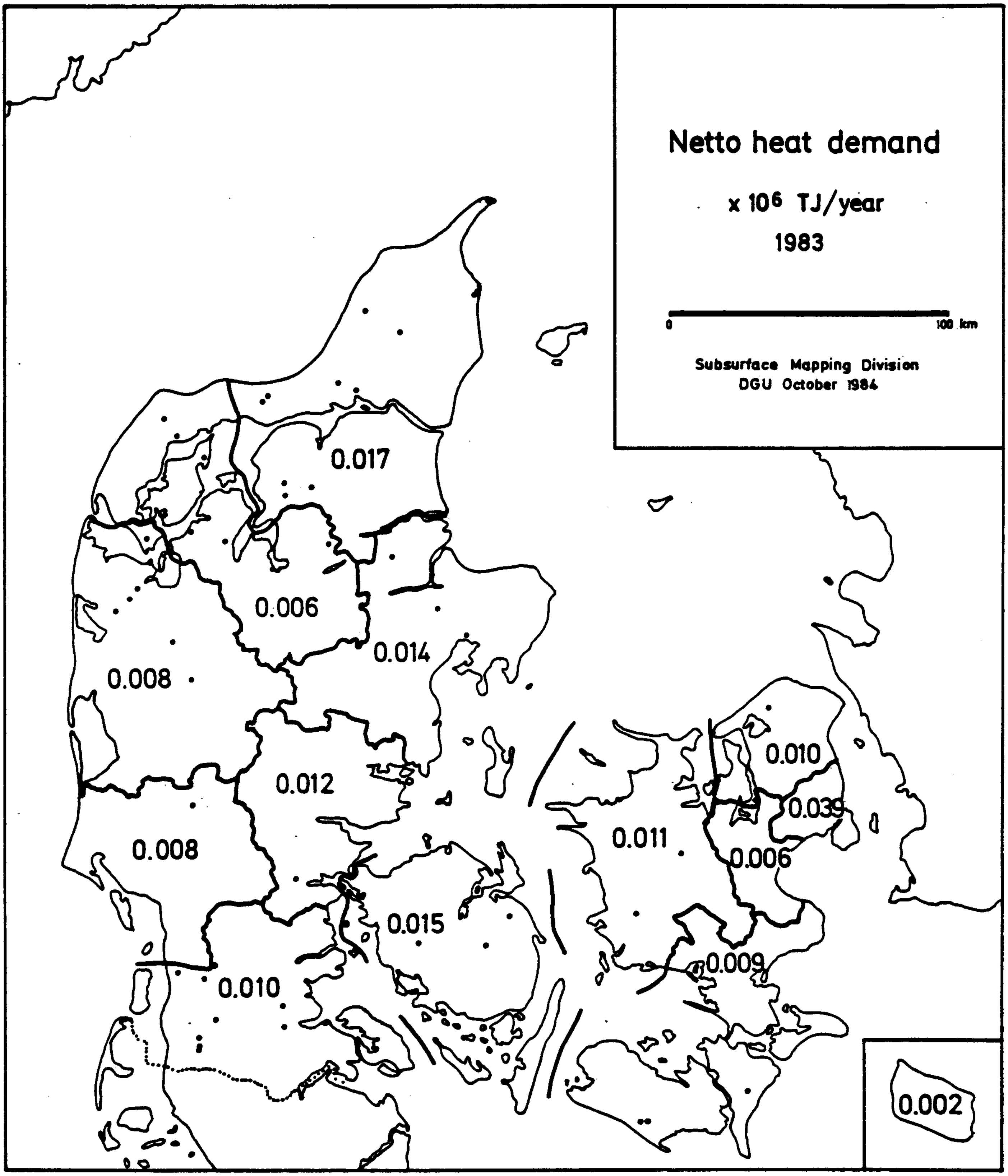

Frederikshavn Member
Geothermal Resources
and Reserves
8.9/ Heat in Place (x 10^6 TJ)
/0.1 Possible Reserves (x 10^6 TJ)
0
100 km
Subsurface Mapping Division
DGU October 1984
In total: 54/4.5
8.9/0.1
2.1/0.1
22.4/2.0
1.1/0.2
16.9/1.8
2.7/0.3

Fig.17



Total heat capasity, C_t, of Skagerrak Formation, Gassum Formation and Haldager Sand as a function of depth.
C_t values based on table I.2. Personal communication from G. Iversen, D.O.N.G. A/S

Fig.18



Netto heat demand distributed on counties, x 10^6 TJ/year, 1983.
Based on Danish Energy Agency (DEA) working document, table III.1

Fig.19

The resources and reserves of low enthalpy geothermal energy sources in Denmark have been assessed.
A summary is given of the possible geothermal reservoirs with emphasis on their reservoir parametres and regional distributions. Based on these data the geothermal resources and reserves are presented.
The Accessible Resources Base, or the heat stored in the rocks and fluids, is found to be 1.45×10^6 TJ/km^2 in the Danish Subbasin.
The Geothermal Resources, which is the heat in place stored in the reservoir volumes, is calculated to 770×10^6 TJ.
The Identified Resources, representing the heat which can be produced, is found to be 206×10^6 TJ.
The Identified Reserves, the energy output when exploiting the Identified Resources, is estimated to be 103×10^6 TJ; of this, about 67×10^6 TJ is considered possible to exploit economically. To put these figures in relief, the total heat demand in Denmark is about 0.17×10^6 TJ per year.

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