Approximate geothermal gradients in Denmark and the Danish North Sea sector

AREA
Denmark
Gtherm
Gradients

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Approximate values of the geothermal gradient are calculated from temperature measurements in thirty onshore exploration wells and thirteen Danish North Sea exploration wells. A regional contour map is presented and discussed in relation to the major geological features in the area. Estimates of the thermal conductivity and the heat flow are given. Average values for the geothermal gradient, the thermal conductivity and the heat flow in the onshore area are determined to 23.2°C/km, 0.0058 cal $cm^{-1}s^{-1}{}^{\circ}C^{-1}$ and 1.34 μcal $cm^{-2}s^{-1}$ respectively.

With the intention of investigating the regional variation of the geothermal gradient in Denmark and the Danish North Sea sector, approximate values of this gradient have been calculated for thirty of the deepest onshore exploration wells (drilled in the period 1950–1968) and thirteen Danish North Sea exploration wells (1966–1970). The area in which the well Dansk Nordsø B–1 (1967) is located has belonged to the German sector since the border treaty of 1971.

A few relatively deep wells in the central part of the North Jylland Saltdome Province have been omitted. These wells were all terminated in the rocksalt of salt structures, and were excluded from the regional analysis by reason of the anomalous temperature fields which exist in and around saltdomes.

The temperature data were mainly obtained during runs of electrical logs by the firm Schlumberger for the Danish American Prospecting Company and since 1962 for Dansk Undergrunds Consortium.

The temperature data

Single temperature measurements in boreholes are usually made with mercury thermometers, which for absolute measurements have an accuracy in the order of 0.01°C. The temperature data from the wells in question are bottom hole and/or maximum temperatures, the latter also normally cor-

responding to the temperature close to the bottom of the borehole. Besides measurements at the final depth, data were often available of intermediate log runs from the most recent wells.

Temperatures measured at the bottom of boreholes a relatively short time after cessation of the drilling activities do not represent the temperature of the undisturbed formation. The circulating drilling mud will have a cooling effect, while the mechanical action of the drilling bit will have a tendency to increase the temperature. Geothermal gradients calculated from temperatures which have not been corrected for these factors are probably lower than the true gradients by 10–15 % (Evans and Coleman 1974).

Only for a minority of the wells under consideration is there information

Table 1. Onshore temperatures and temperature gradients.

Well	Depth below surface in metres	Temperature in °C	Geothermal gradient in °C/km	Formation
Aabenraa 1	2342	65.5	25.3	Pre-Zechstein
Arnum 1	1829	54.5	23.2	Pre-Zechstein
Borglum 1	1516	37.0	19.1	Rhaetic
Fjerritslev 1	907	30.0	24.3	Lower Jurassic
Fjerritslev 2	2059	55.0	22.8	Lower Jurassic
Flyvbjerg 1	1695	40.0	18.9	Keuper
Frederikshavn 2	1026	32.0	23.4	? Triassic
Frederikshavn 3	1093	32.0	23.9	? Triassic
Gassum 1	3036	115.5	35.4	Bunter
Glamsbjerg 1	905	28.0	22.1	Pre-Cambrian
Grindsted 1	1647	67.0	35.8	Pre-Cambrian
Haldager 1	1517	71.0	41.5	Lower Jurassic
Horsens 1	1726	44.0	20.9	Keuper
Honning 1	1922	44.0	18.7	Bunter
Lavo 1	2438	51.0	17.6	? Keuper
Mors 1	5215	133.0	23.1	Triassic
Novling 1	3669	95.0	23.1	Silurian
Ringe 1	1435	40.5	22.7	Lower Permian or Eocambrian
Rodby 1	1530	41.0	21.6	Bunter
Rodby 2	2720	74.5	26.0	Rotliegendes
Rodekro 1	1645	39.0	18.9	Pre-Zechstein
Ronde 1	5237	138.0	23.2	Silurian
Slagelse 1	2972	87.0	26.6	Lower Cambrian or Eocambrian
Thisted 1	908	38.0	33.0	Triassic
Tonder 1	3085	71.0	21.1	Zechstein
Tønder 2	3194	93.0	24.1	Rotliegendes
Uglev 1	1240	54.0	35.3	Rock Salt
Ullerslev 1	1058	34.5	25.1	Triassic
Vedsted 1	2065	53.0	22.3	Rhaetic
Ørslev 1	2564	74.0	25.7	Lower Carboniferous

available about the elapsed time between cessation of circulation and temperature measurement. The given times lie in the interval 3–30 hours, with the majority below 10 hours. This distribution can also be assumed to be representative for the remaining wells.

For the wells where at each depth of measurement a registration has been made at more than one time after cessation of circulation, e.g. after 3 hrs. 5 hrs. 13 hrs. and 25 hrs., it has been possible to plot the temperatures versus time and draw a smooth curve through the points. The asymptotic value of this curve will give a better approximation to the true formation temperature (see e.g. Hedemann 1967). It has been possible to use this method for a few of the most recent onshore wells and for nearly all the North Sea wells. For the remaining wells, the measured temperatures have been used without any correction.

Another uncertainty factor for the determination of the undisturbed formation temperature is that palaeotemperatures may be expected in the underground, stemming from previous periods of glaciation. From models of the temperature variation at the surface it is possible to calculate the resulting decrease in the geothermal gradient. A maximum influence of about 10 % can be expected for a depth of 1000 m, and the influence can be neglected for depths exceeding 1500 m (Kappelmeyer and Haenel 1974, p. 95). As the decrease in the gradient depends on the local variation in surface temperature in the past, it is not possible to make a general correction. Of the wells under consideration, seven have depths of 900–1200 m, and the remaining ones are about 1500 m or deeper. For these reasons no attempt has been made to correct for palaeotemperatures.

Table 2. Offshore (in the North Sea area) temperatures and temperature gradients.

Well	Depth below sea bottom in metres	Temperature in °C	Geothermal gradient in °C/km	Formation
A-1	1740	52.5	27.3	Danien
A-2	1965	74.5	33.9	Upper Cretaceous
B-1	3497	113.5	31.6	Rotliegendes
C-1	3142	87.5	26.8	Pre-Zechstein
D-1	3477	75.5	22.4	Rotliegendes
E-1	4011	129.5	30.6	
E-2	2123	72.0	31.6	
F-1	2342	81.0	33.4	
G-1	3731	118.5	30.6	
H-1	2079	72.0	31.8	
I-1	3820	132.0	31.8	
J-1	1906	76.5	38.5	
K-1	2198	74.0	35.2	

Fig. 1.

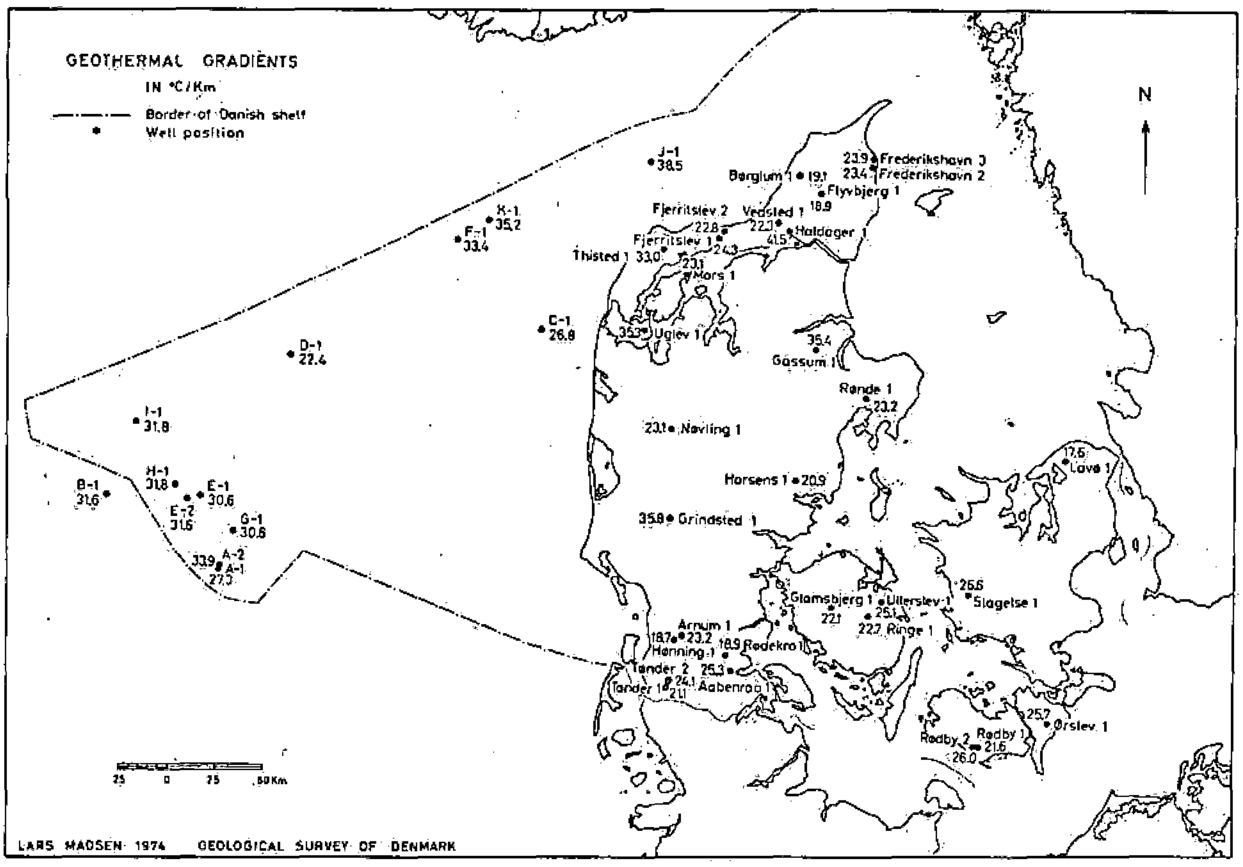
GEOTHERMAL GRADIENTS
IN °C/Km
Border of Danish shelf
Well position
N
J-1 38.5
K-1 35.2
F-1 33.4
C-1 26.8
D-1 22.4
I-1 31.8
H-1 31.8
B-1 31.6
E-1 30.6
E-2 31.6
G-1 30.8
A-2 33.9
A-1 27.3
Børglum 1 19.1
23.9 Frederikshavn 3
23.4 Frederikshavn 2
Flyvbjerg 1
Fjerritslev 2
Vedsted 1 18.9
Haldager 1
Fjerritslev 1
Thisted 1 33.0
Mors 1
Uglev 1
35.4 Gassum 1
Rønde 1 23.2
23.1 Nøvling 1
Horsens 1 20.9
17.6 Løve 1
35.8 Grindsted 1
26.6 Slagelse 1
Glamsbjerg 1
Ullerslev 1
22.7 Ringe 1
Arnum 1
Henning 1
18.9 Rødekro 1
Tønder 2 25.3
Tønder 1
Aabenraa 1
25.7 Ørslev 1
Rødby 2
Rødby 1 21.6
26.0
25 0 25 50 Km
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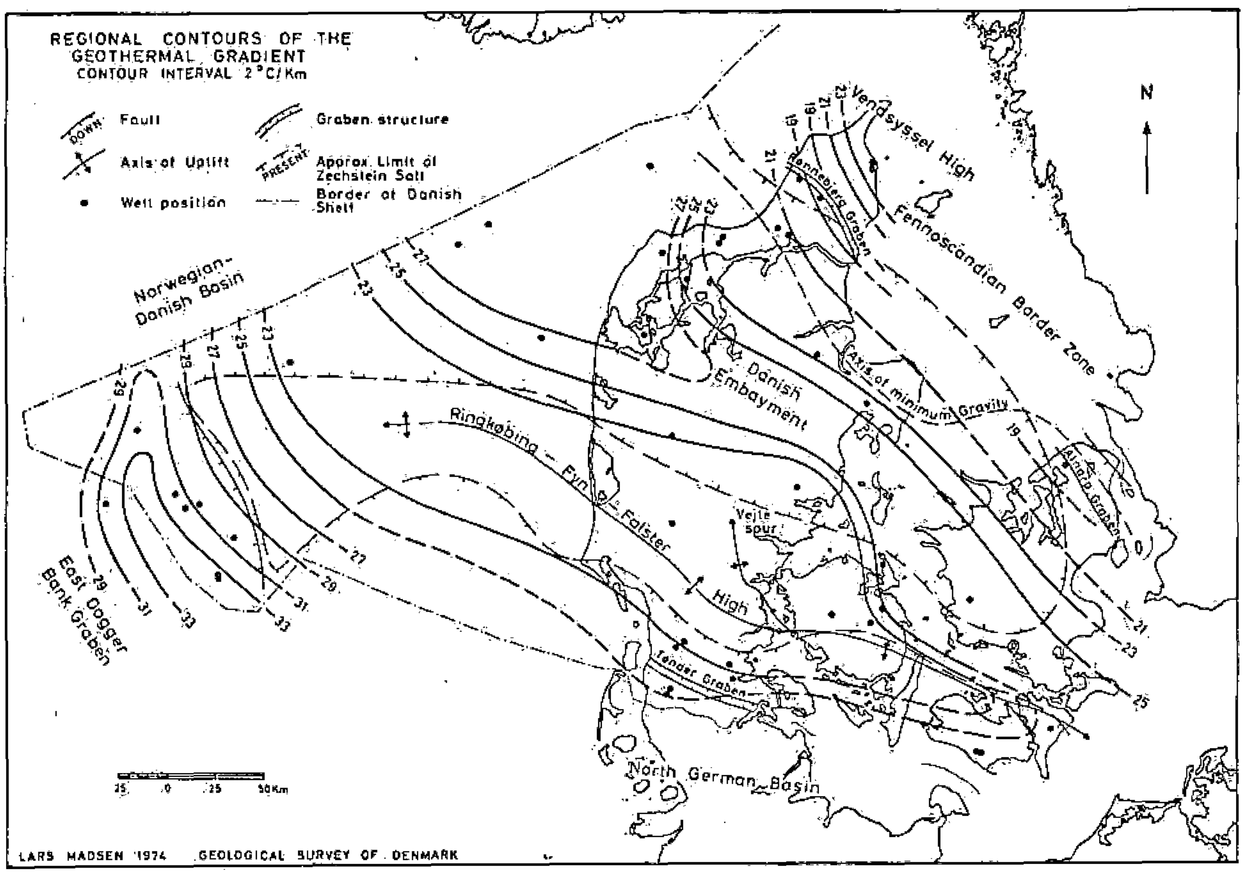
Fig. 2.


REGIONAL CONTOURS OF THE GEOTHERMAL GRADIENT
CONTOUR INTERVAL 2 °C/Km
Fault
Axis of Uplift
Well position
Graben structure
Approx. Limit of Zechstein Salt
Border of Danish Shelf
N
Norwegian-Danish Basin
East Dogger Bank Graben
Vendsyssel High
Fennoscandian Border Zone
Danish Embayment
Axis of minimum Gravity
Ringkøbing – Fyn – Falster High
Vejle spur
Tønder Graben
North German Basin
25 0 25 50 Km
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Calculation of the geothermal gradients

For the calculation of the onshore gradients a surface temperature of 8°C has been applied, representing the average mean annual temperature for the whole country. Offshore, the sea bottom temperatures have been determined from the temperature versus waterdepth curve given in Evans and Coleman 1974.

The depths have been corrected to ground level and sea bottom for onshore and offshore wells respectively. With the exception of Rønde No. 1 and Nøvling No. 1 (Henriksen *in* Rasmussen *et al.* 1971 and 1973) these depths have not been corrected for the deviation of the borehole from the vertical. This implies that the applied depths are somewhat too high, but as the deviation from the vertical is mostly of a relatively small order, it is estimated that the resulting uncertainty in the gradients is of a lower order than the error stemming from the temperatures. However, both factors tend to give too low gradients.

If only one temperature measurement is available from a well, the calculated gradient must be regarded as an average gradient between the surface (or sea bottom) and the depth of that measurement. If more than one temperature determination was available an average gradient was calculated by fitting a regression line to the values with the condition, that it should have an intercept with the temperature axis equal to the surface or sea bottom temperature at the well location.

Table 1 and 2 show the calculated geothermal gradient and the value of the deepest temperature determination for each well together with the depth and stratigraphical position of this determination (further information about the stratigraphy and lithology of the wells can be found in Sorgenfrei and Buch 1964, Rasmussen *et al.* 1971 and 1973, Rasmussen 1972 and 1974). A description of the stratigraphy and lithology of the eight most recent wells in table 2 is being worked out by the geologists at the Geological Survey and will be published by Rasmussen in Danm. geol. Unders., III. række, 44 (in preparation).

The calculated gradients together with the position of the wells are shown in fig. 1.

Discussion of the geothermal gradients

As the geothermal gradient is a function of depth, and the gradients have been determined from wells of different depths, they are not strictly comparable. However, if the relatively high values for the wells Gassum No. 1, Grindsted No. 1 and Haldager No. 1 are considered to be caused by local

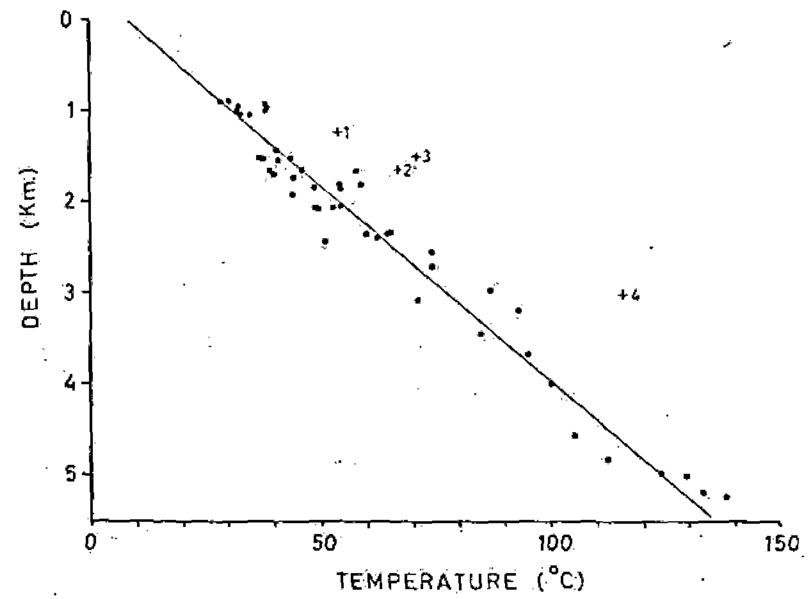

Fig. 3. A plot of temperature versus depth for the thirty onshore wells. The regression line has a slope of 23.2 °C/km and an intercept of 8.2 °C. Data from the Uglev 1 (+1), Grindsted 1 (+2), Haldager 1 (+3) and Gassum 1 well (+4) have been excluded from the analysis.

features, and if for the onshore area the main weight is put on the wells which have been drilled to depths below the Zechstein salt, or which have been drilled where the salt is thin or absent, it is possible to see a regional distribution of the values for the geothermal gradient. A tentative contouring is shown in fig. 2 together with the main structural elements in the area (mainly from Sorgenfrei 1966 and 1969). The general trend of the contours is northwest-southeast.

Low geothermal gradients often correspond to positive structural elements, while high values are found in deep sedimentary basins. It can be seen that an elongate minimum zone is situated on the Ringkøbing-Fyn-Falster High, while the Danish Embayment and the East Dogger Bank Graben represent areas of maximum values.

Considering the onshore area the gradient decreases regionally from about 25°C/km to lesser than 20°C/km in the direction southsouthwest-northeast towards the Fennoscandian Shield. The maximum indicated by the wells Frederikshavn No. 2 and 3 may be relatively local.

Fig. 3 shows a plot of temperature versus depth from all wells in table 1. Data from intermediate log runs have also been included. A standard program has been used to fit a regression line to the points (Gassum No. 1,

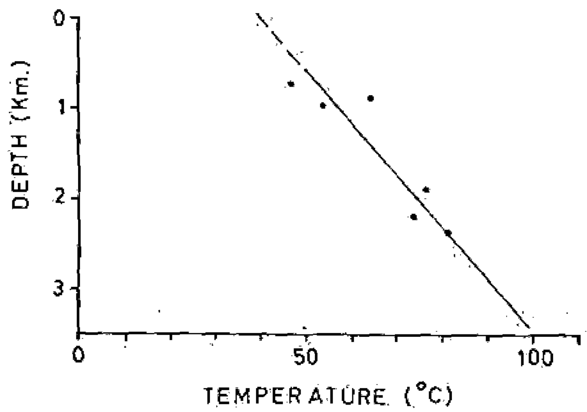

Fig. 4. A plot of temperature versus depth for the wells Dansk Nordsø F–1, J–1 and K–1. The regression line has a slope of 17.5 °C/km and an intercept of 39.5 °C.

Grindsted No. 1, Haldager No. 1 and Uglev No. 1 have been excluded as representing local anomalies). The line has an intercept with the temperature axis of 8.2°C ± 1.9°C and a slope of 23.2°C/km ± 0.7°C/km, which can be regarded as a minimum average value for the geothermal gradient in Denmark.

The maximum zone of the Danish Embayment continues with increasing values towards the northwest in the North Sea area. The temperatures for

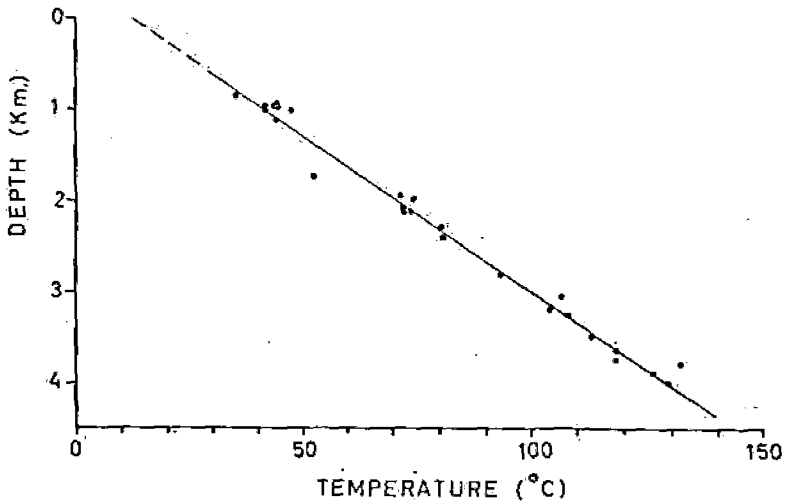

Fig. 5. A plot of temperature versus depth for the eight wells in the East Dogger Bank Graben (Dansk Nordsø A–1, A–2, B–1, E–1, E–2, G–1, H–1 and I–1). The regression line has a slope of 29.2 °C/km and an intercept of 12.9 °C.

the three wells Dansk Nordsø F–1, Dansk Nordsø J–1, and Dansk Nordsø K–1 are plotted versus depth in fig. 4. A regression line fitted to the points has an intercept of 39.5°C ± 6.2°C and a slope of 17.5°C/km ± 3.8°C/km; if the line is determined with the condition that the intercept with the temperature axis must be 7.2°C (average sea bottom temperature at the three wells) it will have a slope of 35.5°C/km. It is obvious that the straight line is not an appropriate model for these data. There must be a high gradient in the upper layers relative to the deeper ones. Concerning the geology of the area it is known that several saltdomes and saltwalls are present and that the wells Dansk Nordsø F–1 and K–1 are situated on or near such structures. The well Dansk Nordsø J–1 is located in the area where the Triassic to Lower Cretaceous sequence reaches its maximum value in the Danish North Sea area with values exceeding 6 km (Childs and Reed 1975, fig. 4).

The minimum of the Ringkøbing-Fyn-Falster High continues in a northwest direction along the High. From here the geothermal gradient increases towards the southwest and reaches a maximum of about 33°C/km in the East Dogger Bank Graben. The order of the contour values for this area is in good accordance with earlier published data for other sectors in the North Sea (Harper 1971 and Evans and Coleman 1974).

In fig. 5 is shown a plot of temperature versus depth for the eight wells in the East Dogger Bank Graben. The line fitted to the points has an intercept of 12.9°C ± 1.7°C and a slope of 29.2°C/km ± 0.7°C/km. If the condition is made that the intercept must be 7.3°C (average of the sea bottom temperatures) then the slope will be 31.2°C/km. This implies that the gradient is higher in the uppermost layers than indicated by the line model.

The East Dogger Bank Graben as a part of the Central Graben is an area characterized by a very thick sequence of Tertiary sediments (low thermal conductivity) and by salt piercement structures. These are probably the main reasons for the high gradient values in this area.

The as yet sole Danish productive oil field, the Dan field is located in the area of maximum gradient values. In this connection it is interesting to note the theories of Klemme 1972 (see Evans and Coleman 1974) that high geothermal gradients enhance petroleum mobility and therefore also enhance migration to structural traps.

Estimation of the heat flow

No Danish determination exists of thermal conductivities for the sediments in the area under consideration. Therefore an estimate of thermal conductivities for the North Sea sediments (Evans and Coleman 1974) has been applied. For each of the onshore and offshore wells the average thermal conductivity and the heat flow have been estimated.

The estimated values of the thermal conductivities for the onshore wells (Gassum, Grindsted, Haldager and Uglev have been omitted) have an average of 0.0058 cal $cm^{-1}s^{-1}°C^{-1}$ and a standard deviation of 0.0007 cal $cm^{-1}s^{-1}°C^{-1}$.

The average of the values for the wells in the East Dogger Bank Graben is 0.0046 cal $cm^{-1}s^{-1}°C^{-1}$ with a standard deviation of 0.0005 cal $cm^{-1}s^{-1}°C^{-1}$.

The corresponding values for the heat flow are 1.34 μcal $cm^{-2}s^{-1}$ $\pm$ 0.27 μcal $cm^{-2}s^{-1}$ for the onshore wells and 1.43 μcal $cm^{-2}s^{-1}$ $\pm$ 0.16 μcal $cm^{-2}s^{-1}$ for the wells in the East Dogger Bank Graben.

It is seen that there is a significant difference between the thermal conductivity for the onshore and the East Dogger Bank Graben area. The relatively low value for the latter is explained by the fact that the Tertiary and Cretaceous sediments, which have a low conductivity, constitute the main part of the stratigraphy in the wells located in this area.

The average values for the heat flow in the two areas indicate a decrease towards the onshore area, but it must be noted that the standard deviations are relatively large and that the temperatures from the offshore wells are to some degree corrected to higher values closer to the true formation temperatures while this is only done for a couple of onshore measurements.

Values of 0.90–1.00 μcal $cm^{-2}s^{-1}$ are common for the heat flow in Precambrian areas; therefore a decrease towards the Fennoscandian Shield could be expected.

A trend analysis of 7th order has been made by Haenel 1974 based on heat flow data from a large part of Europe (however none from the area of Denmark and the North Sea). On his map the contours representing heat flow values of 1.2 and 1.4 μcal $cm^{-2}s^{-1}$ cross Denmark and the North Sea, thereby showing an agreement with the figures estimated above.

Conclusions

Despite the uncertainty factors in the data and the calculations it seems justified to conclude that the order of the values for the geothermal gradient and the heat flow in the Danish area is as could be expected regarding its location relative to the Fennoscandian Shield and the North Sea area.

Dansk sammendrag

For 30 af de dybeste efterforskningsboringer indenfor dansk landområde (perioden 1950–68) samt 13 danske Nordsøboringer (1966–70) er der på grundlag af temperaturer, målt i borehullet, beregnet tilnærmede værdier af den geotermiske gradient. Tabel 1 og 2 giver for hver boring den beregnede gradient og den dybeste temperaturbestemmelse, samt dybden og det stratigrafiske niveau for sidstnævnte. På fig. 1 er vist placeringen af boringerne sammen med værdien af den geotermiske gradient.

Et regionalt konturkort over den geotermiske gradient (fig. 2) viser, at en minimumszone er beliggende over Ringkøbing-Fyn-Falster Højderyggen, mens Det danske Sænkningsområde og Øst Dogger Banke Graven udgør områder med relative maksima. Indenfor det danske landområde aftager gradienten regionalt fra omkring 25 °C/km mod sydsydvest til mindre end 20 °C/km mod nordøst i retning mod Det fennoskandiske Skjold. Et plot af temperaturerne mod dybderne for landboringerne er vist på fig. 3. En ret linie tilpasset punkterne efter mindste kvadraters metode har en hældning på 23,2 °C/km, hvilket kan opfattes som en mindste middelværdi for den geotermiske gradiant i Danmark. I det veldefinerede maksimum over Øst Dogger Banke Graven antager gradienten værdier på mere end 33 °C/km.

Udfra publicerede data for varmeledningsevnen for Nordsøsedimenter er der bestemt en middelværdi for varmeledningsevnen på 0,0058 cal $cm^{-1}s^{-1}°C^{-1}$ og 0,0046 cal $cm^{-1}s^{-1}°C^{-1}$ for henholdsvis det danske landområde og Øst Dogger Banke Graven. Den relativt lave værdi i Øst Dogger Banke Graven skyldes, at hovedparten af de gennemborede lag udgøres af tertiære og kretaciske sedimenter, der har en forholdsvis lav varmeledningsevne. Der er endvidere bestemt en middelværdi for varmestrømningen på 1,34 μcal $cm^{-2}s^{-1}$ og 1,43 μcal $cm^{-2}s^{-1}$ for henholdsvis landområdet og Øst Dogger Banke Graven. Dette indicerer med forbehold for usikkerhed ved bestemmelserne, at varmestrømningen aftager i retning mod det danske landområde. Da værdier i størrelsesordenen 0,90–1,00 μcal $cm^{-2}s^{-1}$ er almindelige for prækambriske områder, kunne det forventes, at værdierne for den geotermiske gradient og varmestrømningen aftog i retning mod Det fennoskandiske Skjold.

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Triassic palynology and stratigraphy of some Danish North Sea boreholes

Finn Bertelsen

Bertelsen, Finn: Triassic palynology and stratigraphy of some Danish North Sea boreholes. *Danm. geol. Unders., Årbog 1974*, pp. 17–32, pl. 1, København, 18. september 1975.

Palynofloras ranging in age from Anisian to Rhaetian are described from the Danish North Sea sector. Anisian-Ladinian (Muschelkalk) assemblages were recovered from the basal part of the Dansk Nordsø A–2 borehole situated in the Central Graben. Rhaetian assemblages occur in the Dansk Nordsø F–1 and the Dansk Nordsø K–1 boreholes drilled in the northwestern part of the Danish Embayment. The Triassic red beds are generally non-palyniferous with rare poductive horizons.

Triassic palynological information from the North Sea offshore area has hitherto been limited to some profiles lying on an E–W directed line through the southern part of the North Sea Basin (Geiger & Hopping 1968). The present study intends to extend the published knowledge of the offshore Triassic deposits by giving the results of palynological investigations carried out within the Danish sector. Due to the rapidly developed palynological research on the British onshore Triassic (Warrington 1974) the stratigraphical "breakdown" of the offshore mainly non-marine deposits has to some degree been successful. However, the occurrence of vertically limited palyniferous sequences, which cause serious trouble in British onshore Triassic correlations seems to be repeated as a norm of the offshore area too.

The Danish offshore area comprises parts of four structurally determined deposition centre during the Triassic (Text-fig. 1): 1) To the north the northwesterly extension of the Danish Embayment, 2) to the west, part of the Central Graben, 3) to the south, a northern part of the North German Basin and 4) the Horn Graben connecting the Danish Embayment with the North German Basin (Childs & Reed 1975).

The Triassic deposits generally show a change from continental arenaceous red beds in the Early Triassic to a more pelitic red bed facies in the Middle-Late Triassic. During the Middle-Late Triassic, evaporitic carbonates, anhydrite and rock salt were also deposited. The climatic change