

Approximate geothermal gradients in Denmark and the Danish North Sea sector

Lars Madsen

Madsen, Lars: Approximate geothermal gradients in Denmark and the Danish North Sea sector. *Danm. geol. Unders., Årbog 1974*, pp. 5–16. København, 18. september 1975.

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 $23.2^{\circ}\text{C}/\text{km}$, $0.0058 \text{ cal cm}^{-1}\text{s}^{-1}^{\circ}\text{C}^{-1}$ and $1.34 \mu\text{cal cm}^{-2}\text{s}^{-1}$ 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 Salt-dome 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 salt-domes.

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 |
| Børglum 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 | 1003 | 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 |
| Hønning 1 | 1922 | 44.0 | 18.7 | Bunter |
| Lavø 1 | 2438 | 51.0 | 17.6 | ? Keuper |
| Mors 1 | 5215 | 133.0 | 23.1 | Triassic |
| Nøvling 1 | 3669 | 95.0 | 23.1 | Silurian |
| Ringe 1 | 1435 | 40.5 | 22.7 | Lower Permian or Eocambrian |
| Rødby 1 | 1530 | 41.0 | 21.6 | Bunter |
| Rødby 2 | 2720 | 74.5 | 26.0 | Rotliegendes |
| Rødekro 1 | 1645 | 39.0 | 18.9 | Pre-Zechstein |
| Rønde 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 |
| Tønder 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 | |

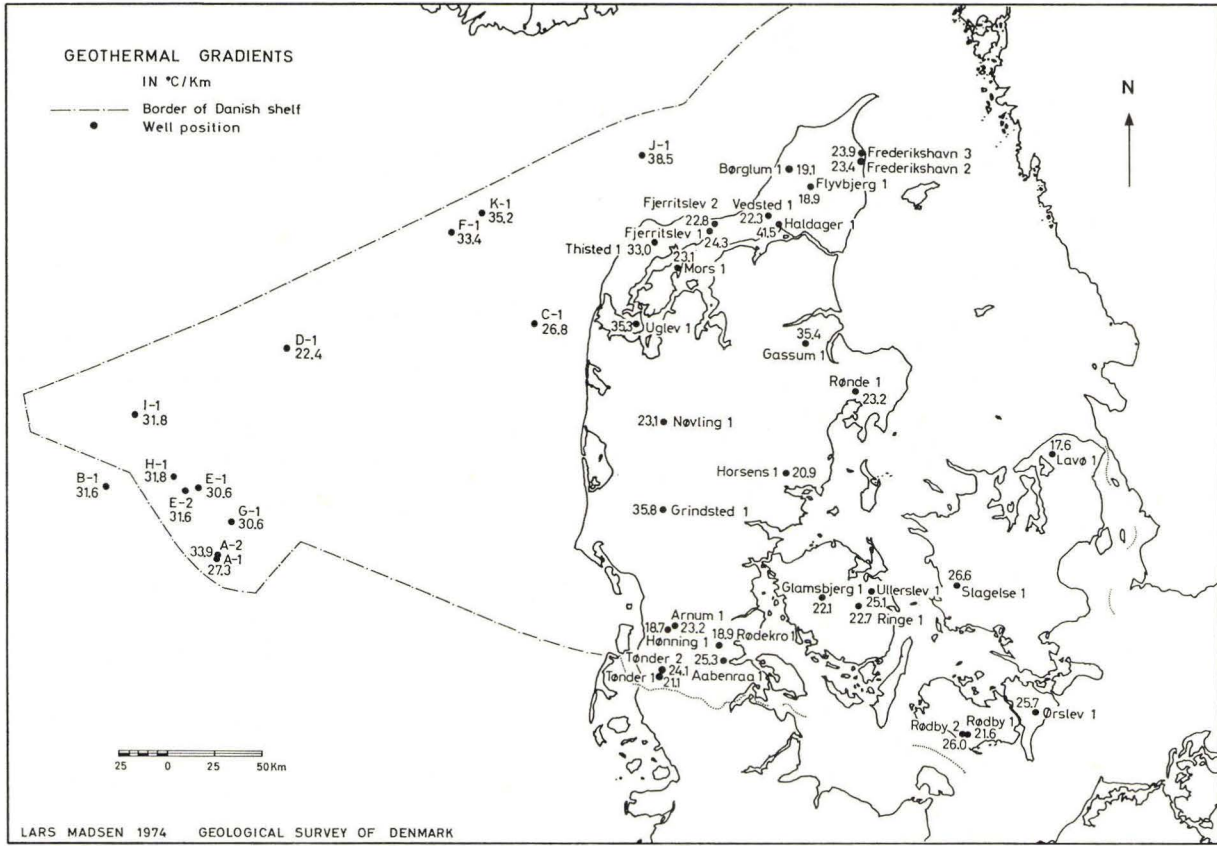
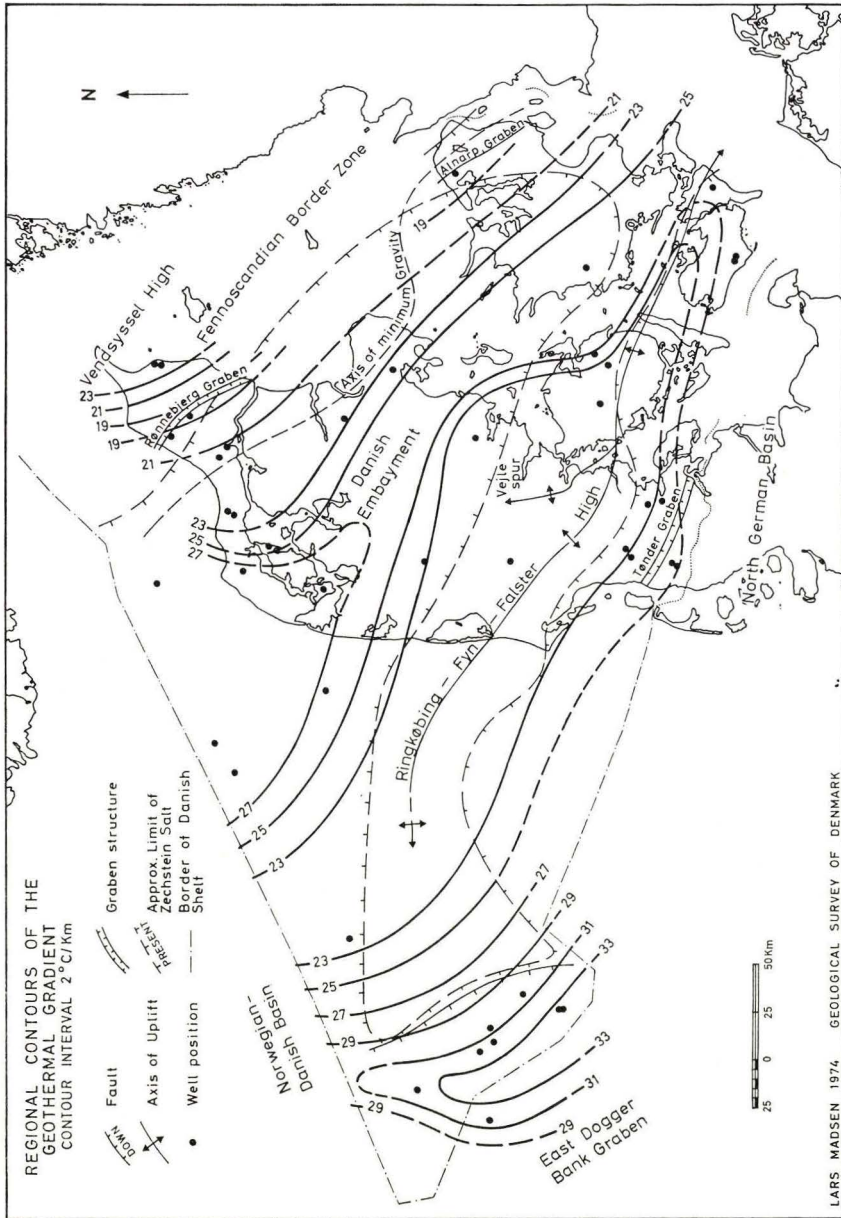


Fig. 1.



LARS MADSEN 1974. GEOLOGICAL SURVEY OF DENMARK

Fig. 2.

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

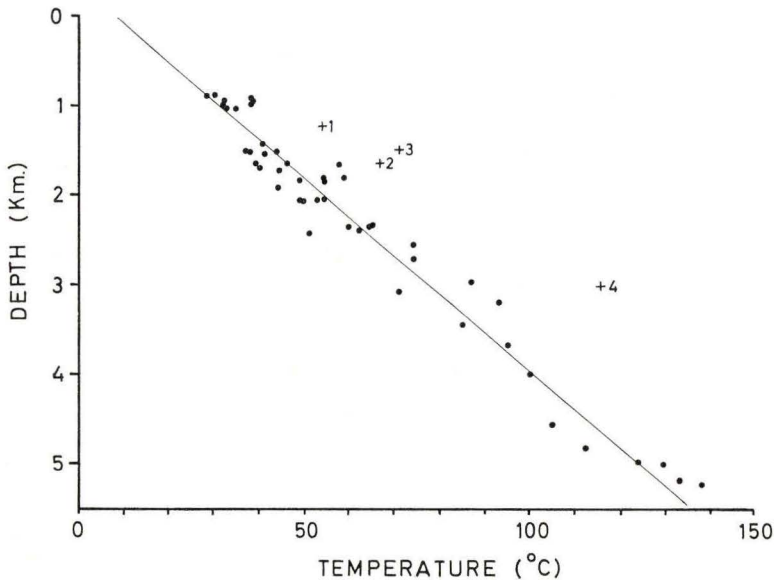


Fig. 3. A plot of temperature versus depth for the thirty onshore wells. The regression line has a slope of $23.2\text{ }^{\circ}\text{C}/\text{km}$ and an intercept of $8.2\text{ }^{\circ}\text{C}$. Data from the Uglev 1 (+1), Grindsted 1 (+2), Haldager 1 (+3) and Gassum 1 well (+4) have been excluded 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 $25\text{ }^{\circ}\text{C}/\text{km}$ to lesser than $20\text{ }^{\circ}\text{C}/\text{km}$ 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,

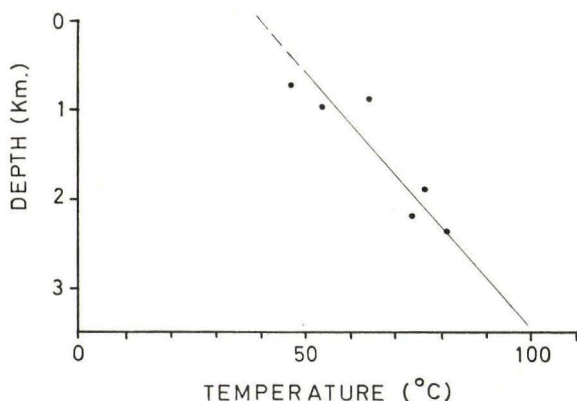


Fig. 4. A plot of temperature versus depth for the wells Dansk Nordsø F-1, J-1 and K-1. The regression line has a slope of $17.5\text{ }^{\circ}\text{C}/\text{km}$ and an intercept of $39.5\text{ }^{\circ}\text{C}$.

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 $8.2^{\circ}\text{C} \pm 1.9^{\circ}\text{C}$ and a slope of $23.2^{\circ}\text{C}/\text{km} \pm 0.7^{\circ}\text{C}/\text{km}$, 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

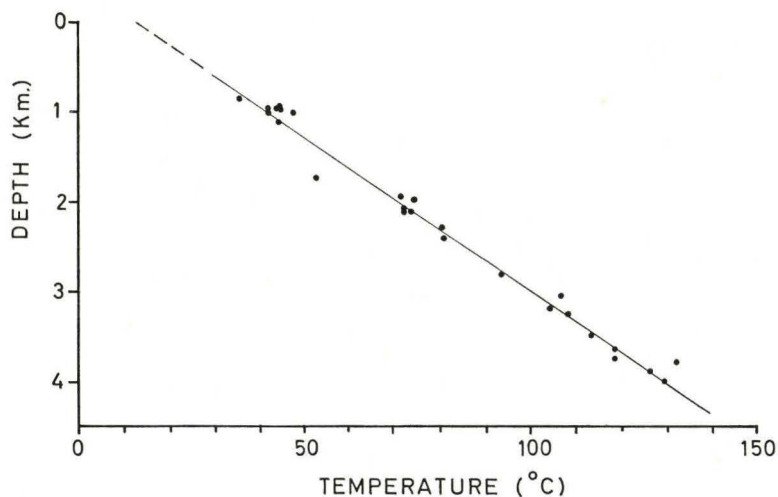


Fig. 5. A plot of temperature versus depth for the eight wells in the East Dogger Bank Graben (Dansk Nordsø A-1, A-2, B-1, E-1, E-2, G-1, H-1 and I-1). The regression line has a slope of $29.2\text{ }^{\circ}\text{C}/\text{km}$ and an intercept of $12.9\text{ }^{\circ}\text{C}$.

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 $39.5^{\circ}\text{C} \pm 6.2^{\circ}\text{C}$ and a slope of $17.5^{\circ}\text{C}/\text{km} \pm 3.8^{\circ}\text{C}/\text{km}$; 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 $35.5^{\circ}\text{C}/\text{km}$. 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 salt domes and salt walls 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 north-west direction along the High. From here the geothermal gradient increases towards the southwest and reaches a maximum of about $33^{\circ}\text{C}/\text{km}$ 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 $12.9^{\circ}\text{C} \pm 1.7^{\circ}\text{C}$ and a slope of $29.2^{\circ}\text{C}/\text{km} \pm 0.7^{\circ}\text{C}/\text{km}$. If the condition is made that the intercept must be 7.3°C (average of the sea bottom temperatures) then the slope will be $31.2^{\circ}\text{C}/\text{km}$. 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 $0.0058 \text{ cal cm}^{-1}\text{s}^{-1}\text{°C}^{-1}$ and a standard deviation of $0.0007 \text{ cal cm}^{-1}\text{s}^{-1}\text{°C}^{-1}$.

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

The corresponding values for the heat flow are $1.34 \mu\text{cal cm}^{-2}\text{s}^{-1} \pm 0.27 \mu\text{cal cm}^{-2}\text{s}^{-1}$ for the onshore wells and $1.43 \mu\text{cal cm}^{-2}\text{s}^{-1} \pm 0.16 \mu\text{cal cm}^{-2}\text{s}^{-1}$ 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 $0.90\text{--}1.00 \mu\text{cal cm}^{-2}\text{s}^{-1}$ 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 $1.4 \mu\text{cal cm}^{-2}\text{s}^{-1}$ 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 Sænkingsområde 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 gradient i Danmark. I det veldefinerede maksimum over Øst Dogger Banke Graven antager gradienten værdier på mere end 33 °C/km.

Ud fra publicerede data for varmeledningsevnen for Nordsøsedimenter er der bestemt en middelværdi for varmeledningsevnen på 0,0058 cal cm⁻¹s⁻¹°C⁻¹ og 0,0046 cal cm⁻¹s⁻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 varmemestrømningen på 1,34 μcal cm⁻²s⁻¹ og 1,43 μcal cm⁻²s⁻¹ for henholdsvis landområdet og Øst Dogger Banke Graven. Dette indikerer med forbehold for usikkerhed ved bestemmelserne, at varmemestrømningen aftager i retning mod det danske landområde. Da værdier i størrelsesordenen 0,90–1,00 μcal cm⁻²s⁻¹ er almindelige for prækambriske områder, kunne det forventes, at værdierne for den geotermiske gradient og varmemestrømningen aftog i retning mod Det fennoskandiske Skjold.

References

- Childs, F. B. and Reed, P. E. C. 1975: Geology of the Dan field and the Danish North Sea. – Danm. geol. Unders. III. række, 43, 24 p.
- Evans, T. R. and Coleman, N. C. 1974: North Sea Geothermal Gradients. – *Nature*, 247, pp. 28–30.
- Haenel, R. 1974: Heat Flow Measurements in Northern Italy and Heat Flow Maps of Europe. – *J. Geophys.* 40, pp. 367–380.
- Harper, M. L. 1971: Approximate Geothermal Gradients in the North Sea Basin. – *Nature*, 230, pp. 235–236.
- Hedemann, H.-A. 1967: Geologische Auswertung von Temperaturdaten aus Tiefbohrungen. – *Erdöl Kohle – Erdgas – Petrochem.* 20, pp. 337–343.
- Kappelmeyer, O. and Haenel, R. 1974: Geothermics, with Special Reference to Application. – *Geoexploration Monographs*, Ser. 1, No. 4. – Gebrüder Borntraeger, Berlin. 238 p.
- Rasmussen, L. B. 1972: Oversigt over dybdeboringerne på dansk landområde 1965–68. – *Dansk geol. Foren. Årsskrift for 1971*, pp. 41–48.

- Rasmussen, L. B. 1974: Some geological results from the first five Danish exploration wells in the North Sea, Dansk Nordsø A-1, A-2, B-1, C-1, and D-1. – *Danm. geol. Unders. III. række*, 42, 46 p.
- Rasmussen, L. B., Baartman, J. C., Henriksen, S. E., Kristoffersen, F. N., Dinesen, A., Bang, I., Stenestad, E., Buch, A., Christensen, O. B., Michelsen, O., Hansen, T. J. og Jacobsen, F. L. 1973: Dybdeboringen Nøvling nr. 1 i Midtjylland (Engl. summary). – *Danm. geol. Unders. III. række*, 40, 164 p.
- Rasmussen, L. B., Dinesen, A., Henriksen, S. E., Bang, I., Stenestad, E., Buch, A., Christensen, O. B., Michelsen, O. og Jacobsen, F. L. 1971: Dybdeboringen Rønde nr. 1 på Djursland. (Engl. summary). – *Danm. geol. Unders. III. række*, 39, 123 p.
- Sorgenfrei, T. 1966: Strukturgeologischer Bau von Dänemark. – *Z. Geol.* 15, pp. 641–660.
- Sorgenfrei, T. 1969: Geological perspectives in the North Sea Area. – *Meddr dansk geol. Foren.* 19, pp. 160–196.
- Sorgenfrei, T. and Buch, A. 1964: Deep Tests in Denmark 1935–1959. – *Danm. geol. Unders. III. række*, 36, 146 p.