Formation temperatures in the Danish Central Graben

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The formation temperatures are mapped in the depths of 1, 2, 3, and 4 km in the Central Graben (Danish North Sea). The general trend is increasing temperatures towards the north-eastern fault boundary of the graben. Positive temperature anomalies are found around the Tyra Field in a depth of 1 km. Fluid movements in this area is possible. The observed temperature is high around the top of salt structures. The temperature is high where there is a thick cover of the low conductive, Lower Cretaceous and Jurassic shales. The top Jurassic temperature is mainly a function of the burrial depth with increasing temperatures from about 80°C at the southern part of the Central Graben to about 125°C at the northern part. Locally the temperature is higher than 140°C. The temperature maps reflect the general geological trend and the temperature seems to be of conductive origin, except in the area of the Tyra Field where convection of fluids may occur. Temperature as a function of time is calculated for top and base of the J-4 Unit at some locations. Temperature through time of the J-4 Unit is increasing from the Southern Salt-dome Province towards the northern Tail End Graben. The Eocene rise of surface temperature has heated the subsurface temperature.

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About forty off-shore wells have been investigated to evaluate the formation temperatures.

Values of approximate geothermal gradients in the Danish North Sea sector have been evaluated and published by Madsen (1975) who mentions that the values obtained are probably 10–15% too low as no corrections are applied on the collected bottom hole temperatures.

An important question is, if transfer of heat by water circulation is comparable with transfer of heat by conduction. This point is discussed in three recent papers (Oxburgh & Andrews-Speed 1981, Andrews-Speed et al. 1982, and Carstens & Finstand 1981) describing the present temperature field in the southwestern and northern North Sea.

The results of a preliminary study of the formation temperatures for the central and northern part of the Danish Central Graben (Michelsen 1982) are revised and included in the present work.

The formation temperatures are related to the structural style of the area especially to the salt structures, which are an important factor in the Danish area.

Principles of temperature mapping

Temperature mapping is usually based on temperature measurements and heat flow determinations, but as pointed out in Jensen (1983b) temperature mapping can also be carried out simply by observing borehole temperatures and variations of temperature gradients within the formations, if sufficient temperature measurements are available.

The method of correcting the bottom hole temperature values used in this paper was used by Evans and Colemann (1974). Observed and corrected temperatures are shown in table 1. Mean gradients are calculated with reference to the measured temperature at sea floor (Evans and Colemann 1974)

Table 1. Temperatures and mean gradients.

Well	Depth b. ML (m)	Last temp. (°C)	Corr. temp. (°C)	Mean grad. (°C km^{-1})	Corr. grad. (°C km^{-1})	Type	TSC (hrs.)	Drill rate ft hr.$^{-1}$
A-1	1740	52	–	26	30	Logs	?	–
A-2	982	43	–	38	44	Logs	?	50
	1967	74?	–	35	38	Logs		20
Adda-1	1139	41	45	33	39	Logs	6	0.4?
	2074	74	–	32	36	Tests	–	–
	2206	72	76	31	34	Logs	18	1
	2976	94	101	31	34	Logs	18	3
B-1	1000	40	40	33	40	Logs	5	80
	2280	79	80	32	35	Logs	15	50
	3039	106	104	32	34	Logs	13	40
	3497	116?	118	32	34	Logs	12.5	8
Bo-1	1302	42	44	28	34	Logs	6	100
	2085	75	–	32	36	Tests	–	–
	2248	70	74	30	33	Logs	17	20
	2667	93	102	36	38	Logs	25	4
D-1	996	52	55	48	55	Logs	8	90
	1730	67?	67	34	39	Logs	11	22
	3375	74	76	21	23	Logs	30	9
E-1	1000	46	47	40	47	Logs	6	90
	1997	66	–	29	33	Tests	–	–
	2028	67	–	30	33	Tests	–	–

Well	Depth b. ML (m)	Last temp. (°C)	Corr. temp. (°C)	Mean grad. (°C km^{-1})	Corr. grad. (°C km^{-1})	Type	TSC (hrs.)	Drill rate ft hr.$^{-1}$
	2391	80	81	31	34	Logs	26	6
	3171	94	–	27	30	Logs	6	27
	3865	122	–	30	32	Tests	–	–
	4012	122	–	29	30	Logs	10	8.0
	4012	126	–	30	31	Logs	13	8.0
E-2	992	42	–	35	43	Logs	?	90
	2124	68	70	29	33	Logs	7	35
E-3	1013	38	–	31	38	Logs	4	120
	2217	73	75	30	34	Logs	15	40
	2594	63	–	22	24	Logs	?	30
E-4	1161	62	68	52	58	Logs	5	60
	1942	71	–	33	37	Tests	–	–
	2223	73	73	30	33	Logs	20	40
G-1	987	43	45	39	46	Logs	5	90
	2114	73	74	32	35	Logs	22	12
	3732	117	122	31	33	Logs	10	11
H-1	991	41	43	36	43	Logs	6	80
	1986	67	–	30	34	Tests	–	–
	2076	67	68	29	32	Logs	26	50
I-1	1142	43	47	35	41	Logs	6	90
	2708	108	–	37	40	Tests	–	–
	2818	92	97	32	34	Logs	24	13
	3257	105	110	32	34	Logs	18	10
	3822	129	139	35	36	Logs	10	2
L-1	1137	38	38	28	34	Logs	6	90
	2620	74	78	27	30	Logs	12	6
M-1	990	38	38	32	38	Logs	4	48
	1969	70	–	32	36	Logs	?	240
	2024	66	65	29	32	Logs	8	240
	2232	70	70	29	31	Logs	6	240
M-2	1042	26	26	17	25	Logs	8	80
	2019	71	71	31	35	Logs	14	43
M-3	1966	70	80	37	41	Logs	6	75
M-4	1890	63	–	30	33	Logs	6	40
	1996	62	62	28	32	Logs	15	40
M-5	1974	66	–	30	33	Logs	5	13
M-6	1993	66	–	30	33	Logs	3	30
M-7	2007	64	68	30	34	Logs	10	20
M-8	1207	44	–	31	37	Logs	3	100
	2728	84	90	31	33	Logs	12	8
	3325	119?	161?	46?	48?	Logs	10	15
	3580	114	–	30	32	Logs	?	?
	3581	119	124	33	35	Logs	10	16
N-1	978	34	41	34	42	Logs	4	80

Well	Depth b. ML (m)	Last temp. (°C)	Corr. temp. (°C)	Mean grad. (°C km^{-1})	Corr. grad. (°C km^{-1})	Type	TSC (hrs.)	Drill rate ft hr.$^{-1}$
	2483	70	70	25	28	Logs	9	33
N-2	2220	79	83	34	37	Logs	18	100
N-3	1031	35	39	31	38	Logs	5	60
	1811	56	66	32	36	Logs	8	40
	2224	76	84	34	38	Logs	12	50
O-1	1153	44	45	33	39	Logs	6	12
	2527	77	79	29	31	Logs	9?	12
	2664	93	–	32	35	Logs	3	3
	3217	110	106	31	33	Logs	12	3
	3395	177	177	33	35	Logs	12	2
P-1	1324	33	33	20	25	Logs	6	60
	3040	83	89	27	29	Logs	15	8
	3388	102	–	28	30	Logs	?	25
Q-1	1778	44	46	22	26	Logs	7	40
	3680	106	108	28	29	Logs	21	10
	4090	127	–	29	31	Logs	6	12
	4434	129	–	28	29	Logs	6	10
Ruth-1	1152	36	–	25	31	Logs	?	50
	1638	61	66	37	41	Logs	15	10
T-1	1148	32	–	22	28	Logs	6	90
	2047	70	75	33	37	Logs	18	75
	2321	89	95	38	41	Logs	14	46
	2564	107	113	42	44	Logs	21	55
U-1	1332	39	39	24	29	Logs	6	?
	2985	98	110	35	37	Logs	25	10
	3748	149	157	40	42	Logs	13	18
	4334	144	147	33	34	Logs	16	18
	4818	172	177	36	37	Logs	19	13
V-1	1135	36	39	28	34	Logs	6	50
	3234	97	114	33	35	Logs	22	8
	3774	113	–	28	30	Logs	5	?
Vagn-1	1144	46	53	40	46	Logs	11	90
W-1	1396	36	40	23	28	Logs	9	100
	3748	107	109	27	29	Logs	24	7

and corrected gradients are computed by using 0°C (accepted mean value for the Quarternary) as sea floor temperature. Table 2 contains values of observed and assumed temperature gradients, which were used for the temperature mapping.

Table 2.

Well	Cen-1 to Cen-4 and chalk units	L. Cretaceous and Jurassic shales
A-1	–	54*
Adda-1	28	35
B-1	31	30
Bo-1	32	67
E-1	20	31
E-3	26*	–
E-4	6	–
G-1	26	30
H-1	22	44*
I-1	30	42
M-1-M-8	37*	–
N-1	33	–
O-1	25	36
P-1	28	–
Q-1	32	–
U-1	26*	72
V-1	26*	62
Vagn-1	56	–
W-1	28	–

* = assumed

For the wells B-1 and D-1 pre Rotliegendes gradient of 31° C/km was assumed. For the Well P-1 a pre Jurassic gradient of 36° C/km was assumed and for the U-1 well a gradient of 37° C/km was assumed in the Triassic.

General comments about the temperature maps

The temperature maps for 1, 2, 3, and 4 km depth and "Top Jurassic" temperatures are shown in figs. 2–6. The locations of the wells are shown in fig. 1.

For all the maps the preliminary contouring was based on wells which are believed to be regionally representative of temperature as these wells were drilled outside salt structures. However, an occurrence of flat salt bodies could not be excluded beneath some of them, but as they are flat the temperature influence will be small. Wells which are drilled near fault zones have also been regarded as regionally representative, as the heat refracting effect usually is small around faults, and as there are no clear evidence of temperature disturbance caused by water and gases moving in these zones. An exception from this may be the upper 1–2 km around the Tyra Field (see later).

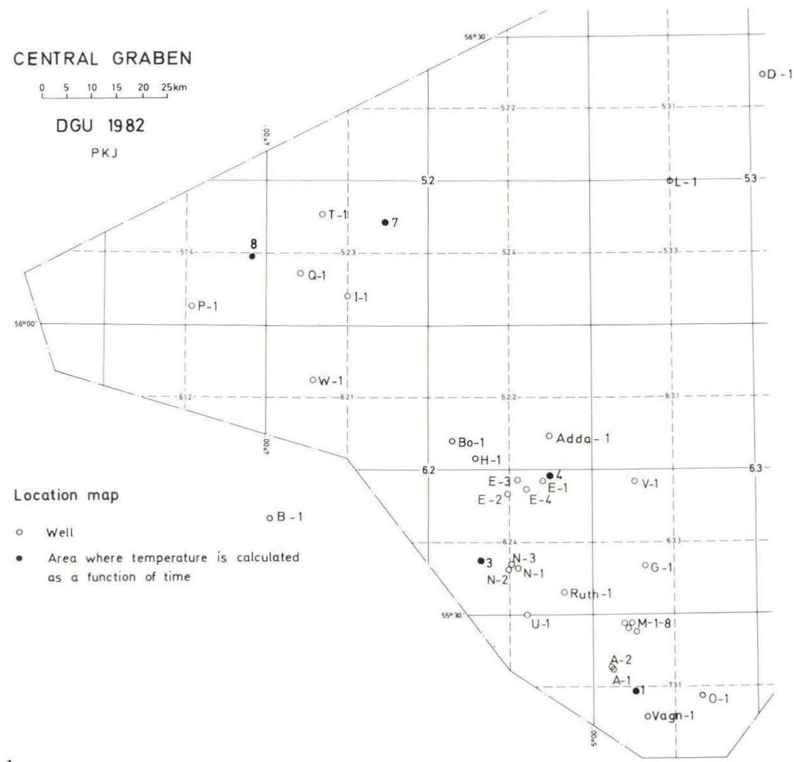

Fig. 1.

After the preliminary temperature maps were drawn, the influence of the salt structures were included by using measured temperature values and theoretical modelling (Jensen 1981). Wells which are accepted as regional thermal representative are Q-1, P-1, W-1, Bo-1, Adda-1, E-1, G-1, U-1, M-8 and, O-1, although flat salt pillows have been interpreted beneath the last three wells on basis of seismics.

Temperature map, 1 km depth, *fig. 2*

All measurements close to 1 km depth are extrapolated or interpolated linearly to 1 km depth. The general trend of the temperature variation in the Central Graben is characterized by increasing temperatures, from 25 to 40°C, from SW- to NE-direction. Temperature anomalies are found around the Tyra Field where temperatures exceeds 50°C.

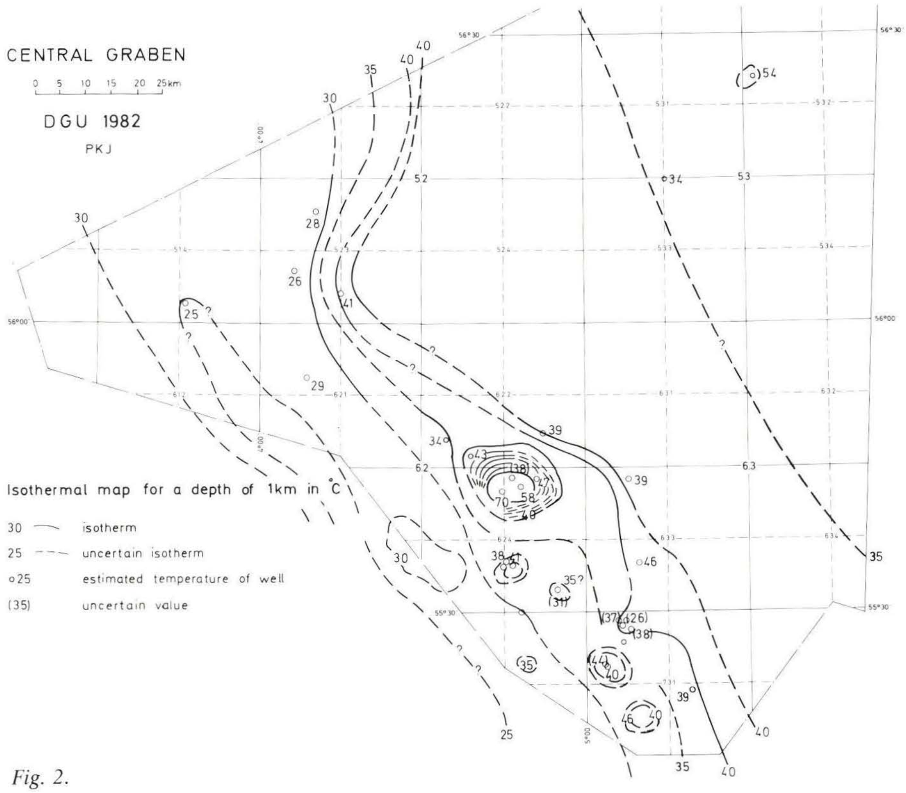

Fig. 2.

Temperature map, 2 km depth, *fig. 3*

Extrapolation or interpolation of temperatures in a well are normally based on the observed gradient in the Tertiary Cen 1–4 Units and the Chalk Group. If this gradient cannot be obtained, an assumed gradient from nearby wells is used. There is no evidence of increasing gradients towards the main faults at the NE-boundary of the Graben. A mean regional gradient for the Cen 1–4 Units and the Chalk Group of 26°C/km is accepted. Above salt structures the gradient is clearly higher. There is no evidence of change of gradient from the Cen 1–4 Units to the Chalk Group.

The higher temperature gradients which may be observed close to the NE-fault boundary are characteristic for the first kilometer only and this tendency disappears for the deeper levels.

The temperature anomaly around the Tyra Field is not seen at a depth of 2 km. The extremely high temperature anomalies which are obtained for the 1 km depth around the Tyra gas field and the normal conditions in 2 km depth could be an indication of escaping formation fluids (or gasses?) towards the

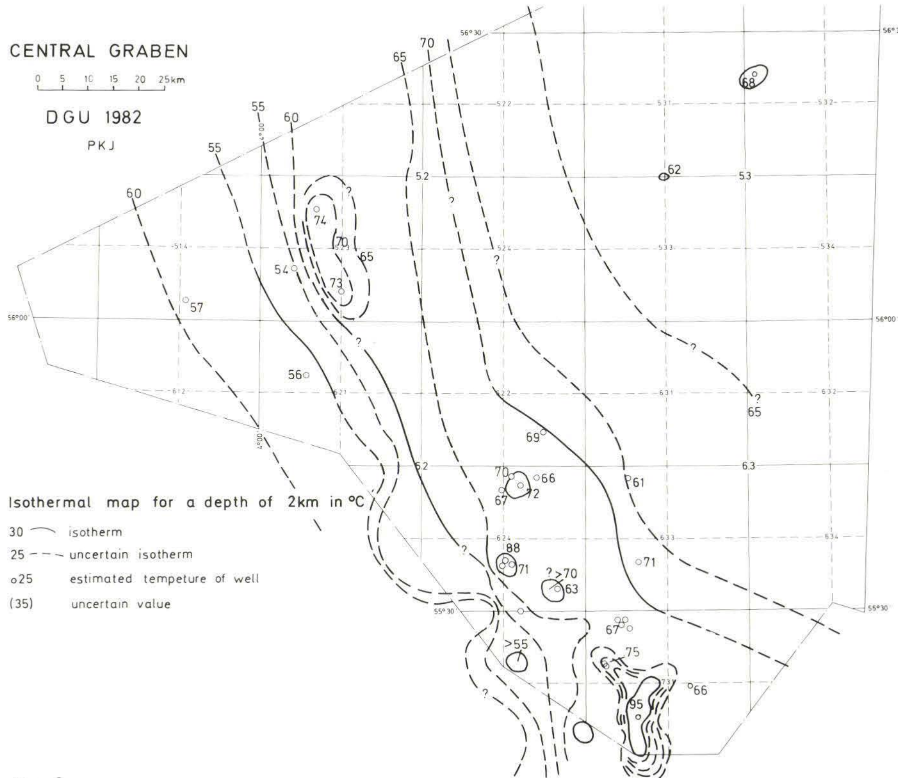

Fig. 3.

surface from a level between 1 and 2 km. In deeper levels temperature conditions seem to be normal.

Depths to Base Upper Cretaceous are found by using approximate depth conversion of two way time map of Top Lower Cretaceous and isopach map of the Chalk Group (Michelsen 1982).

Temperature map, 3 km depth, *fig. 4*

For the calculations of the temperature field for this depth it is necessary to include the value of the mean gradient corresponding to the Lower Cretaceous/Jurassic shales. A regional value of 42°C per km is estimated. This gradient is characteristic for Lower Cretaceous and Jurassic shales, as a high gradient is typical for a high porous overpressured shale. The lower conductivity of the biotumen content will also contribute to a higher gradient. The temperatures are now increasing towards areas with a thick cover of Lower Cretaceous/Jurassic shales making a good insulater (see Top Jurassic

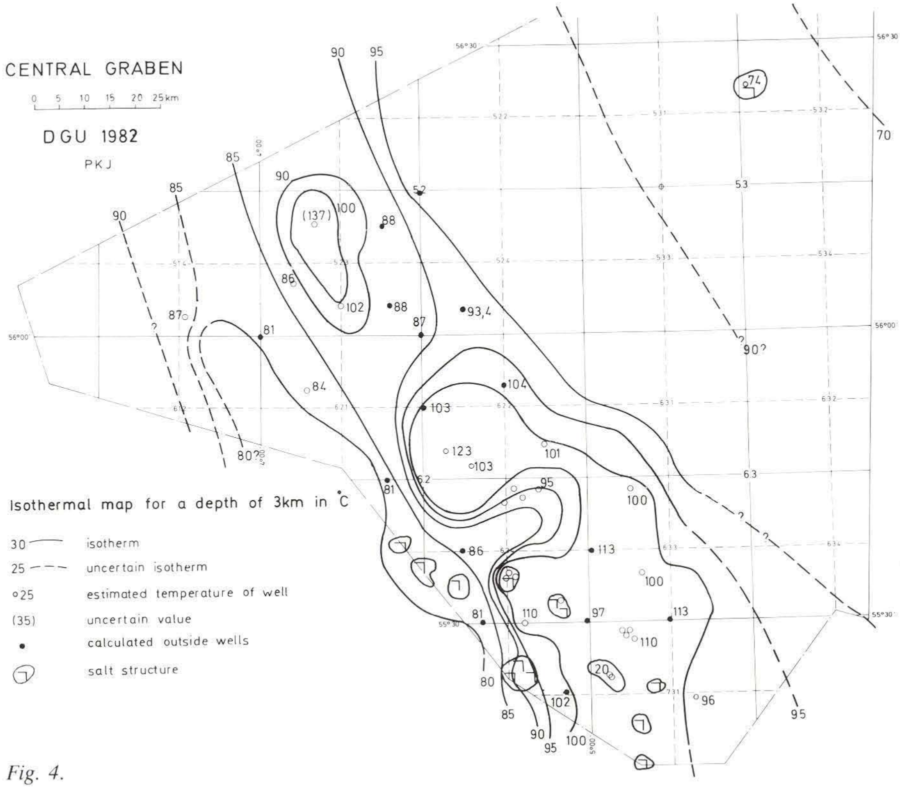

Fig. 4.

temperature map fig. 6). The temperature field around the salt structures in the Southern Saltdome Province is uncertain.

Temperature map, 4 km depth, *fig. 5*

Temperatures are strongly increasing towards areas with a thick Jurassic sequence, because of the low conductivity of the shales as explained above.

Temperature map, "Top Jurassic", *fig. 6*

The "Top Jurassic" isothermal map reflects the major trend of the "Top Jurassic" depth map as the depth is varying considerably. The temperatures are low, about 80°C in the southern part, where the depth to the "Top Jurassic" is about 2300 m and it is increasing towards the NE with maximum about 130°C at a depth of 3600 m. In local, deep subbasins the temperature increases to more than 140°C. For this map the temperature anomalies

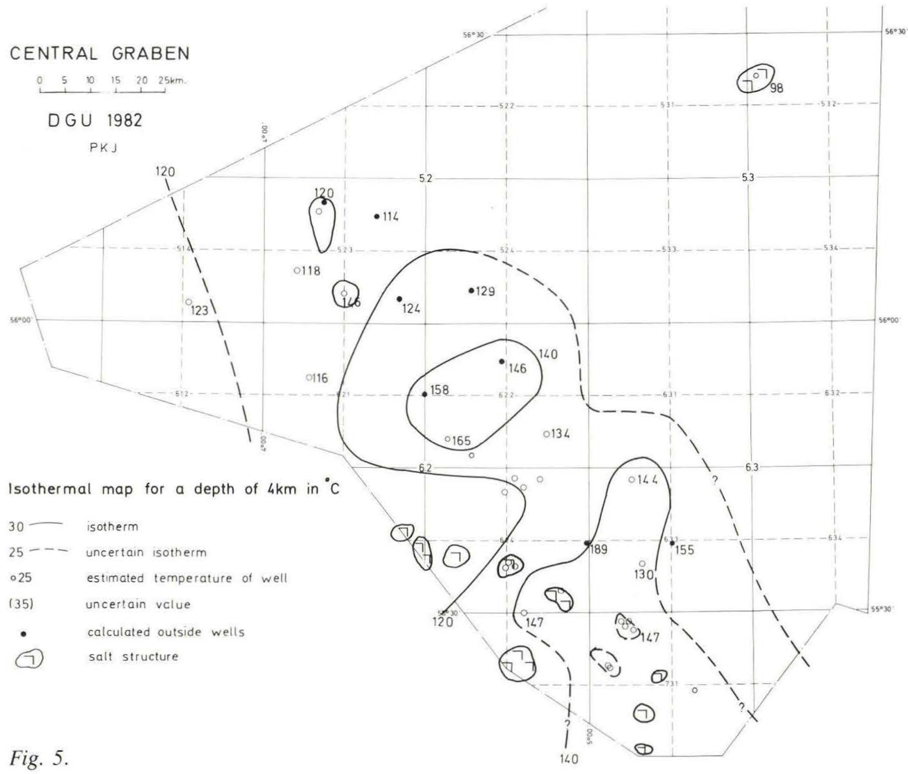

Fig. 5.

around salt structures have not been quantified due to insufficient data. The influence of salt structures is discussed later.

The temperature of about 110°C at the I-1 well is supposed to be locally influenced by the underlying salt.

Temperature controlling mechanisms

The validity of the temperature maps depends on our knowledge of a number of temperature controlling mechanisms. According to the report: Geology of the Danish Central Graben (Michelsen 1982) chap. 4.0. the main temperature controlling mechanisms may be summarized as follows:

1) *Heat flow.* As there are no heat flow determinations in the Danish North Sea sector, we can only guess that the heat flow is enhanced beneath the Central Graben, which usually is the case for graben systems.

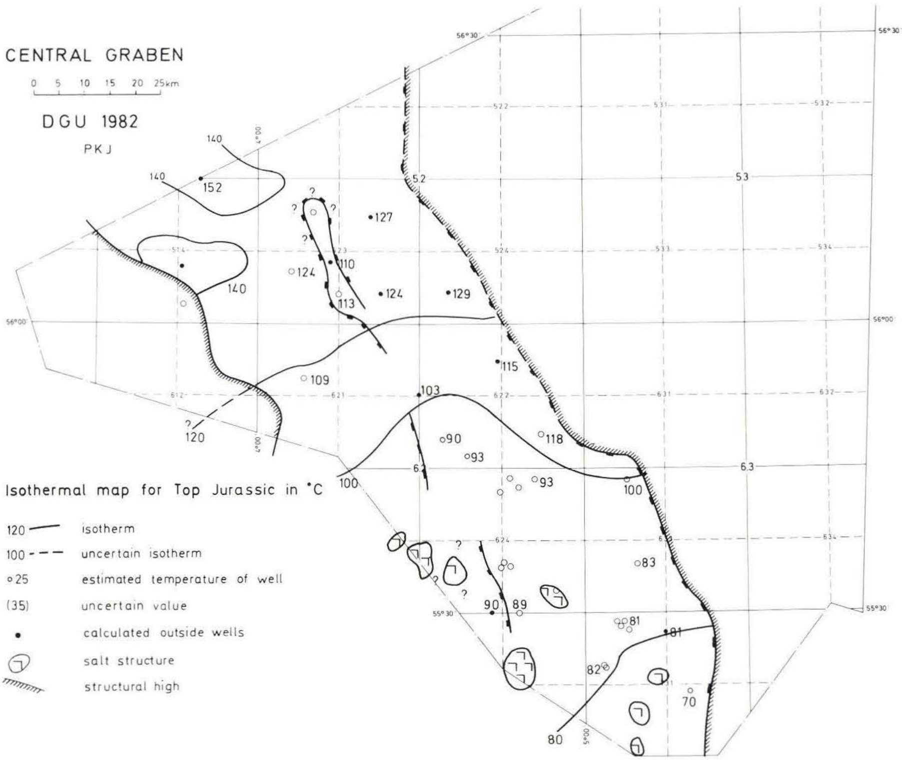

Fig. 6.

2) *Influence of salt structures.* Various numerical calculations have been made to determine the influence of the highly conductive salt structures on temperature, i.e. Balling (1978), and Jensen (1983a). It is clear, that there is a positive anomaly around the top of a salt structure and a negative anomaly around the root of the structure.
3) *Rock movements.* In the North Sea rock movements caused by faulting or folding are too slow to give any influence on subsurface temperature.
4) *Deep circulation of water.* The paper of Andrews-Speed et al. (1982) points out that deep circulation of water influence the temperature distribution in the British North Sea sector. Also Carstens and Finstad (1981) find identification of circulation connected to the fracture system in Norwegian North Sea. The data from the Danish North Sea do not give a definite answer whether deep water circulation influence the temperature field. It may be observed that the temperature gradient at 1 km depth increases towards the main fault boundary at the eastern margin of the Graben. Untill now it seems that the upper 1 km of the unconsolidated

sequence is responsible for this increase. A possible explanation could be a lateral decrease of conductivity of the upper 1 km sediments towards the eastern fault.

At deeper levels an increase of gradients towards the main fault boundary cannot be detected. This is an indication that there are no increase of heat flow towards the fault, but heat flow determinations have to be carried out to give a definite answer. If heat flow is increasing towards the fault it could be caused by deep circulation of water.

5) *Intrusions.* Intrusion of igneous rocks during tectonical active periods could locally have heated surrounding rocks in a short geological time.
6) *Surface temperature.* The rise of surface temperature especially in the Eocene has heated the subsurface to a great depth. The importance of this effect is discussed later.

Formation temperature through time

To get a rough idea of regional differences of genesis of oil and gas, knowledge of the past temperatures of the Upper Jurassic J-4 Unit is essential.

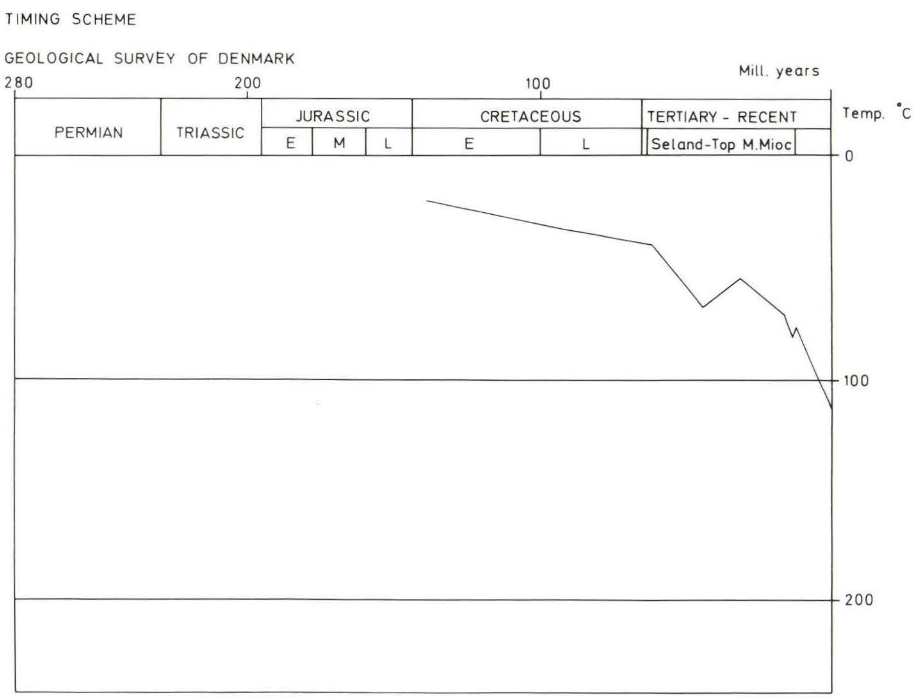

Fig. 7. Top Jurassic temperature at the well I-1.

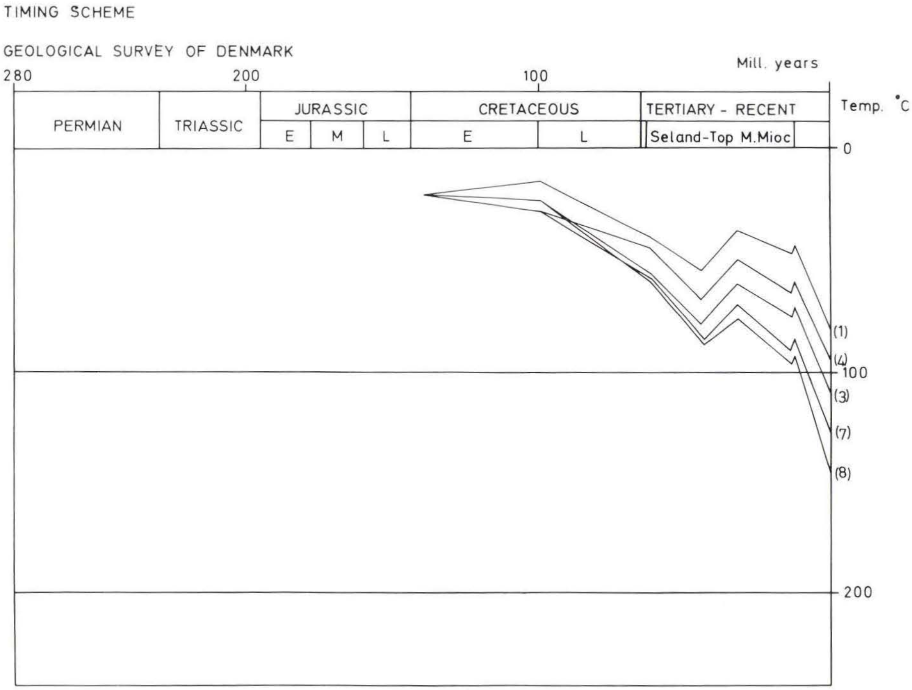

Fig. 8. Temperature of top J–4 Unit. See fig. 1 for localities.

Using depth of top and base of the J-4 Unit through time (see diagrams for the post-Triassic sequence in the Danish Central Graben, Holm 1983) and using recent temperature gradients together with surface temperature as a function of time, temperature at the top and at the base of the J-4 Unit has been estimated, figs. 7–9. The burial depth as a function of time is not corrected for hiati and compaction and the temperature gradients of the formations are assumed constant through time. A simplified surface temperature curve has been used in the present work based on Buchardt (1978) where information about surface temperature during the Tertiary and the Cretaceous is given.

The trend for the Central Graben shows clearly increase of J-4 Unit temperature from the Southern Salt-dome Province towards the northern Tail End Graben (see fig. 8). Assuming equal compounds of organic matter for the whole Central Graben area (an assumption which very well may be violated), we conclude that the maturity increases from south to north. This implies that the oil and gas developed firstly towards the north. Examining figs. 7 and 8 shows that the maturity of the top J-4 Unit at the I-1 well is probably higher than at the E-1 well but lower than the surrounding areas.

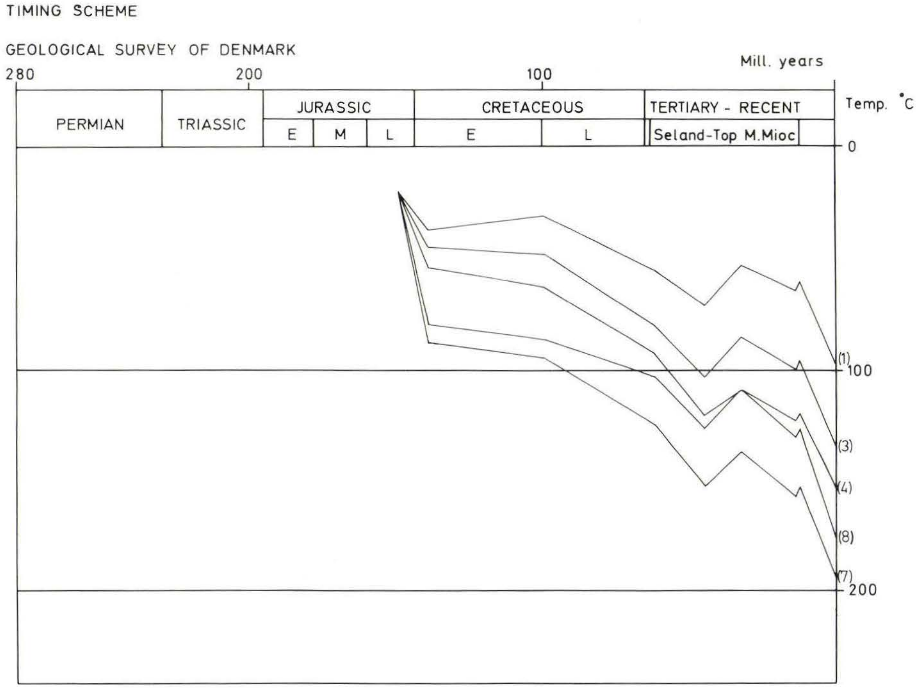

Fig. 9. Temperature of base J–4 Unit. See fig. 1 for localities.

The rise of surface temperature during the Eocene by approximately about 20°C is clearly reflected in the subsurface temperature and there is no doubt that this influence the maturation evolution.

Fig. 9 also shows a similar trend for the base J-4 Unit as for the top J-4 Unit concerning the areas (1), (4) and (7). Enhanced maturation of organic matter on top of salt structures is expected. Examples of this are given in Rashid and McAlary (1977) and Rashid (1978). It must be expected that maturation is restrained for rocks around the bases of the salt structures, due to the negative temperature anomalies there.

Identification of salt structures

The positive temperature anomalies which may be observed above salt structures are caused by a very high heat conductivity of halite. The structural highs North- and South-Arne are influenced by salt. At North-Arne a thick layer of salt was penetrated at the bottom of the T-1 well. The temperature measured at the I-1 well indicate that also the South-Arne structure is influenced by thick accumulations of salt. If we use high temperature anomalies as identifications of salt structures, the following structures or fields in the Southern Salt-dome Province are probably situated above salt structures: Gorm, Anne and Vagn.

Validity of the temperature maps

It is difficult to quantify the uncertainties of the temperature calculations. The difficulties of obtaining reliable temperatures have been discussed by Carstens and Finstad (1981). Uncertainties of the depth to Top Jurassic could be of the order of 600 m, which means an error of up to 25°C in areas, where there are no well control.

The validity of the curves fig. 7–9 is restricted by the lack of a study of hiati, compaction, age of more horizons, past heat flow conditions and past heat conductivities.

Conclusions

Subsurface mapping has been carried out in the Danish Central Graben based on all the temperature data available. The temperature maps reflect the general geological trend. An increase of temperature gradient from 25°C to 40°C is observed towards the fault boundary of the Graben in the NE-direction for a depth of 1 km. For deeper levels a similar trend cannot be detected. Around the Tyra gas field a positive temperature anomaly is found. A high gradient of 42°C km^{-1} is believed to be representative for the Lower Cretaceous and Jurassic shales. Positive temperature anomalies are identified above salt structures. Temperatures for the top J-4 Unit are increasing from about 80°C at the Southern Salt-dome province at depth of 2300 m to about 130°C at the Tail End Graben at a depth of 3600 m. The temperature controlling mechanism seems to be heat conduction, although influence from deep circulation of water cannot be excluded. Temperature through time of the Top J-4 Unit is increasing from the South to the North.

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Dansk sammendrag

Formationstemperaturer er kortlagt i den danske del af Centralgraven (Nordsøen). Temperaturkort gives for dybderne 1, 2, 3 og 4 km. Herudover præsenteres et "Top Jura" temperaturkort. Middelgradienten til en dybde af 1 km viser stigning fra ca. 25°C/km i den østlige del til ca.

40°C/km i den vestlige del. En tilsvarende tendens kan ikke spores i dybere niveauer. En positiv temperaturanomali er konstateret omkring Tyra feltet. En høj middelgradient (42°C/km) i de nedre kretasiske og jurassiske skifre præger temperaturbilledet i disse skifre samt i underliggende formationer. Positive temperaturanomalier er konstateret over saltstrukturer. Top J-4 Unit temperaturen stiger fra ca. 80°C i den sydlige del af Centralgraven i en dybde af 2300 m til ca. 130°C i den nordlige del i en dybde af 3600 m. Temperaturbilledet kan forklares ved varmeledning, men dyberegående cirkulation af formationsvand kan ikke udelukkes. Temperaturer for Top J-4 Unit som funktion af tid er stigende fra syd mod nord.

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