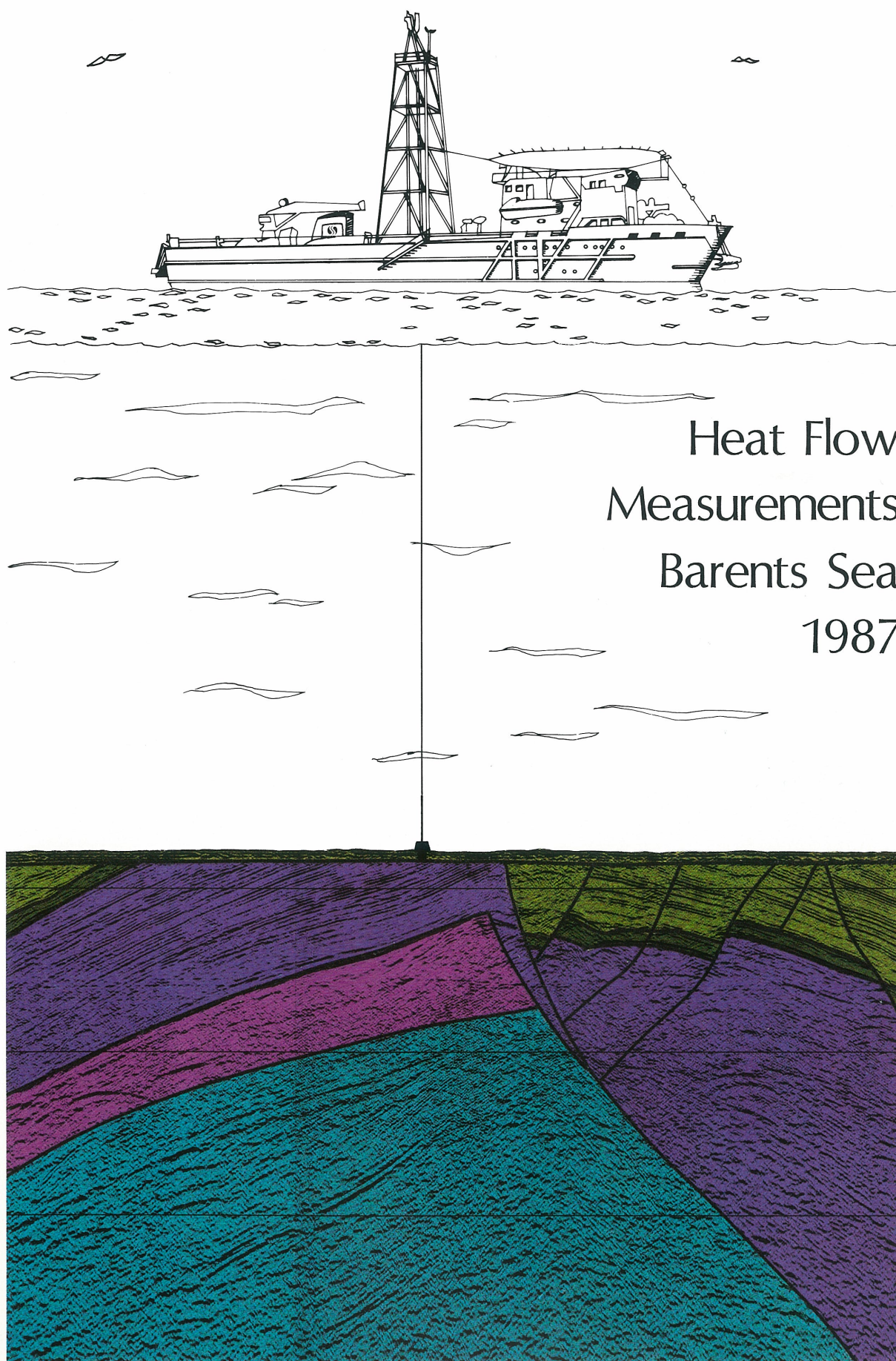




Heat Flow
Measurements
Barents Sea
1987

REPORT

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REPORT TITLE:

**HEAT FLOW MEASUREMENTS
BARENTS SEA 1987**

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BP Petroleum Development (Norway) Ltd., Esso Norge a.s,
Norsk Agip A/S and Elf Aquitaine Norge A/S.

SUMMARY:

Heat flow has been measured in three shallow boreholes in the Nordkapp Basin (sites 7227/11-U-01, 7230/08-U-01 and 7230/05-U-05). The measurements are performed in thermally undisturbed Quaternary sediments, below the zone influenced by annual temperature fluctuations, and down to a maximum depth of about 32 m.

The temperature measurements have an absolute accuracy of 0.02°C. The relative resolution is within $\pm 0.005^\circ\text{C}$ to $\pm 0.015^\circ\text{C}$ depending on combination of probes.

The thermal conductivity is determined by detailed investigations by needle probe and compare well with theoretical conductivity calculated from sediment composition. An anisotropy in thermal conductivity is found in the samples, but is different for the three sites (0% - 20%).

Two models for climatic correction are presented, and one of those is accounted for in the final heat flow values. The final heat flow values are given with indicated upper and lower boundaries that vary from site to site and that deviate 3-12% from the recommended values.

One of the sites is located on the top of a salt structure. This structure is mapped and the effect of the salt bodies on an assumed regional heat flow is modelled by a finite element computer program.

At site 7227/11-U-01 a sample of in situ or nearly in situ rock was obtained. Results from analyses of this sample are included in the report.

KEY WORDS:	
Heat flow	Nordkapp Basin
Temperature gradients	Salt structures
Thermal conductivity	Modelling

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APPENDICES

I FIELD OPERATIONS AND INSTRUMENTATION

II REPORT FROM THERMAL CONDUCTIVITY ANALYSIS IN AARHUS, DENMARK

III DETAILS OF HEAT FLOW MODELLING RESULTS

PREFACE

This report presents the results of the IKU project "Heat Flow Measurements Barents Sea 1987". The project was supported by the following companies:

BP Petroleum Development Ltd. Norway, Elf Aquitaine Norge a/s, Esso Norge a.s and Norsk Agip A/S.

Their participation is gratefully acknowledged.

The field work was carried out on board the M/S Bucentaur. J. Sættem coordinated the field work and has also acted as project manager.

Fugro-McClelland Engineers B.V, The Netherlands performed the temperature measurements and the on board thermal conductivity measurements.

Niels Balling, University of Aarhus, Denmark, has carried out additional investigations of the thermal conductivity on selected Quaternary samples.

A selection of seismic line sections and gravity data across a salt structure close to site 7230/05-U-05 were kindly made available by The Norwegian Petroleum Directorate.

The following persons have contributed to the heat flow study:

Field work: L. Rise, H. Rendall, L. Husvik, G. Elvebakk and J. Sættem.

Laboratory analyses: H. Rendall, H. Weiss and D.A. Westgaard.

Calculation of thermal conductivity in the Quaternary based on sediment composition: Ø. Johansen.

Mapping of salt structure beneath site 7230/05-U-05: S. Fanavoll.

Gravity data modelling: T.H. Høye, S. Fanavoll and Ø. Sylta.

Heat flow modelling: Ø. Sylta and E. Thorbergsen.

Study of bedrock sample from site 7227/11-U-01: O. Skarbø, V. Fjerdingsstad, T.L. Leith, H. Weiss and N. Aarhus.

Drawing: R. Angell-Petersen.

Typing: K. Dahlen Brønner.

Responsible for reporting and calculation of final heat flow values:
J. Sættem.

UNIT CONVERSIONS

All the values on heat flow and thermal conductivity in this report are for consistency given in SI units. Heat flow is given in mW/m^2 and thermal conductivity is given in W/m K . These parameters can be transformed to the units frequently used in the oil industry according to the conversion factors given below. A conversion factor of 0.4184 is used by Farouki (1981) and Aylward and Findlay (1971). Kappelmayer and Haenel (1974) used 0.4186. This difference is, however, insignificant in the present context.

$$1 \text{ mcal/cm s } ^\circ\text{C} = (0.4184)^{-1} \text{ W/m K}$$

$$1 \text{ HFU} = 1 \text{ mcal/cm s}$$

$$1 \text{ mcal/cm s} = (41.84)^{-1} \text{ mW/m}^2$$

1. SUMMARY

1.1 Heat flow measurements

Heat flow is measured in three shallow boreholes in the Nordkapp Basin. The measurements were performed in shallow boreholes (maximum depth: 32.5 m) during late July - early August 1987. The drilling vessel was the norwegian drillship M/S Bucentaur.

Temperature gradients have been determined for depth intervals ranging from 12.92 m - 17.69 m to 15.42 m - 31.85 m. The individual temperature measurements have an accuracy of 0.02 K and have a resolution relative to other temperature measurements in the same hole of about 0.005 K, 0.01 K or 0.015 K depending on probe configuration.

Horizontal and vertical thermal conductivity has been measured in situ and on sediment samples by use of needle probe. Such measurements are done in two different laboratories by use of different types of needle probes. Thermal conductivity is also calculated as the geometric mean of sediment compounds. The above data has provided a good basis for calculation and evaluation of vertical thermal conductivity for the three sites, and the standard deviations of mean values is in the order of 3% of the mean values.

A model for climatic correction of the measured temperature gradients is accounted for in the final heat flow values given in Table 1.1. A further discussion of the heat flow results is given in Chapter 5.

Table 1.1 Final heat flow values for the 1987 IKU heat flow sites. Upper and lower limits are obtained by combining upper and lower limits of both thermal conductivity and temperature gradient simultaneously. Minimum model of climatic correction is assumed.

Site	Heat flow (mW/m ²)		
	Recommended value	Lower limit	Upper limit
7227/11-U-01	45.9	41.7	50.1
7230/08-U-01	54.2	52.9	56.2
7230/05-U-05	104	96.2	112

1.2 Heat flow modelling

Site 7230/05-U-05 is located above a major salt structure. This structure has been mapped, and a modelling has been done to quantify the heat flow anomaly caused by this structure.

Based on the mapped geometry and different assumptions about thermal conductivity distribution, the maximum surface heat flow anomaly is found to be within 27-47% (recommended value 40%) higher than the "undisturbed" heat flow at the base of the model (25 km). If this is combined with the heat flow value from site 7230/05-U-05 on top of the salt structure, the heat flow at 25 km becomes 74 mW/m² (65-88 mW/m²). This is significantly higher than the heat flow measured at sites 7227/11-U-01 and 7230/08-U-01.

1.3 Bedrock sample from site 7227/11-U-01

An in situ or nearly in situ bedrock sample was obtained at site 7227/11-U-01. The sample comprises a greenish grey claystone which contains 78% cristobalite. The sample has been dated by palynology to a Late Paleocene age.

The organic content is low and the sediment has no source potential. $T_{\max}$ values are 427 and 421°C and the vitrinite reflectance is 0.33%.

2. INTRODUCTION

2.1 Previous work

As a part of the IKU Barents Sea Mapping Program, heat flow data have been collected at 11 sites in the southwestern Barents Sea since summer 1985.

Accurate temperature measurements and measurements of thermal conductivity from corresponding levels were obtained at six of the seven sites investigated in 1985 and at two sites in 1986. This data was obtained from depth intervals ranging from 13-31 m to 11-65 m below the seabed.

The calculated heat flow values have been subjected to corrections for transient effects from the late Quaternary temperature history, which may affect the uppermost 1500 - 2000 m below the seabed. A relatively thorough investigation of the Quaternary sediments has also been carried out.

This report presents the results from three sites in the Nordkapp Basin which were investigated in 1987. The report also comprises modelling of heat flow around a salt structure in the area. The 1987 project has benefitted from the experience gained in the previous projects, and in the present report we have for example avoided the fairly thorough discussion of the background for effects of the climatic corrections accounted for in the final heat flow values, because this has been given in previous reports.

2.2 Selection and description of heat flow sites

The 3 drilled heat flow sites were chosen to give data from a variety of both structural and geographical positions within the Nordkapp Basin.

Site 7227/11-U-01 is located close to the southeastern flank in the western part of the basin, and is an optimized position to give a basinal situation and to avoid heating from salt structures. Sites 7230/08-U-01 and 7230/05-U-05 were located in the eastern part of the Nordkapp Basin. 7230/08-U-01 was located close to the southern flank of the basin in an area not affected by salt, and 7230/05-U-05 was located on top of a salt structure.

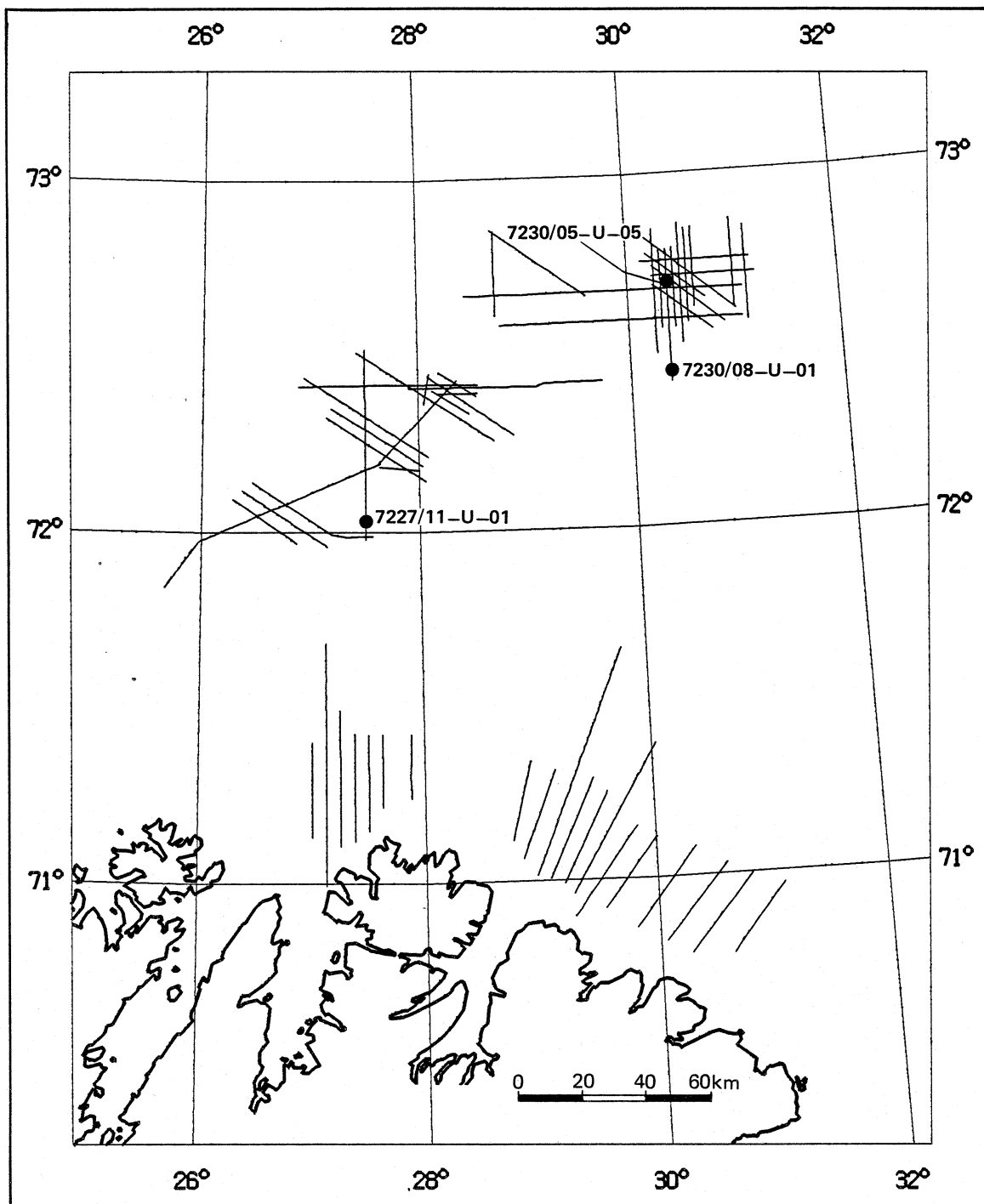


Figure 2.1 Location of the 1987 heat flow sites in the Nordkapp Basin. The 1986 and 1987 IKU shallow seismic lines are also shown.

The latter was drilled in combination with a bedrock coring site, and a particular objective of this site was to investigate the effect on shallow heat flow from salt structures.

The utilized heat flow measurement method relies on soil conditions that allow penetration of the sediments with a thermistor needle, and a minimum Quaternary sediment thickness of about 30 m is preferred in order to obtain sufficient datapoints in thermally undisturbed sediments. In good conditions however, even a sediment thickness of about 20 m would be sufficient to obtain fairly accurate heat flow data.

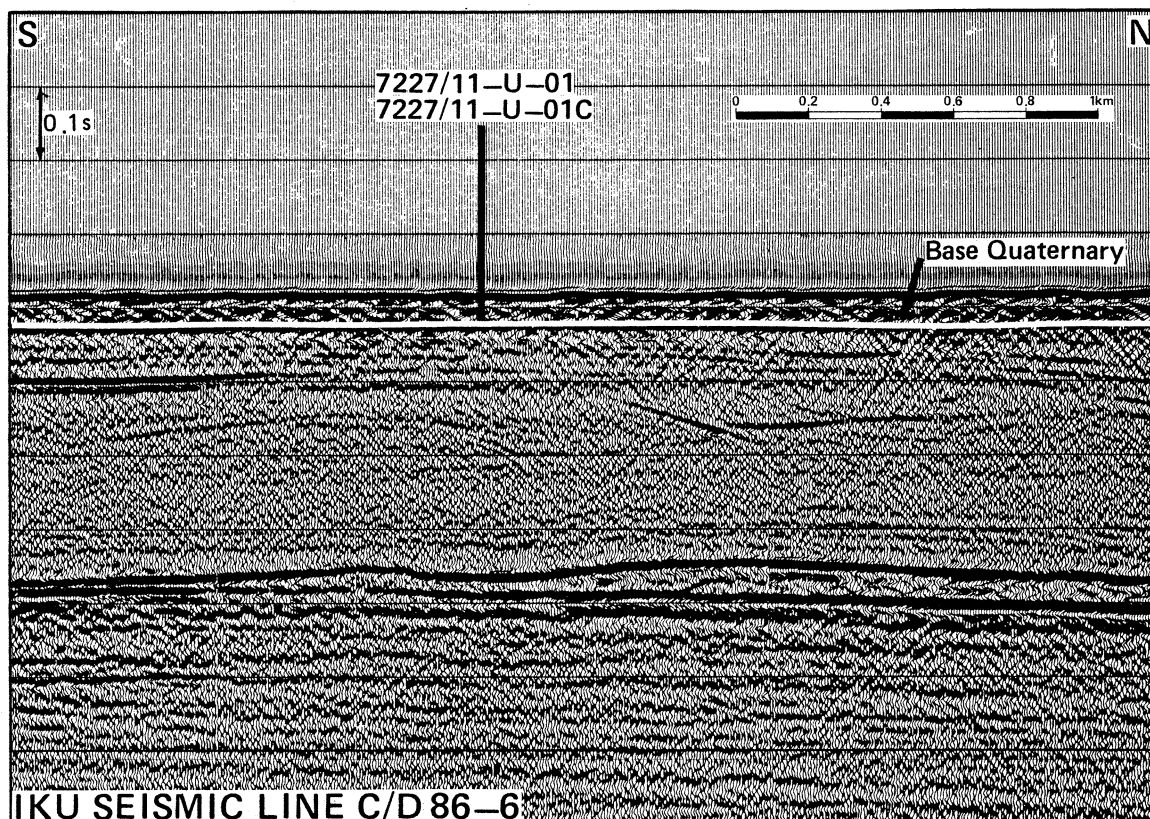


Figure 2.2 Seismic section across site 7227/11-U-01.

At site 7227/11-U-01 fairly high sediment stiffness was expected as a regional intra Quaternary reflector approached the seabed from the north. Samples were taken from approx. 5 m and downwards and the analysis on all the samples shows a fairly high degree of consolidation (Table 4.3). Due to the soil conditions it was necessary to redrill the hole after having shifted position slightly, in order to obtain sufficient data. Top bedrock was found at 32.5 m. For convenience data from both holes are referred to site 7227/11-U-01.

At site 7230/08-U-01 more favourable conditions were found, and none of the undrained shear strength tests from the sampled interval gave values above 100 kPa. Top bedrock was estimated at 45 m but was not penetrated.

The shallow seismic data indicate that older Quaternary sediments occur at site 7230/05-U-05 than at site 7230/08-U-08, and therefore somewhat stiffer sediments could be expected. This was also found during drilling, with a significant increase in undrained shear strength at about 15 m. Top bedrock was found at 23.3 m.

Positions and some key data for the different sites are given in Table 2.1.

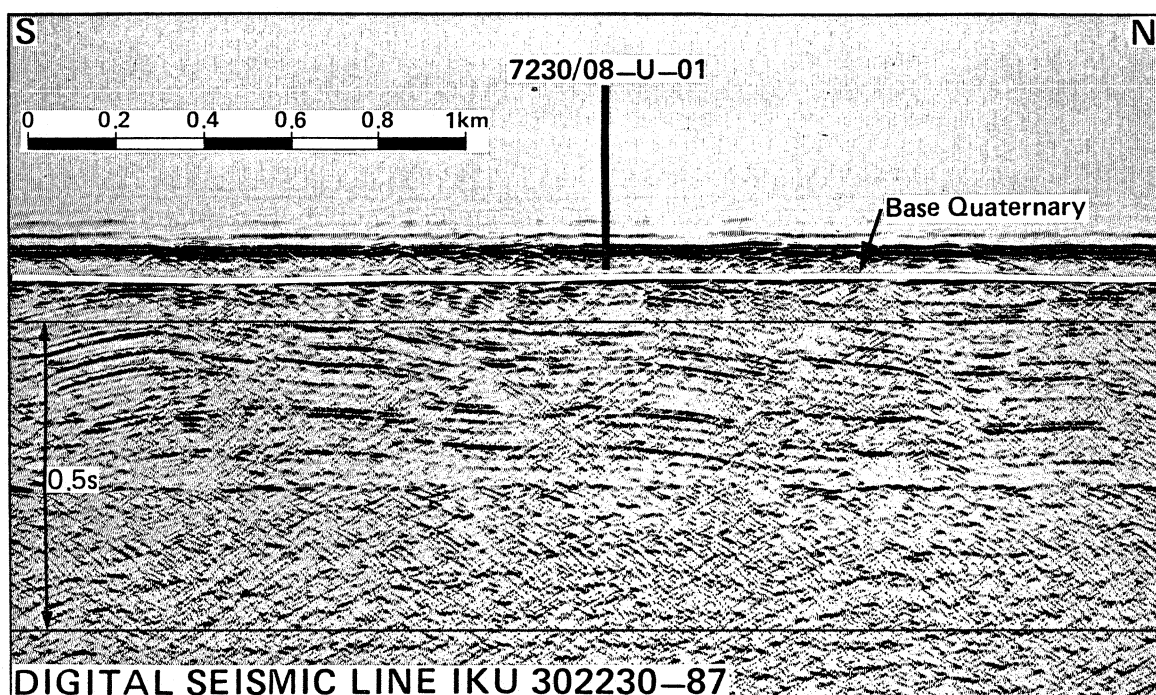


Figure 2.3 Seismic section across site 7230/08-U-01.

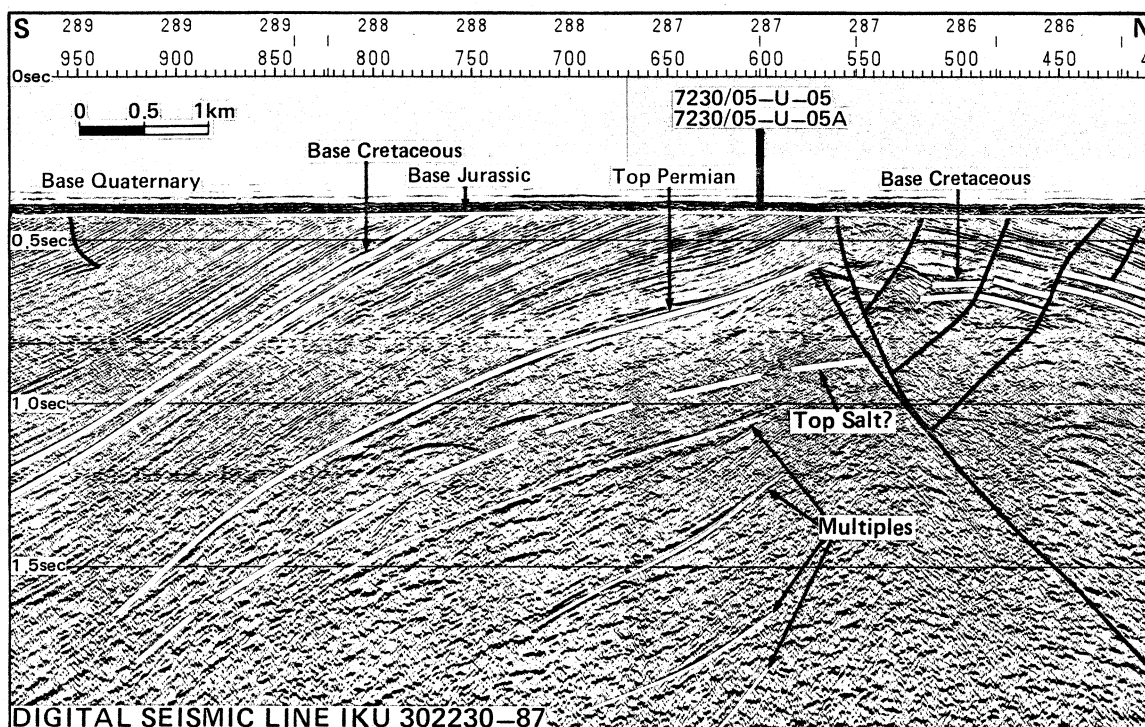


Figure 2.4 Seismic section across site 7230/05-U-05. This section is also used for heat flow modelling.

2.3 Summary of field work

A description of the field work, including description of instrumentation, procedures and a brief outline of the on site work, is given in Appendix I. For convenience we repeat some of the production statistics here.

The working conditions varied from excellent to difficult with respect to soil conditions, weather and sea state.

The data recovery is summarized in Table 2.2.

Table 2.1 Key data for the 1987 heat flow sites in the Nordkapp Basin.
Coordinates in brackets are UTM coordinates (CM 27° east).

Site	Seismic line	Shot point	Coordinates	Water depth (m)	Quaternary thickness (m)	TD (m)
7227/11 -U-01	C/D86-6	300	72°01'15.81'' 27°29'59.31'' (517219.9 7991570.4)	280.5	32.5	13
-U-01C	----"----	299.9	72°01'15.86 27°29'56.75 (517195.3 7991571.9)	280.5	32.5	32.5
7230/08 -U-01	IKU-302230 -87	2500	72°25'45.59 30°22'34.38'' (613712.2 8040236.9)	283	45	30
7230/05 -U-05	IKU-302230 -87	604	72°42'07.14'' 30°22'32.09'' (611981.7 8070607.9)	286	23.3	17.5
-U-05A	-----"-----	606.3	72°42'6.00'' 30°22'31.64'' (611979.5 8070571.8)	286	23.3	49.9

Some of the measurements in the table above have less reliability than the other, and some of the temperature measurements are "parallel measurements" at practically the same depth. This is discussed further in Chapter 3 and Chapter 4. Selected results from the sample analysis are given in Chapter 4 as a background for an evaluation of the thermal conductivity data. A detailed sample description of the Quaternary samples will be given in a separate report.

Table 2.2 Data recovery from the 1987 IKU heat flow sites.

Site	Quaternary samples		Temperature measurements	In situ thermal conductivity measurements
	No. of samples	Acc. length (m)		
7227/11-U-01	11	4.31	6	0
7230/08-U-01	5	3.52	22	7
7230/05-U-05	4	1.66	10	3
Total time consumption (hours):				
On site work 97				
Weather stand by 9				
Sailing 8				

3. TEMPERATURE GRADIENTS

3.1 Summary

The temperature data and the calculation of temperature gradients for the three investigated sites are presented and discussed in Sections 3.3 through 3.5. In Table 3.1 below we summarize the main conclusions. The table gives the temperature gradient and what is judged to be lower and upper limit of the value of this gradient. The indications of lower and upper limits are conservative estimates, and are based on evaluation of individual temperature measurements, the datasets from each site and calibration results. This is discussed further in the description of each site below and in Appendix I.

Table 3.1 Temperature gradients (recommended value and lower and upper limit) for the 1987 heat flow sites.

Site	Temperature gradient (10^{-3}K/m)		
	Recommended value	Lower limit	Upper limit
7227/11-U-01	22.8	20.7	24.9
7230/08-U-01	35.6	35.2	36.5
7230/05-U-05	69.3	66.0	72.7

3.2 Measurement technique

For details of the temperature measurement procedure reference is made to Appendix I.

The basic principle used for the temperature measurements is that electric resistance across a down-hole thermistor is a function of the temperature of this thermistor. This relation is given by an equation of the form:

$$1/(T+273.15) = A+B \ln R$$

where

T = in situ temperature ($^{\circ}\text{C}$)

R = electric resistance (Ω)

A = calibration constant ($^{\circ}\text{C}^{-1}$)

B = calibration constant ($^{\circ}\text{C}^{-1}$).

The calibration constants and constants for converting measured voltage across the thermistors to resistance are determined by comparing measured voltage to a known reference temperature and determine the constants that give the best fit to the reference temperature. The calibration is described in Appendix I.

Each measurement lasts for about 15 - 20 min (900 - 1200 s). A typical voltage record is shown in Figure 3.1.

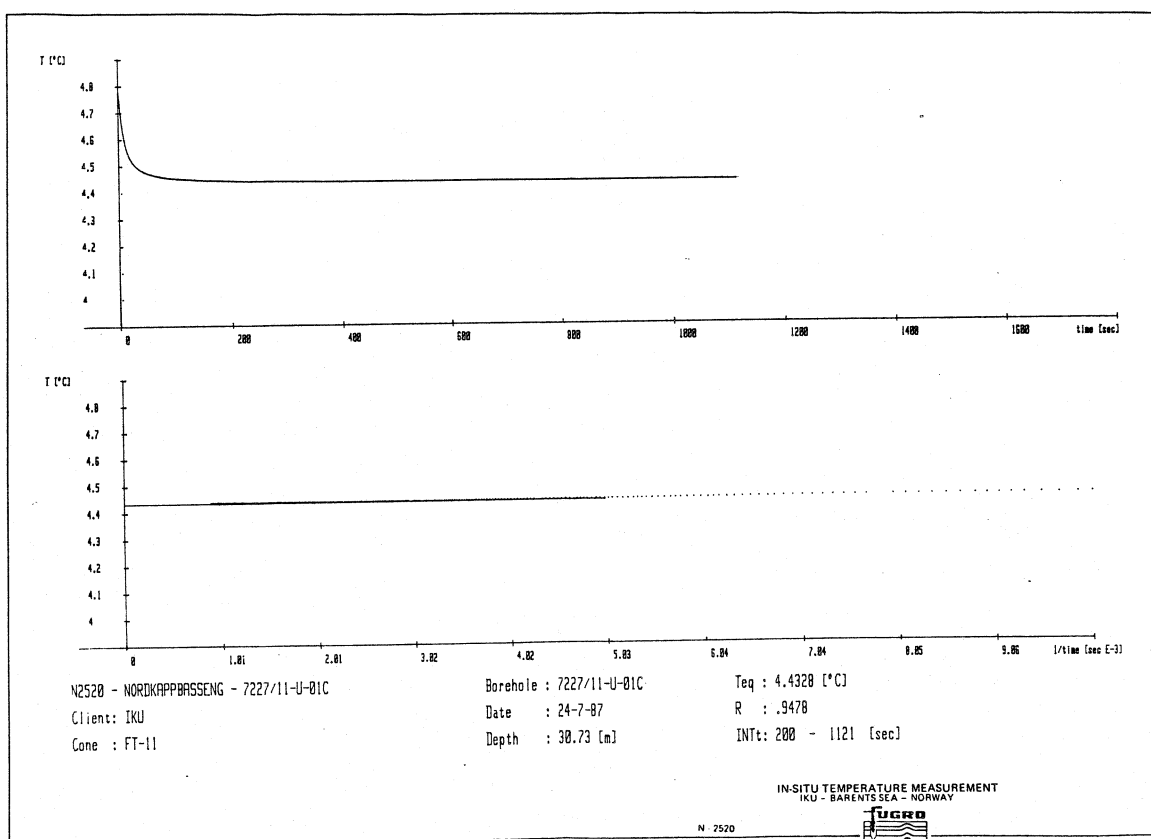


Figure 3.1 Example of a plot of temperature versus time (upper plot) and temperature versus $1/\text{time}$ with extrapolation of temperature towards $1/\text{time} = 0$ (lower plot).

The corresponding temperatures will describe a function decreasing exponentially with time towards an asymptotic value that represents in situ temperature. This asymptotic value can be found from a plot of temperature versus $1/\text{time}$. This plot will under ideal conditions describe a straight line, and an extrapolation of this line towards $1/\text{time} = 0$ will give the equilibrium temperature.

In tests where temperature versus $1/\text{time}$ does not describe a straight line,

the most reliable segment of this plot must be chosen as the basis for extrapolation. It is important that this time segment does not exceed into the response time of the down-hole probe (15-20 min. after push-in) as the results will then be affected by heat transfer through the probe housing.

An alternative approach to establishing equilibrium temperature has been tried in some occasions where there apparently has been some temperature influence on the thermistor from the borehole. In these cases the temperature has been plotted against $1 + t_1/t$ where t_1 is the time available for bottomhole formation temperature disturbance (i.e. the time elapsed since the drilling stopped until the measurement was made) and t is the cooling time. This method was used by Taylor et al. (1985) using an equation developed by Lachenbruch and Brewer (1959), in calculation of temperatures in a well offshore Canada.

The method does not account for the distance from the borehole to the thermistor, and it is therefore uncertain how applicable it is to the present temperature measurement method. A possibility to bypass this problem is to choose a value for t , that gives the best possible fit to a straight line for the plot of temperature versus $1 + t_1/t$. In the two alternative temperatures given here $t_1 = 900$ s has been used.

Our conclusion is that rather poor data may be improved by this method. The result may, however, be somewhat arbitrary due to the poor control of several influencing factors. The alternative temperature data should therefore not be used together with undisturbed high quality data unless it is absolutely necessary, as this will reduce the quality of the total data set.

Table 3.2 Final equilibrium temperatures from the IKU heat flow measurements 1987. Uncertain values are given in brackets. "Time interval used for extrapolation" refers to which part of the plot in Fig. 3.1 that is used to determine a straight line extrapolation to $1/t \text{ (s}^{-1}\text{)} = 0$. Mid = mid point thermistor (ref. Appendix I). Alt = alternative temperature (see text, this chapter).

Site	Test	Probe assembly	Test depth (m)	Probe depth below drill bit (m)	Probe depth below sampler penetr. (m)	Temperature (°C)	Time interval used for extrapolation (s)	Comments
7227/11-U-01 and -01c	WHT1	FHT2	19.48	.64	0.13	(4.196) (4.195) (4.177)	100-200 200-584 200-584	Mid Mid Mid Alt
	WT2	FT13	21.29	1.63		4.217	200-820	
	WT3	FT20	26.18	1.58		4.307	200-913	
	WT4	FT11	30.73	1.26		4.433	200-1121	
7230/08-U-01	WHT1	FHT4	15.45 15.42	1.42 1.31	0.57 0.54	3.465 3.457	200-751 200-751	Mid
	WHT2	FHT4	16.47 16.44	2.43 2.40	1.58 1.55	3.501 3.493	200-922 200-922	Mid
	WHT3	FHT4	17.04 17.01	3.00 2.97	2.35 2.32	3.521 3.514	201-914 201-914	Mid
	WHT4	FHT7	19.77 19.77	0.88 0.88	0.07 0.07	(3.684) (3.677)	475-779 500-779	Mid Mid
	WHT5	FHT9	21.07 21.04	1.07 1.04	0.27 0.24	3.665 3.685	250-892 200-892	Mid
	WHT6	FHT9 FHT9	22.00 21.97	2.00 1.97	1.20 1.17	3.699 3.720	200-914 200-914	Mid
	WHT7	FHT9 FHT9	22.66 22.63	2.66 2.63	1.86 1.83	3.721 3.743	200-911 200-911	Mid
	WHT8	FHT5	24.93	1.01	0.06	3.817	200-941	
	WHT8	FHT5	24.90	0.98	0.23	3.833	200-941	Mid
	WHT9	FHT5	25.89	1.97	1.17	3.851	200-904	
	WHT9	FHT5	25.86	1.94	1.14	3.869	200-904	Mid
	WHT10	FHT6	30.96	1.10	0.34	4.044	199-913	
	WHT10	FHT6	30.93	1.07	0.31	4.052	199-913	Mid
	WHT11	FHT6	31.85	1.99	1.23	4.076	200-903	
	WHT11	FHT6	31.82	1.96	1.20	4.083	200-903	Mid
7230/05-U-05	WHT1	FHT5	12.95	1.02	0.28	3.410	200-916	
	WHT1	FHT5	12.92	0.99	0.25	3.434	200-913	Mid
	WHT2	FHT5	13.63	1.7	0.96	3.443	200-1095	
	WHT2	FHT5	13.60	1.67	0.93	3.463	200-1095	Mid
	WHT3	FHT5	14.69	2.76	2.02	3.520	200-803	
	WHT3	FHT5	14.66	2.73	1.99	3.550	200-803	Mid
	WHT4	FHT4	16.34	0.49	0.49	(3.822)	100-155	Mid
	WHT4	FHT4	16.34	0.49	0.49	(3.594)	100-155	Mid Alt
	WT5	FT15	17.69	0.19	0.19	3.733	200-928	

3.3 Site 7227/11-U-01

At site 7227/11-U-01 four datapoints are obtained across a depth interval of 11.25 m (Table 3.2 and Fig. 3.2). It is also shown which thermistor probe assembly that is used for each individual temperature/depth - point. Data from tip- and midpoint thermistors are plotted with different symbols. The uppermost datapoint (probe FHT2 at 19.48 m) is somewhat uncertain as the thermistor in this case was located only 0.13 m below the cavity from the sampling (although calculation of the equilibrium temperature by the alternative method gave a slightly better fit to the overall dataset). Several possible ways of combining the datapoints are checked in order to choose the most reliable gradient and frame the uncertainties in the data.

Due to the uncertainty in the datapoint at 19.48 m, we choose to use only the data from 21.29 m, 26.18 m and 30.73 m to calculate the most reliable gradient. This gives a gradient of $22.8 \cdot 10^{-3}$ K/m (regression coefficient 0.9932). Inclusion of the original mid point temperature at 19.48 m (4.196 °C) gives a gradient of $21.4 \cdot 10^{-3}$ K/m, while use of only the alternative equilibrium temperature at 19.48 m gives a gradient of $22.3 \cdot 10^{-3}$ K/m (regression coefficients of 0.9924 and 0.9955 respectively).

An evaluation of the uncertainty of the gradient can also be achieved by adding and subtracting the total uncertainty from accuracy and resolution limits which are approximately 0.01 K (ref. Appendix I), to the data at 21.29 m and 30.73 m. This gives lower and upper limits of $20.7 \cdot 10^{-3}$ K/m and $24.9 \cdot 10^{-3}$ K/m (regression coefficients 0.9920 and 0.9940).

To conclude we choose $22.8 \cdot 10^{-3}$ K/m as temperature gradient for this site, and $20.7 \cdot 10^{-3}$ K/m and $24.9 \cdot 10^{-3}$ K/m as lower and upper boundaries. The given boundaries are regarded as extreme values as they are based on maximum deviation in opposite directions in the datapoints at 21.29 m and 30.73 m.

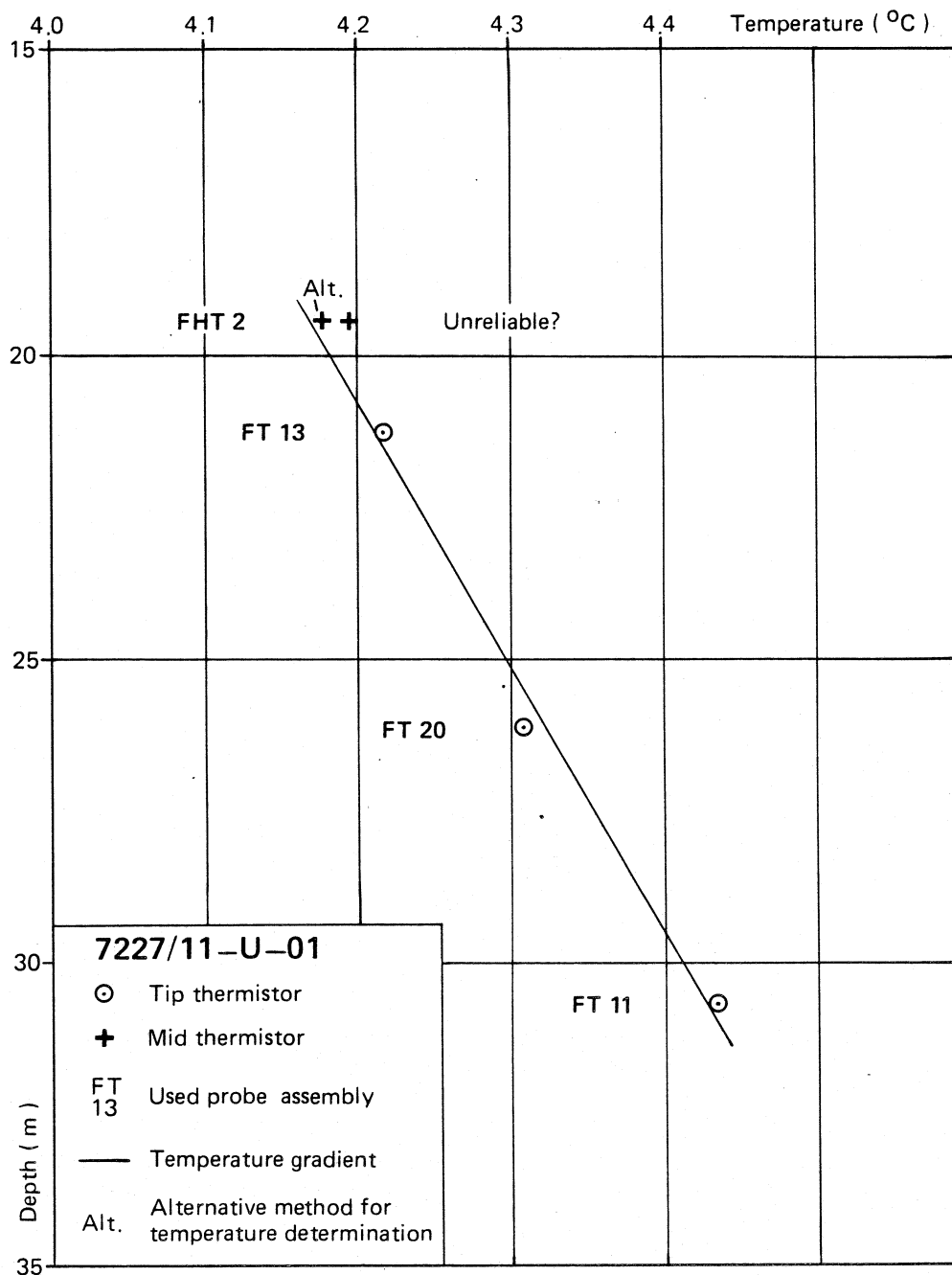


Figure 3.2 Temperature - depth plot from site 7227/11-U-01.

3.4 Site 7230/08-U-01

The equilibrium temperatures obtained at site 7230/08-U-01 (Table 3.2) are plotted versus depth in Figure 3.3. Two of the datapoints (probe FHT7 at 19.77 m) clearly do not fit with the general data set and are excluded in the calculations. The reason for the high temperatures measured in this

case is probably influence from the borehole, as the thermistor in this occasion was located only .07 m below the cavity from the sampling due to high penetration resistance.

Two striking observations can be made from this plot. Firstly, the data from individual thermistors give quite consistent temperature gradients. Secondly there is a slight "sidetracking" between the different interval gradients and between tip- and mid-thermistors. I.e. the absolute temperature level is slightly different for different thermistors. This may partly be due to the limitation in accuracy of individual thermistors, which at this particular site can be distinguished due to the internal consistency in data from individual thermistors. Fugro-McClelland, however, reports that the mid thermistors are less reliable than the tip thermistors. (The data from the mid thermistors may be hampered by unfavourable geometrical conditions both during calibration and field measurement).

As the most likely gradient representative for the measured interval we choose $35.6 \cdot 10^{-3}$ K/m which is obtained by linear regression through FHT4 and FHT9 tip thermistor data which is obtained across 7.24 m depth interval and which is also the dataset giving the best fit to a straight line (regression coefficient 0.9999). We have in this case found it most correct to exclude the data from thermistors FHT5 and FHT6 in the calculation of the gradient. The reason for this is the "sidetracking" in the temperature data described above which is also clearly visible in Figure 3.3.

A linear regression through all datapoints (except the FHT7 data) gives a gradient of $38.0 \cdot 10^{-3}$ K/m (regression coefficient 0.9921). Regression through intervals obtained by individual thermistors and probes, however, give gradients that range from 34.8 to $37.5 \cdot 10^{-3}$ K/m with regression coefficients ranging from 0.9993 to 1.0 (1.0 corresponding to regression through two datapoints only). Exclusion of all regressions through only two datapoints gives a range in gradients of 35.2 to $36.5 \cdot 10^{-3}$ K/m, which we believe is a maximum interval framing the true gradient.

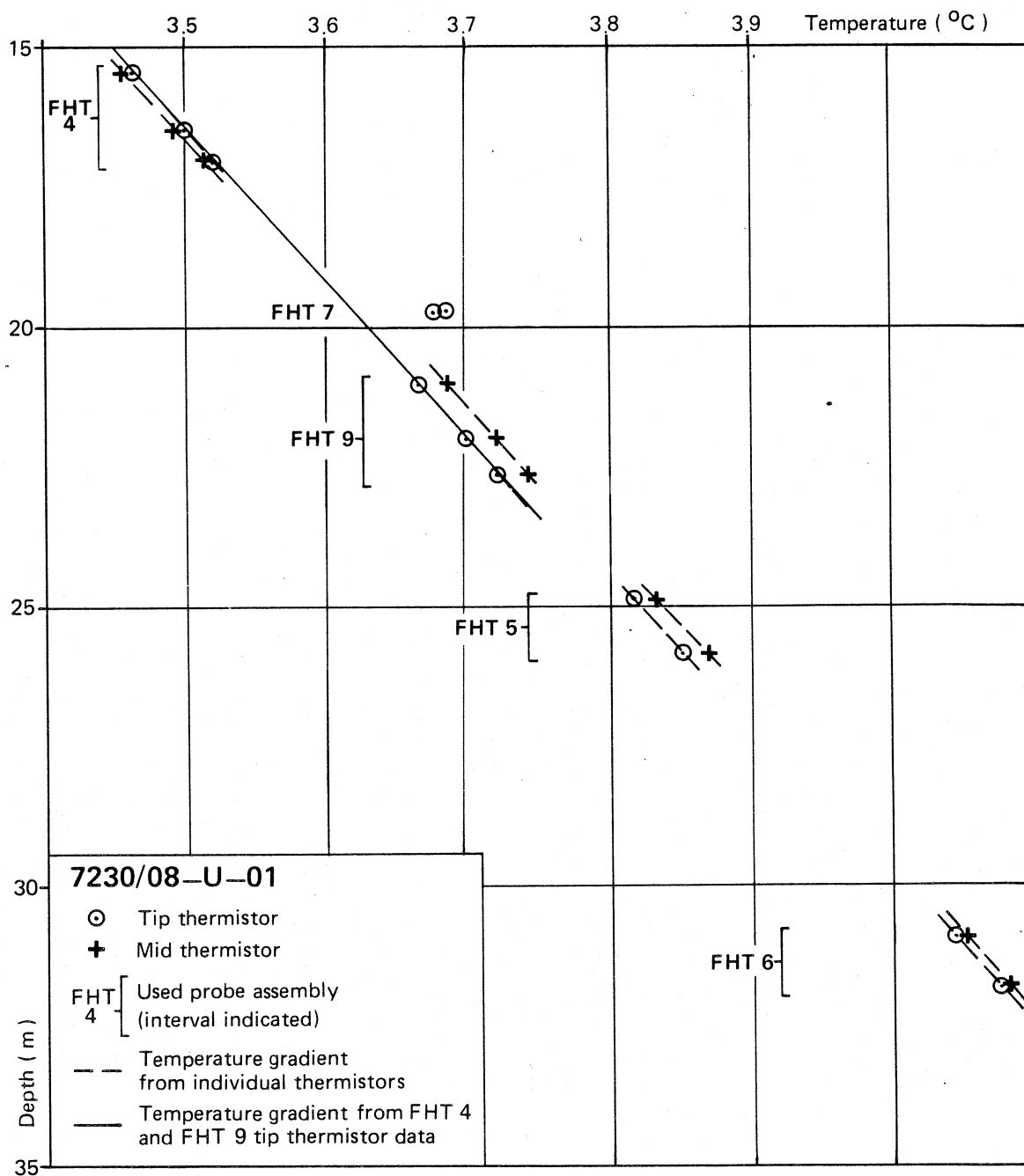


Figure 3.3 Temperature - depth plot from site 7230/08-U-01

3.5 Site 7230/05-U-05

Less datapoints were obtained at this site than at site 7230/08-U-01 due to thinner Quaternary overburden and difficult soil conditions. The data are, however, sufficient to establish a fairly accurate gradient. The obtained

temperature/depth points are summarized in Table 3.2, and a corresponding plot is shown in Figure 3.4. One of the datapoints in Figure 3.4 (probe FHT4 at 16.34 m) is calculated by the alternative method (Section 3.2), but due to technical problems the calculated temperature at this depth relies on a time interval of only 55 s and is regarded as unreliable. This is also evident from Figure 3.4.

The remaining datapoints fit well to a linear temperature gradient across the whole interval, although the mid- and tip thermistors of probe FHT5 again show a fairly consistent difference in temperature (0.016 - 0.03 K).

The best fit in the data from this site is found by linear regression through the three FHT5 tip thermistor points and the datapoint at 17.69 m, which gives a temperature gradient of $69.3 \cdot 10^{-3}$ K/m (regression coefficient 0.9991) across a 4.74 m depth interval. We suggest that this value is used in the calculation of heat flow at this site.

A linear regression through the data from the three tip thermistor data points of FHT5 gives a gradient of $64.0 \cdot 10^{-3}$ K/m (regression coefficient 0.9949), whereas regression through the mid thermistors gives a gradient of $68.0 \cdot 10^{-3}$ K/m (regression coefficient of 0.9879). Combining all the FHT5-data gives a gradient of $65.6 \cdot 10^{-3}$ K/m. These gradients are, however, obtained across only 1.77 m depth interval. Regression through all the data (excluding FHT4) gives a gradient of $66.4 \cdot 10^{-3}$ K/m (regression coefficient 0.9910) across 4.74 m depth interval. From the various alternatives given above we choose $66 \cdot 10^{-3}$ K/m as lower limit for the in situ gradient.

As for the dataset from site 7227/11-U-01 uncertainties in the gradient can also be evaluated by adding and subtracting the uncertainty limits to the upper and lower datapoints and then fit a straight line through the new dataset (including only tip thermistor data). Between different probes used at this site the uncertainty is found to be within ± 0.015 K and for different temperatures from the same probe the uncertainty is within ± 0.005 K (Appendix I). This exercise indicates that the upper limit of the gradient may be $73.4 \cdot 10^{-3}$ K/m whereas the lower limit may be $65.3 \cdot 10^{-3}$ K/m. The lower values evident by all the other approaches above do however indicate that $73.4 \cdot 10^{-3}$ K/m is a somewhat high limit. We maintain $66 \cdot 10^{-3}$ K/m as the lower limit and choose $72.7 \cdot 10^{-3}$ K/m (which is obtained by only adding the uncertainty of the FT15 data relative to the FHT5 data, to the temperature at 17.69 m) as the upper limit.

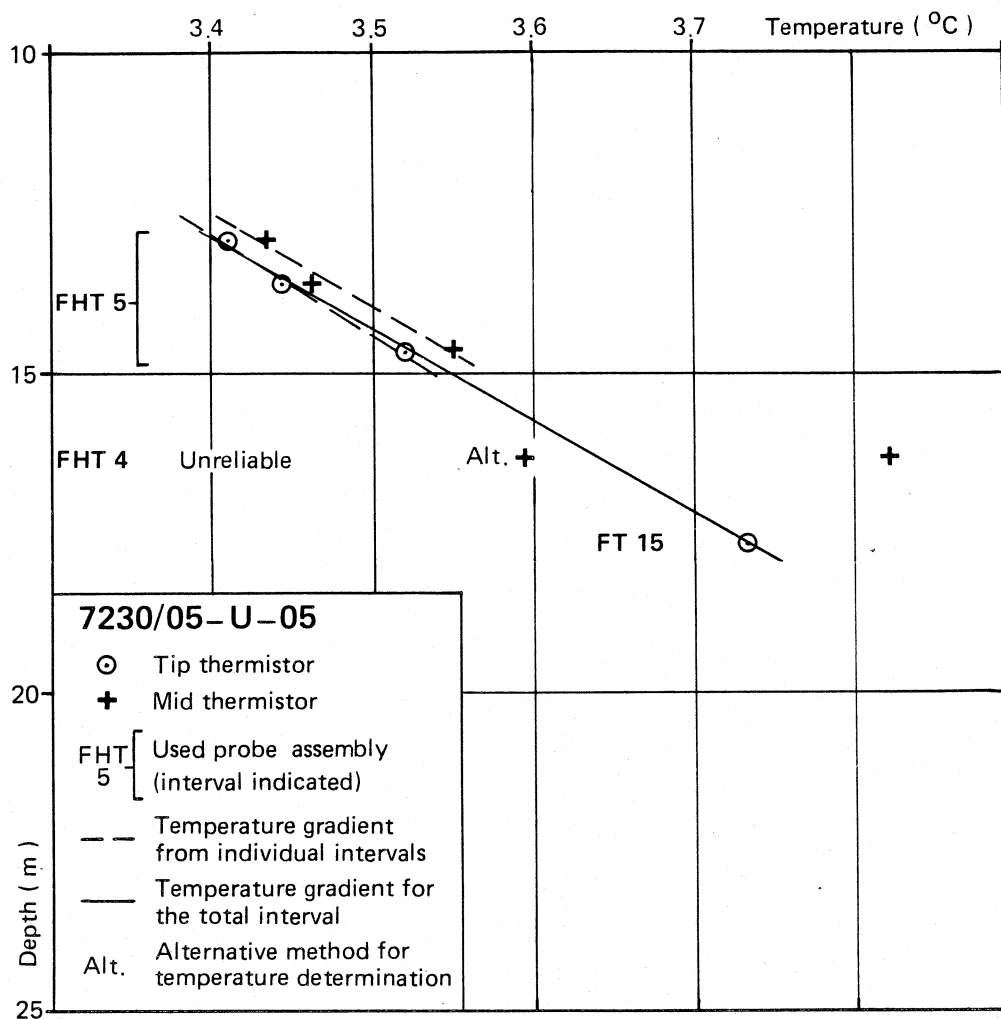


Figure 3.4 Temperature - depth plot from site 7230/05-U-05.

4. THERMAL CONDUCTIVITY

4.1 Summary

Thermal conductivity of sediment samples was measured in the laboratory on board during the cruise using a standard needle probe. Thermal conductivity was also measured in situ using a modified needle probe combined with the thermistor probe (Appendix I). To strengthen the reliability of the thermal conductivity data, selected samples were also sent to an independent laboratory at the University of Aarhus in Denmark for similar measurements. The results of these measurements are summarized in Table 4.1 and Table 4.2.

Physical properties (routine soil mechanical testing and mineralogy) have been recorded. From this data we have calculated theoretical thermal conductivity and also been able to perform a check of the saturation of the samples to ensure that no gas voids in the samples influenced on the measurements. This is described in detail in Section 4.3.

The results of the different measurements are compared and discussed in Section 4.4. In Section 4.5 mean thermal conductivity is calculated for each site in the interval in which the temperature gradient has been established.

We conclude that the vertical thermal conductivity is as follows for the three investigated sites (the uncertainty interval (ref. Section 4.5.3) is given in brackets): 7227/11-U-01: 1.75 W/m K (1.73-1.77), 7230/08-U-01: 1.40 W/m K (1.38-1.42), 7230/08-U-01: 1.44 W/m K (1.40-1.48).

4.2 Field measurements

Thermal conductivity was measured on board on sediment samples using a needle probe (von Herzen & Maxwell 1959) of 100 mm length and 3 mm diameter. The measurements were done with the needle oriented both axially and perpendicular to the sample axis (vertically and horizontally in the sediment). This was done because previous experience has shown that the thermal conductivity could be slightly anisotropic, with the horizontal value being higher than the vertical. From the measurements in the two directions the vertical thermal conductivity can be calculated from the

following relation (Penner 1963; Balling et al. 1981):

$$K_w = (K_h K_v)^{\frac{1}{2}}$$

where K_w is the result from measurement with the needle oriented perpendicular to the probe axis, yielding a weighed mean of vertical and horizontal thermal conductivity, K_h is the result of the measurement with the needle oriented axially, yielding horizontal thermal conductivity, and K_v is the vertical thermal conductivity. If K_v and K_h differ, K_v is the parameter to be used in calculation of heat flow. The relation between the two parameters is commonly expressed as the coefficient of anisotropy: $A = K_h/K_v = K_h^2/K_w^2$.

All the given values from the on board measurements are the mean of three independent measurements, which strengthen the reliability of the data. Further details on the laboratory procedures are given in Appendix I and the results are discussed in Section 4.4, but we give the following comments to the values given in Table 4.1.

Some of the values are given with an (x) behind. These are results that we believe are influenced by coarse rock fragments close to the needle probe, resulting in too high values compared to the bulk sample property. These readings are identified by inspection of radiographs of the samples which show both the presence of rock fragments and the cavity from the needle position. An example of this from site 7230/08-U-01 is shown in Figure 4.1.

The length/diameter ratio of the needle probe is 30/1 which should ensure that infinite source theory can be applied. In the case with the needle oriented perpendicular to the sample axis, however, the effective length is limited by the sample diameter which is approximately 63 mm for site 7227/11-U-01 and approx. 71 mm for sites 7230/08-U-01 and 7230/05-U-05. The limitation in this case will be the thermally insulating interface between soil and air, and this geometry probably has influenced the measurements resulting in too low K_w - values. This will in turn result in too low K_v - values.

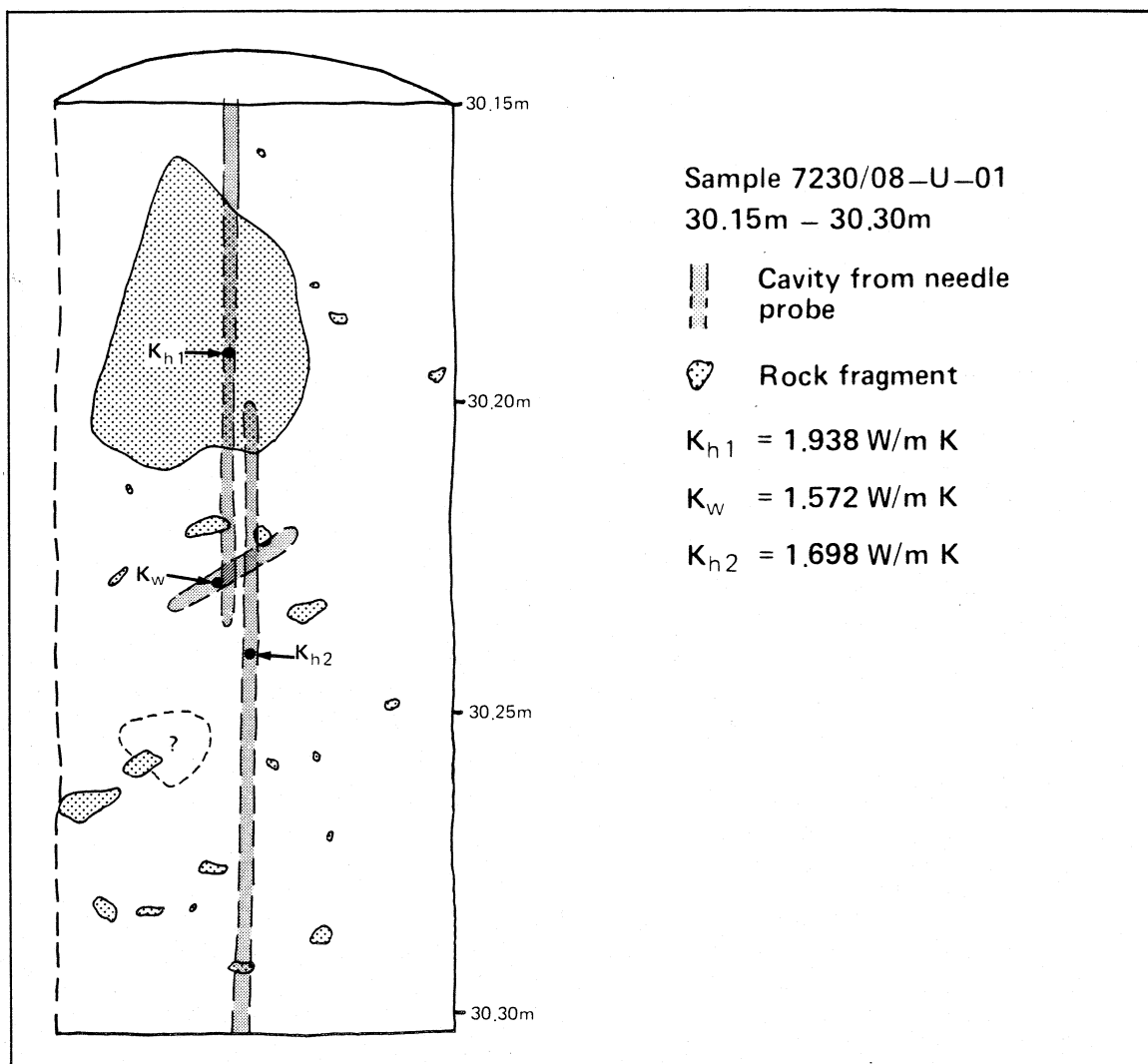


Figure 4.1 Redrawn radiograph of a sample subjected to thermal conductivity measurement. There is a clear influence from a rock fragment in one of the K_h -values and probably slightly in the K_w -value.

The in situ thermal conductivity measurement gives the horizontal component, and is measured in two of the boreholes. The values above 24.90 m in borehole 7230/08-U-01 give slightly higher values than what is found in the laboratory. The values from 21.04 m, 21.97 m and 22.63 m depth are probably not reliable as they show a poor linearity on the plot of temperature versus log time. An effect that may cause high values (and also the observed poor linearity) in this data is the possible presence of rock fragments close to the probe. This can however not be verified for the in situ tests.

Table 4.1 Field thermal conductivity measurements. An "x" behind some of the values indicates that they probably are influenced by clasts close to the probe. Values given in parenthesis are regarded as unreliable (see text). The following thermal conductivities are given: K_h = horizontal, K_w = weighted mean of horizontal and vertical, K_v = vertical, K_{ih} = horizontal, measured in situ.

Site	Depth (m)	Thermal cond. (W/m K)				Anisotropy K_h/K_v
		K_h	K_w	K_v	K_{ih}	
7227/11-U-01	05.75	1.94x	1.77	1.62x		1.20x
	19.11	1.71				
	19.14		1.64	1.56		1.12
	19.16	1.73				
	19.91		1.75	1.65		1.12
	19.95	1.92				
	19.98	1.79				
	20.19	1.71				
	20.21		1.70	1.67		1.03
	20.25	1.75				
	25.13	1.81x				
	25.16		1.67	1.58x		1.12x
	25.18	1.73				
	25.28	1.89x				
	25.31		1.66	1.49x		1.24x
	25.33	1.81				
	29.94	1.70				
	29.96		1.64	1.56		1.11
	29.99	1.74				
	30.09	1.66				
	30.12		1.65	1.64		1.02
	30.14	1.68				
7230/08-U-01	14.34	1.53				
	14.35		1.47x	1.43x		1.05x
	14.37	1.49				
	14.47	1.46				
	14.48		1.41	1.33		1.13
	14.50	1.54				
	16.44				1.58	
	19.10	1.52				
	19.11		1.49	1.47		1.03
	19.12	1.54				
	19.25	1.54				
	19.27		1.43	1.33		1.15
	19.28	1.51				
	20.13	1.39				
	20.14	1.40	1.38	1.36		1.03
	20.24	1.51				
	20.27		1.54x	1.54x		1.00x
	20.29	1.55				
	20.54	1.54				
	20.57		1.44	1.34		1.16
	20.59	1.56				
	21.04				(1.61)	
	21.97				(1.60)	
	22.63				(1.57)	
	24.08	1.57	1.35	1.16		1.35
	24.18	1.51				
	24.21		1.42	1.35		1.12
	24.23	1.50				
	24.48	1.55				
	24.51		1.39	1.26		1.23
	24.53	1.55				
	24.90				1.60	
	30.93				1.72	
	31.82				1.75	
	30.08		1.54	1.39		1.23
	30.09	1.71				

Table 4.1 continued

Site	Depth (m)	Thermal cond. (W/m K)				Anisotropy K_h/K_v
		K_h	K_w	K_v	K_{ih}	
7230/08-U-01 cont.	30.10	1.71				
	30.20	1.94x				
	30.23		1.57	1.36x		1.34x
	30.25	1.70				
	30.55	1.74				
	30.58		1.61	1.47		1.21
	30.61	1.79				
7230/05-U-05	12.15	1.79				
	12.18		1.48	1.24		1.42
	12.21	1.73				
	12.30	1.74				
	12.34		1.52	1.31		1.34
	12.36	1.78				
	12.92				1.75	
	13.60				1.71	
	14.66				1.76	
	15.21	1.81				
	15.25		1.56	1.37		1.28
	15.28	1.72				
	17.06	(2.15)				
	17.11	1.60				

4.3 Measurements at the University of Aarhus

A selection of Quaternary samples have been subjected to thermal conductivity measurements by the Geophysical Laboratory at the University of Aarhus, Denmark. The measurements were performed by use of a needle probe with the following specifications:

probe length: 50 mm
 probe diameter: 1.5 mm

The results of these measurements are presented in Table 4.2. and are also included in the plots in Figures 4.4, 4.5 and 4.6.

All the values are mean results of more than two and frequently five repetitive readings with the needles orientated similarly as during the on board measurements. This needle length is sufficiently short to ensure that no boundary effects due to the sample diameter occur in the data. A short report by Niels Balling, University of Aarhus, is enclosed in Appendix II.

There is generally an excellent fit between horizontal thermal conductivity measured on board and measured in the laboratory in Aarhus. This indicates that the instruments are properly calibrated and that reliable values are obtained. For further discussion of the data reference is made to Sections 4.4 and 4.5.

Table 4.2 Thermal conductivity measurements performed at the University of Aarhus.

Site	Depth	Thermal cond. (W/m K)		Anisotropy
	(m)	K_h	K_v	K_h/K_v
7227/11-U-01	19.11	1.61	1.71	0.94
	19.14	1.62	1.63	0.99
	19.17	1.62	1.68	0.97
	19.87	1.78	1.90	0.93
	19.92	1.88	1.81	1.04
	19.96	1.98	1.79	1.10
	20.17	1.89	1.86	1.01
	20.22	1.85	1.90	0.97
	20.26	1.81	1.85	0.98
	25.11	1.62	1.76	0.92
	25.16	1.61	1.74	0.93
	25.20	1.60	1.81	0.88
	25.26	1.87	1.61	1.16
	25.31	1.82	1.71	1.06
	25.35	1.77	1.82	0.97
	29.92	1.83	1.71	1.07
	29.97	1.77	1.65	1.07
	30.01	1.70	1.65	1.03
	30.07	1.63	1.69	0.97
	30.11	1.66	1.76	0.94
	30.16	1.68	1.80	0.93
7230/08-U-01	14.45	1.50	1.31	1.14
	14.48	1.50	1.32	1.13
	14.51	1.49	1.35	1.11
	19.08	1.52	1.51	1.01
	19.13	1.46	1.47	0.99
	19.17	1.40	1.50	0.93
	20.52	1.55	1.38	1.12
	20.57	1.50	1.44	1.04
	20.61	1.45	1.45	1.00
	24.46	1.49	1.33	1.12
	24.50	1.50	1.37	1.09
	24.55	1.51	1.37	1.11
	30.53	1.68	1.57	1.07
	30.58	1.70	1.41	1.20
	30.63	1.71	1.38	1.24
7230/05-U-05	12.13	1.55	1.58	0.98
	12.18	1.64	1.41	1.16
	12.23	1.72	1.27	1.36
	12.29	1.66	1.40	1.19
	12.33	1.72	1.29	1.33
	12.38	1.77	1.33	1.33
	15.20	1.79	1.50	1.19
	15.25	1.79	1.52	1.18
	15.29	1.78	1.62	1.10

4.4 Theoretical calculation of thermal conductivity

4.4.1 Analyses of physical properties

Several physical properties are analysed on selected Quaternary samples. A purpose of these analyses has been to enable correlations between sediment composition and thermal conductivity. Furthermore this gives important data in the continuous attempt in reconstruction of the Quaternary history of the region, which in turn influences the measured temperature gradients. A complete documentation of the analyses performed on the Quaternary material will be given in a separate report. In Table 4.3 we have extracted the most relevant data for evaluation of thermal conductivity. These data comprise the following parameters:

- z - depth (m)
- z-ref - depth (m) to which neighbouring data are referred for correlation
- W_{unit} - wet unit weight of the sample, (kN/m³)
- w - water content in per cent of dry weight sample, (%)
- S_u - undrained shear strength obtained by the falling cone method, (kN/m²)
- S_r - remoulded shear strength obtained by the falling cone method, (kN/m²)
- V_h - horizontal sound velocity, (m/s)
- V_v - vertical sound velocity, (m/s)
- Qtz - quartz content in per cent of mineral fraction
- Chl - chlorite content in per cent of mineral fraction
- thermal conductivity (W/m K)
 - K_h - horizontal
 - K_w - weighted mean
 - K_i - in situ
 - K_v - vertical
 - A - coefficient of anisotropy

In Table 4.3.A two depths are given, where z is the real depth at which the different tests are performed and z-ref is the depth to which the different results are correlated in Table 4.3.B for use in crossplots and calculations. (Mean values are used in Table 4.3.B in the cases where more than one value for the same parameter are referred to the same z-ref.)

Table 4.3.A Physical properties of Quaternary samples from the 1987 heat flow sites. z: exact test depth. z-ref: neighbouring tests referred to a common reference depth. (Explanations to abbreviations are given in the text.)

SITE	Z (m)	Z-ref	Dens	W	Sv	Sr	Vh	Vv	Qtz	Chl	Kh	Kw	Ki
7227/11-U-01	5.57	5.57	0.0	0.0	88.0	0.0	0	0	0.0	0.0	0.000	0.000	0.000
7227/11-U-01	5.71	5.75	21.4	15.6	0.0	0.0	0	0	0.0	0.0	0.000	0.000	0.000
7227/11-U-01	5.67	5.75	0.0	0.0	0.0	0.0	0	0	25.0	6.0	0.000	0.000	0.000
7227/11-U-01	13.20	13.2	0.0	23.7	102.1	0.0	0	0	0.0	0.0	0.000	0.000	0.000
7227/11-U-01	14.52	14.52	21.4	19.8	115.8	0.0	0	0	0.0	0.0	0.000	0.000	0.000
7227/11-U-01	16.26	16.27	0.0	26.0	0.0	0.0	0	0	0.0	0.0	0.000	0.000	0.000
7227/11-U-01	16.27	16.27	0.0	0.0	102.1	0.0	0	0	0.0	0.0	0.000	0.000	0.000
7227/11-U-01	17.86	17.86	0.0	23.5	0.0	0.0	0	0	0.0	0.0	0.000	0.000	0.000
7227/11-U-01	17.87	17.87	0.0	0.0	74.1	0.0	0	0	0.0	0.0	0.000	0.000	0.000
7227/11-U-01	18.36	18.36	21.4	21.4	0.0	0.0	0	0	0.0	0.0	0.000	0.000	0.000
7227/11-U-01	19.00	19.11	21.2	19.2	0.0	0.0	0	0	0.0	0.0	0.000	0.000	0.000
7227/11-U-01	19.03	19.11	0.0	0.0	0.0	0.0	0	0	30.0	4.0	0.000	0.000	0.000
7227/11-U-01	19.06	19.11	0.0	0.0	251.1	0.0	0	0	0.0	0.0	0.000	0.000	0.000
7227/11-U-01	19.11	19.11	0.0	0.0	0.0	0.0	0	0	0.0	0.0	1.709	0.000	0.000
7227/11-U-01	19.14	19.11	0.0	0.0	225.0	0.0	1830	1780	0.0	0.0	0.000	1.637	0.000
7227/11-U-01	19.16	19.11	0.0	0.0	0.0	0.0	0	0	0.0	0.0	1.734	0.000	0.000
7227/11-U-01	19.78	19.78	0.0	0.0	251.1	0.0	0	0	0.0	0.0	0.000	0.000	0.000
7227/11-U-01	19.79	19.91	0.0	0.0	0.0	0.0	0	0	20.0	8.0	0.000	0.000	0.000
7227/11-U-01	19.82	19.91	21.5	17.1	0.0	0.0	0	0	0.0	0.0	0.000	0.000	0.000
7227/11-U-01	19.88	19.91	0.0	0.0	0.0	0.0	0	0	0.0	0.0	1.790	0.000	0.000
7227/11-U-01	19.91	19.91	0.0	0.0	0.0	0.0	0	0	0.0	0.0	0.000	1.750	0.000
7227/11-U-01	19.95	19.91	0.0	0.0	0.0	0.0	0	0	0.0	0.0	1.919	0.000	0.000
7227/11-U-01	20.0	20.0	0.0	0.0	251.1	0.0	0	0	0.0	0.0	0.000	0.000	0.000
7227/11-U-01	20.31	20.25	0.0	0.0	0.0	0.0	0	1834	0.0	0.0	0.000	0.000	0.000
7227/11-U-01	20.19	20.25	0.0	0.0	0.0	0.0	0	0	0.0	0.0	1.707	0.000	0.000
7227/11-U-01	20.21	20.25	0.0	0.0	0.0	0.0	0	0	0.0	0.0	0.000	1.699	0.000
7227/11-U-01	20.25	20.25	0.0	0.0	0.0	0.0	0	0	0.0	0.0	1.748	0.000	0.000
7227/11-U-01	24.77	24.77	20.5	23.3	52.5	0.0	0	0	0.0	0.0	0.000	0.000	0.000
7227/11-U-01	24.96	24.96	0.0	0.0	51.0	51.0	0	0	0.0	0.0	0.000	0.000	0.000
7227/11-U-01	25.03	25.13	21.2	21.9	0.0	0.0	0	0	20.0	6.0	0.000	0.000	0.000
7227/11-U-01	25.05	25.13	0.0	0.0	102.0	0.0	0	0	0.0	0.0	0.000	0.000	0.000
7227/11-U-01	25.13	25.13	0.0	0.0	0.0	0.0	0	0	0.0	0.0	1.808	0.000	0.000
7227/11-U-01	25.15	25.13	0.0	0.0	105.0	0.0	1940	1820	0.0	0.0	0.000	0.000	0.000
7227/11-U-01	25.16	25.13	0.0	0.0	0.0	0.0	0	0	0.0	0.0	0.000	1.673	0.000
7227/11-U-01	25.18	25.13	0.0	0.0	0.0	0.0	0	0	0.0	0.0	1.734	0.000	0.000
7227/11-U-01	25.28	25.30	0.0	0.0	0.0	0.0	0	0	0.0	0.0	1.892	0.000	0.000
7227/11-U-01	25.30	25.30	0.0	0.0	130.0	0.0	1850	1840	0.0	0.0	0.000	0.000	0.000
7227/11-U-01	25.31	25.30	0.0	0.0	0.0	0.0	0	0	0.0	0.0	0.000	1.662	0.000
7227/11-U-01	25.33	25.30	0.0	0.0	0.0	0.0	0	0	0.0	0.0	1.807	0.000	0.000
7227/11-U-01	29.60	29.60	20.8	23.8	0.0	0.0	0	0	0.0	0.0	0.000	0.000	0.000

Table 4.3.A Physical properties of Quaternary samples from the 1987 heat flow sites. z: exact test depth. z-ref: neighbouring tests referred to a common reference depth. (Explanations to abbreviations are given in the text.)

SITE	Z (m)	Z-ref	Dens	W	Sv	Sr	Vh	Vv	Qtz	Chl	Kh	Kw	Ki
7227/11-U-01	29.67	29.60	0.0	0.0	102.1	0.0	0	0	0.0	0.0	0.000	0.000	0.000
7227/11-U-01	29.87	29.94	21.3	19.9	115.8	0.0	0	0	21.0	7.0	0.000	0.000	0.000
7227/11-U-01	29.94	29.94	0.0	0.0	0.0	0.0	0	0	0.0	0.0	1.698	0.000	0.000
7227/11-U-01	29.96	29.94	0.0	0.0	150.0	0.0	0	0	0.0	0.0	0.000	1.636	0.000
7227/11-U-01	29.99	29.94	0.0	0.0	0.0	0.0	0	0	0.0	0.0	1.744	0.000	0.000
7227/11-U-01	30.00	29.94	0.0	0.0	0.0	0.0	1890	1905	0.0	0.0	0.000	0.000	0.000
7227/11-U-01	30.09	30.11	0.0	0.0	0.0	0.0	0	0	0.0	0.0	1.658	0.000	0.000
7227/11-U-01	30.11	30.11	0.0	0.0	175.0	0.0	0	0	0.0	0.0	0.000	0.000	0.000
7227/11-U-01	30.12	30.11	0.0	0.0	0.0	0.0	0	0	0.0	0.0	0.000	1.652	0.000
7227/11-U-01	30.14	30.11	0.0	0.0	0.0	0.0	0	0	0.0	0.0	1.679	0.000	0.000
7227/11-U-01	30.15	30.11	0.0	0.0	0.0	0.0	1800	1785	0.0	0.0	0.000	0.000	0.000
7230/08-U-01	14.13	14.12	0.0	0.0	30.3	27.0	0	0	0.0	0.0	0.000	0.000	1.581
7230/08-U-01	14.12	14.12	19.4	32.6	0.0	0.0	0	0	0.0	0.0	0.000	0.000	0.000
7230/08-U-01	14.32	14.32	0.0	0.0	30.3	27.0	0	0	0.0	0.0	0.000	0.000	0.000
7230/08-U-01	14.30	14.32	0.0	0.0	0.0	0.0	1721	1650	0.0	0.0	0.000	0.000	0.000
7230/08-U-01	14.35	14.35	0.0	0.0	94.7	0.0	0	0	0.0	0.0	0.000	1.470	0.000
7230/08-U-01	14.36	14.35	20.1	27.0	0.0	0.0	0	0	0.0	0.0	0.000	0.000	0.000
7230/08-U-01	14.34	14.35	0.0	0.0	0.0	0.0	0	0	0.0	0.0	1.530	0.000	0.000
7230/08-U-01	14.37	14.35	0.0	0.0	0.0	0.0	0	0	0.0	0.0	1.486	0.000	0.000
7230/08-U-01	14.39	14.35	0.0	0.0	0.0	0.0	0	0	34.0	7.0	0.000	0.000	0.000
7230/08-U-01	14.48	14.48	0.0	0.0	45.0	0.0	1630	0	0.0	0.0	0.000	1.411	0.000
7230/08-U-01	14.47	14.48	0.0	0.0	0.0	0.0	0	0	0.0	0.0	1.459	0.000	0.000
7230/08-U-01	14.50	14.48	0.0	0.0	0.0	0.0	0	0	0.0	0.0	1.537	0.000	0.000
7230/08-U-01	18.84	18.84	19.0	34.3	0.0	0.0	0	0	0.0	0.0	0.000	0.000	0.000
7230/08-U-01	18.86	18.84	0.0	0.0	30.4	15.2	0	0	0.0	0.0	0.000	0.000	0.000
7230/08-U-01	19.08	19.10	0.0	0.0	0.0	0.0	1674	1638	0.0	0.0	0.000	0.000	0.000
7230/08-U-01	19.10	19.10	0.0	0.0	0.0	0.0	0	0	0.0	0.0	1.523	0.000	0.000
7230/08-U-01	19.11	19.10	0.0	0.0	0.0	0.0	0	0	0.0	0.0	0.000	1.494	0.000
7230/08-U-01	19.12	19.10	0.0	0.0	36.0	0.0	0	0	0.0	0.0	1.540	0.000	0.000
7230/08-U-01	19.25	19.27	19.9	28.1	0.0	0.0	0	0	0.0	0.0	1.530	0.000	0.000
7230/08-U-01	19.27	19.27	0.0	0.0	0.0	0.0	0	0	0.0	0.0	0.000	1.426	0.000
7230/08-U-01	19.28	19.27	0.0	0.0	0.0	0.0	0	0	0.0	0.0	1.505	0.000	0.000
7230/08-U-01	19.32	19.27	0.0	0.0	79.5	52.5	1686	1660	23.0	4.0	0.000	0.000	0.000
7230/08-U-01	20.11	20.13	0.0	0.0	0.0	0.0	0	0	18.0	10.0	0.000	0.000	0.000
7230/08-U-01	20.12	20.13	19.3	31.5	0.0	0.0	0	0	0.0	0.0	0.000	0.000	0.000
7230/08-U-01	20.13	20.13	0.0	0.0	0.0	0.0	0	0	0.0	0.0	1.388	0.000	0.000
7230/08-U-01	20.14	20.13	0.0	0.0	0.0	0.0	0	0	0.0	0.0	1.401	1.375	0.000
7230/08-U-01	20.16	20.13	0.0	0.0	62.3	0.0	1695	1620	0.0	0.0	0.000	0.000	0.000
7230/08-U-01	20.24	20.27	19.9	28.8	0.0	0.0	0	0	0.0	0.0	1.514	0.000	0.000
7230/08-U-01	20.27	20.27	0.0	0.0	69.2	0.0	1835	1708	0.0	0.0	0.000	1.536	0.000

Table 4.3.A Physical properties of Quaternary samples from the 1987 heat flow sites. z: exact test depth. z-ref: neighbouring tests referred to a common reference depth. (Explanations to abbreviations are given in the text.)

SITE	Z (m)	Z-ref	Dens	W	Sv	Sr	Vh	Vv	Qtz	Chl	Kh	Kw	Ki
7230/08-U-01	20.29	20.27	0.0	0.0	0.0	0.0	0	0	0.0	0.0	1.549	0.000	0.000
7230/08-U-01	20.43	20.54	0.0	0.0	0.0	0.0	1782	1663	0.0	0.0	0.000	0.000	0.000
7230/08-U-01	20.54	20.54	0.0	0.0	0.0	0.0	0	0	0.0	0.0	1.539	0.000	0.000
7230/08-U-01	20.57	20.54	0.0	0.0	0.0	0.0	0	0	0.0	0.0	0.000	1.439	0.000
7230/08-U-01	20.59	20.54	0.0	0.0	0.0	0.0	0	0	0.0	0.0	1.556	0.000	0.000
7230/08-U-01	21.04	21.04	0.0	0.0	0.0	0.0	0	0	0.0	0.0	0.000	0.000	1.607
7230/08-U-01	21.97	21.97	0.0	0.0	0.0	0.0	0	0	0.0	0.0	0.000	0.000	1.601
7230/08-U-01	22.63	22.63	0.0	0.0	0.0	0.0	0	0	0.0	0.0	0.000	0.000	1.597
7230/08-U-01	23.98	23.98	19.9	29.7	52.5	31.9	0	0	0.0	0.0	0.000	0.000	0.000
7230/08-U-01	24.03	24.08	0.0	0.0	0.0	0.0	0	0	22.0	6.0	0.000	0.000	0.000
7230/08-U-01	24.04	24.08	0.0	0.0	0.0	0.0	1642	1647	0.0	0.0	0.000	0.000	0.000
7230/08-U-01	24.08	24.08	0.0	0.0	0.0	0.0	0	0	0.0	0.0	1.571	1.350	0.000
7230/08-U-01	24.10	24.08	19.8	29.2	60.3	44.1	0	0	0.0	0.0	0.000	0.000	0.000
7230/08-U-01	24.18	24.20	0.0	0.0	0.0	0.0	0	0	0.0	0.0	1.511	0.000	0.000
7230/08-U-01	24.19	24.20	20.1	29.2	0.0	0.0	0	0	0.0	0.0	0.000	0.000	0.000
7230/08-U-01	24.20	24.20	0.0	0.0	0.0	0.0	1666	1642	0.0	0.0	0.000	0.000	0.000
7230/08-U-01	24.21	24.20	0.0	0.0	0.0	0.0	0	0	0.0	0.0	0.000	1.424	0.000
7230/08-U-01	24.23	24.20	0.0	0.0	0.0	0.0	0	0	0.0	0.0	1.503	0.000	0.000
7230/08-U-01	24.24	24.20	0.0	0.0	74.1	51.0	0	0	0.0	0.0	0.000	0.000	0.000
7230/08-U-01	24.17	24.20	0.0	0.0	0.0	0.0	0	0	27.0	4.0	0.000	0.000	0.000
7230/08-U-01	24.35	24.35	0.0	0.0	0.0	0.0	1670	1677	0.0	0.0	0.000	0.000	0.000
7230/08-U-01	24.48	24.50	0.0	0.0	0.0	0.0	0	0	0.0	0.0	1.546	0.000	0.000
7230/08-U-01	24.50	24.50	0.0	0.0	0.0	0.0	1670	1632	0.0	0.0	0.000	0.000	0.000
7230/08-U-01	24.51	24.50	0.0	0.0	0.0	0.0	0	0	0.0	0.0	0.000	1.394	0.000
7230/08-U-01	24.53	24.50	0.0	0.0	0.0	0.0	0	0	0.0	0.0	1.548	0.000	0.000
7230/08-U-01	24.90	24.90	0.0	0.0	0.0	0.0	0	0	0.0	0.0	0.000	0.000	1.597
7230/08-U-01	30.07	30.10	20.7	24.2	0.0	0.0	0	0	39.0	4.0	0.000	0.000	0.000
7230/08-U-01	30.08	30.1	0.0	0.0	0.0	0.0	0	0	0.0	0.0	0.000	1.539	0.000
7230/08-U-01	30.09	30.10	0.0	0.0	0.0	0.0	0	0	0.0	0.0	1.710	0.000	0.000
7230/08-U-01	31.10	30.10	0.0	0.0	71.6	0.0	0	0	0.0	0.0	1.705	0.000	0.000
7230/08-U-01	30.17	30.20	0.0	0.0	0.0	0.0	0	0	25.0	5.0	0.000	0.000	0.000
7230/08-U-01	30.20	30.20	0.0	0.0	0.0	0.0	0	0	0.0	0.0	1.938	0.000	0.000
7230/08-U-01	30.22	30.20	20.5	24.3	0.0	0.0	0	0	0.0	0.0	0.000	0.000	0.000
7230/08-U-01	30.23	30.20	0.0	0.0	0.0	0.0	0	0	0.0	0.0	0.000	1.572	0.000
7230/08-U-01	30.25	30.20	0.0	0.0	71.6	58.4	1753	2055	0.0	0.0	1.698	0.000	0.000
7230/08-U-01	30.40	30.40	0.0	0.0	0.0	0.0	1706	1724	0.0	0.0	0.000	0.000	0.000
7230/08-U-01	30.58	30.55	0.0	0.0	77.0	0.0	1643	1797	0.0	0.0	0.000	1.608	0.000
7230/08-U-01	30.55	30.55	0.0	0.0	0.0	0.0	0	0	0.0	0.0	1.743	0.000	0.000
7230/08-U-01	30.61	30.55	0.0	0.0	0.0	0.0	0	0	0.0	0.0	1.788	0.000	0.000

Table 4.3.A Physical properties of Quaternary samples from the 1987 heat flow sites. z: exact test depth. z-ref: neighbouring tests referred to a common reference depth. (Explanations to abbreviations are given in the text.)

SITE	Z (m)	Z-ref	Dens	W	Sv	Sr	Vh	Vv	Qtz	Chl	Kh	Kw	Ki
7230/05-U-05	9.07	9.12	19.3	33.6	0.0	0.0	0	0	0.0	0.0	0.000	0.000	0.000
7230/05-U-05	9.12	9.12	0.0	0.0	24.0	18.6	0	0	0.0	0.0	0.000	0.000	0.000
7230/05-U-05	9.24	9.24	19.5	32.8	0.0	0.0	0	0	20.0	8.0	0.000	0.000	0.000
7230/05-U-05	9.26	9.24	0.0	0.0	25.0	18.6	0	0	0.0	0.0	0.000	0.000	0.000
7230/05-U-05	9.38	9.38	19.7	32.4	27.0	18.6	0	0	0.0	0.0	0.000	0.000	0.000
7230/05-U-05	12.0	12.15	20.6	25.7	0.0	0.0	0	0	0.0	0.0	0.000	0.000	0.000
7230/05-U-05	12.03	12.15	0.0	0.0	0.0	0.0	0	0	16.0	18.0	0.000	0.000	0.000
7230/05-U-05	12.07	12.15	0.0	0.0	74.0	0.0	0	0	0.0	0.0	0.000	0.000	0.000
7230/05-U-05	12.15	12.15	0.0	0.0	0.0	0.0	0	0	0.0	0.0	1.793	0.000	0.000
7230/05-U-05	12.18	12.15	0.0	0.0	95.0	0.0	0	0	0.0	0.0	0.000	1.478	0.000
7230/05-U-05	12.21	12.15	0.0	0.0	0.0	0.0	0	0	0.0	0.0	1.728	0.000	0.000
7230/05-U-05	12.30	12.30	0.0	0.0	0.0	0.0	0	0	0.0	0.0	1.738	0.000	0.000
7230/05-U-05	12.34	12.30	0.0	0.0	0.0	0.0	0	0	0.0	0.0	0.000	1.517	0.000
7230/05-U-05	12.36	12.30	0.0	0.0	0.0	0.0	0	0	0.0	0.0	1.780	0.000	0.000
7230/05-U-05	12.92	12.92	0.0	0.0	0.0	0.0	0	0	0.0	0.0	0.000	0.000	1.747
7230/05-U-05	13.60	13.60	0.0	0.0	0.0	0.0	0	0	0.0	0.0	0.000	0.000	1.711
7230/05-U-05	14.66	14.66	0.0	0.0	0.0	0.0	0	0	0.0	0.0	0.000	0.000	1.763
7230/05-U-05	15.01	15.05	22.0	21.0	115.8	0.0	0	0	0.0	0.0	0.000	0.000	0.000
7230/05-U-05	15.02	15.05	0.0	0.0	0.0	0.0	0	0	16.0	18.0	0.000	0.000	0.000
7230/05-U-05	15.05	15.05	0.0	0.0	0.0	0.0	1872	0	0.0	0.0	0.000	0.000	0.000
7230/05-U-05	15.09	15.09	0.0	0.0	251.1	0.0	0	0	0.0	0.0	0.000	0.000	0.000
7230/05-U-05	15.21	15.25	0.0	0.0	0.0	0.0	0	0	0.0	0.0	1.812	0.000	0.000
7230/05-U-05	15.25	15.25	0.0	0.0	251.1	0.0	1888	1787	0.0	0.0	0.000	1.558	0.000
7230/05-U-05	15.28	15.25	0.0	0.0	0.0	0.0	0	0	0.0	0.0	1.717	0.000	0.000
7230/05-U-05	17.06	17.06	22.5	12.8	0.0	0.0	0	0	0.0	0.0	2.015	0.000	0.000
7230/05-U-05	17.11	17.06	0.0	0.0	0.0	0.0	0	0	0.0	0.0	1.596	0.000	0.000
7230/05-U-05	17.12	17.06	0 0	0.0	0.0	0.0	0	0	35.0	3.0	0.000	0.000	0.000

Table 4.3.B Physical properties of Quaternary samples from the 1987 heat flow sites. z-ref: neighbouring tests referred to a common reference depth. (Explanations to abbreviations are given in the text.)

SITE	z-ref	Dens	W %	Su	So	Vh	Vv	Qrtz	Clrt	Kh	Kw	Ki	Kv	A
7227/11-U-01	5.57	0.0	0.0	88.0	0.0	0.	0.	0.0	0.0	0.000	0.000	0.000	0.000	0.000
7227/11-U-01	5.75	21.4	15.6	115.8	0.0	2032.	0.	25.0	6.0	1.940	1.773	0.000	1.620	1.197
7227/11-U-01	13.20	0.0	23.7	102.1	0.0	0.	0.	0.0	0.0	0.000	0.000	0.000	0.000	0.000
7227/11-U-01	14.52	21.4	19.8	115.8	0.0	0.	0.	0.0	0.0	0.000	0.000	0.000	0.000	0.000
7227/11-U-01	16.27	0.0	26.0	102.1	0.0	0.	0.	0.0	0.0	0.000	0.000	0.000	0.000	0.000
7227/11-U-01	17.86	0.0	23.5	0.0	0.0	0.	0.	0.0	0.0	0.000	0.000	0.000	0.000	0.000
7227/11-U-01	17.87	0.0	0.0	74.1	0.0	0.	0.	0.0	0.0	0.000	0.000	0.000	0.000	0.000
7227/11-U-01	18.36	21.4	21.4	0.0	0.0	0.	0.	0.0	0.0	0.000	0.000	0.000	0.000	0.000
7227/11-U-01	19.11	21.2	19.2	238.1	0.0	1830.	1780.	30.0	4.0	1.722	1.637	0.000	1.557	1.106
7227/11-U-01	19.78	0.0	0.0	251.1	0.0	0.	0.	0.0	0.0	0.000	0.000	0.000	0.000	0.000
7227/11-U-01	19.91	21.5	17.1	0.0	0.0	0.	0.	20.0	8.0	1.855	1.750	0.000	1.651	1.123
7227/11-U-01	20.00	0.0	0.0	251.1	0.0	0.	0.	0.0	0.0	0.000	0.000	0.000	0.000	0.000
7227/11-U-01	20.25	0.0	0.0	0.0	0.0	0.	1834.	0.0	0.0	1.728	1.699	0.000	1.670	1.034
7227/11-U-01	24.77	20.5	23.3	52.5	0.0	0.	0.	0.0	0.0	0.000	0.000	0.000	0.000	0.000
7227/11-U-01	24.96	0.0	0.0	51.0	51.0	0.	0.	0.0	0.0	0.000	0.000	0.000	0.000	0.000
7227/11-U-01	25.13	21.2	21.9	103.5	0.0	1940.	1820.	20.0	6.0	1.771	1.673	0.000	1.580	1.121
7227/11-U-01	25.30	0.0	0.0	130.0	0.0	1850.	1840.	0.0	0.0	1.850	1.662	0.000	1.493	1.239
7227/11-U-01	29.60	20.8	23.8	102.1	0.0	0.	0.	0.0	0.0	0.000	0.000	0.000	0.000	0.000
7227/11-U-01	29.94	21.3	19.9	132.9	0.0	1890.	1905.	21.0	7.0	1.721	1.636	0.000	1.555	1.107
7227/11-U-01	30.11	0.0	0.0	175.0	0.0	1800.	1785.	0.0	0.0	1.669	1.652	0.000	1.636	1.020
7230/08-U-01	14.12	19.4	32.6	30.3	27.0	0.	0.	0.0	0.0	0.000	0.000	1.581	0.000	0.000
7230/08-U-01	14.32	0.0	0.0	30.3	27.0	1721.	1650.	0.0	0.0	0.000	0.000	0.000	0.000	0.000
7230/08-U-01	14.35	20.1	27.0	94.7	0.0	0.	0.	34.0	7.0	1.508	1.470	0.000	1.433	1.052
7230/08-U-01	14.48	0.0	0.0	45.0	0.0	1630.	0.	0.0	0.0	1.498	1.411	0.000	1.329	1.127
7230/08-U-01	18.84	19.0	34.3	30.4	15.2	0.	0.	0.0	0.0	0.000	0.000	0.000	0.000	0.000
7230/08-U-01	19.10	0.0	0.0	36.0	0.0	1674.	1638.	0.0	0.0	1.518	1.494	0.000	1.470	1.032
7230/08-U-01	19.27	19.9	28.1	79.5	52.5	1686.	1660.	23.0	4.0	1.530	1.426	0.000	1.330	1.150
7230/08-U-01	20.13	19.3	31.5	62.3	0.0	1695.	1620.	18.0	10.0	1.395	1.375	0.000	1.355	1.029
7230/08-U-01	20.27	19.9	28.8	69.2	0.0	1835.	1708.	0.0	0.0	1.532	1.536	0.000	1.540	0.995
7230/08-U-01	20.54	0.0	0.0	0.0	0.0	1782.	1663.	0.0	0.0	1.548	1.439	0.000	1.338	1.156
7230/08-U-01	21.04	0.0	0.0	0.0	0.0	0.	0.	0.0	0.0	0.000	0.000	1.607	0.000	0.000
7230/08-U-01	21.97	0.0	0.0	0.0	0.0	0.	0.	0.0	0.0	0.000	0.000	1.601	0.000	0.000
7230/08-U-01	22.63	0.0	0.0	0.0	0.0	0.	0.	0.0	0.0	0.000	0.000	1.597	0.000	0.000
7230/08-U-01	23.98	19.9	29.7	52.5	31.9	0.	0.	0.0	0.0	0.000	0.000	0.000	0.000	0.000
7230/08-U-01	24.08	19.8	29.2	60.3	44.1	1642.	1647.	22.0	6.0	1.571	1.350	0.000	1.160	1.354
7230/08-U-01	24.20	20.1	29.2	74.1	51.0	1666.	1642.	27.0	4.0	1.507	1.424	0.000	1.345	1.120
7230/08-U-01	24.35	0.0	0.0	0.0	0.0	1670.	1677.	0.0	0.0	0.000	0.000	0.000	0.000	0.000
7230/08-U-01	24.50	0.0	0.0	0.0	0.0	1670.	1632.	0.0	0.0	1.547	1.394	0.000	1.256	1.232
7230/08-U-01	24.90	0.0	0.0	0.0	0.0	0.	0.	0.0	0.0	0.000	0.000	1.597	0.000	0.000

Table 4.3.B Physical properties of Quaternary samples from the 1987 heat flow sites. z-ref: neighbouring tests referred to a common reference depth. (Explanations to abbreviations are given in the text.)

SITE	z-ref	Dens	W %	Su	So	Vh	Vv	Qrtz	Clrt	Kh	Kw	Ki	Kv	A
7230/08-U-01	30.10	20.7	24.2	71.6	0.0	0.	0.	39.0	4.0	1.708	1.539	0.000	1.387	1.231
7230/08-U-01	30.20	20.5	24.3	71.6	58.4	1753.	2055.	25.0	5.0	1.818	1.572	0.000	1.359	1.337
7230/08-U-01	30.40	0.0	0.0	0.0	0.0	1706.	1724.	0.0	0.0	0.000	0.000	0.000	0.000	0.000
7230/08-U-01	30.55	0.0	0.0	77.0	0.0	1643.	1797.	0.0	0.0	1.766	1.608	0.000	1.465	1.205
7230/05-U-05	9.12	19.3	33.6	24.0	18.6	0.	0.	0.0	0.0	0.000	0.000	0.000	0.000	0.000
7230/05-U-05	9.24	19.5	32.8	25.0	18.6	0.	0.	20.0	8.0	0.000	0.000	0.000	0.000	0.000
7230/05-U-05	9.38	19.7	32.4	27.0	18.6	0.	0.	0.0	0.0	0.000	0.000	0.000	0.000	0.000
7230/05-U-05	12.15	20.6	25.7	84.5	0.0	0.	0.	16.0	18.0	1.761	1.478	0.000	1.241	1.419
7230/05-U-05	12.30	0.0	0.0	0.0	0.0	0.	0.	0.0	0.0	1.759	1.517	0.000	1.308	1.344
7230/05-U-05	12.92	0.0	0.0	0.0	0.0	0.	0.	0.0	0.0	0.000	0.000	1.747	0.000	0.000
7230/05-U-05	13.60	0.0	0.0	0.0	0.0	0.	0.	0.0	0.0	0.000	0.000	1.711	0.000	0.000
7230/05-U-05	14.66	0.0	0.0	0.0	0.0	0.	0.	0.0	0.0	0.000	0.000	1.763	0.000	0.000
7230/05-U-05	15.05	22.0	21.0	115.8	0.0	1872.	0.	16.0	18.0	0.000	0.000	0.000	0.000	0.000
7230/05-U-05	15.09	0.0	0.0	251.1	0.0	0.	0.	0.0	0.0	0.000	0.000	0.000	0.000	0.000
7230/05-U-05	15.25	0.0	0.0	251.1	0.0	1888.	1787.	0.0	0.0	1.765	1.558	0.000	1.376	1.283
7230/05-U-05	17.06	22.5	12.8	0.0	0.0	0.	0.	35.0	3.0	1.806	0.000	0.000	0.000	0.000

In the literature correlations between thermal conductivity and other physical properties are given both on a theoretical basis (conductivity of multi compound media) as well as on an empirical basis (e.g., Bullard & Day 1961; Johansen 1975; Matsuda & von Herzen 1985). Such correlations of the Barents Sea data thus provide quality control of the measured thermal conductivity.

4.4.2 Calculation method

In marine sediments, the major factor determining the thermal conductivity is generally assumed to be the water content. Since the sediments will be fully saturated, this parameter simply reflects the volumetric composition of the material (solid fraction - water saturated void fraction). Another factor of significance in such binary mixtures is the thermal conductivity of the solid fraction, which is determined by the mineral composition of the sediment.

A method for computation of the thermal conductivity of water saturated sediments, which has gained wide acceptance, is based on the geometric mean equation (Johansen 1975; Farouki 1981; Matsuda & von Herzen 1986), i.e.:

$$K = K_w^n K_s^{(1-n)} \quad (1)$$

where

K_w is the thermal conductivity of water,
 K_s , mineral thermal conductivity,
 n , void fraction (water)
 $(1-n)$, solid fraction (minerals)

Equation 1 may also be used inversely to determine thermal conductivity of the solid fraction, presumed that the saturated conductivity and the volumetric composition are known.

The thermal conductivity of the solid fraction may also be estimated by a corresponding equation, presumed that information is available of the mineral composition and that the thermal conductivity of the mineral constituents is known:

$$K_s = K_1^{n_1} K_2^{n_2} \dots K_i^{n_i} \quad (2)$$

where K_i and n_i are the thermal conductivity and volume fractions of the mineral constituents.

By an inspection of the mineralogical composition determined from the samples, the mineralogical composition is found to be acceptably represented by three constituents, i.e. quartz, chlorite and an unspecified rest. Thermal conductivities for these are given in Table 4.4.

When the measurements are made on board or later in an on shore laboratory, the core samples may have undergone changes implying loss of water due to drainage, or expansion of gas causing gas filled voids in the samples. The temperature of the samples will also deviate from the in situ conditions. In order to adjust the measurements to in situ condition, corrections for these effects must be applied.

Temperature variations have opposite effects on thermal conductivity of water and mineral grains. For the low water content sediments encountered here the effects cancel each other, and temperature deviations may therefore be neglected.

For a check and a quantification of the remaining factors, the following procedures are applied:

Presumed that the gas filled voids are limited to a few volume percent, corrections for lack of saturation may be made by the use of the Hashin-Shtrikman upper bound (HS-bound), which represents a mixture where a low conductivity material (gas) is homogeneously dispersed in a high conductivity (solid) matrix (Johansen 1975).

When the conductivity ratio is large (i.e. $K_s/K_f \gg 1$), the upper HS-bound may be approximated by:

$$K = f(v) K_{sat} \quad (3)$$

where

$$f(v) = 2 (1 - v)/(2 + v)$$

K_{sat} , conductivity of saturated sediments,

v , void volume fraction (gas filled).

The adjustment of a measured conductivity to saturation thus implies division of the measured value by the factor $f(v)$, where v is derived from the density data of the sample. This presumes knowledge of the following parameters:

- Wet density: γ (measured)
- Water content by dry weight: w (measured)
- Density of solids: γ_s (estimated to 2700 kg/m³)

From these parameters, the following may be derived:

$$\text{- Dry density: } \gamma_d = \gamma / (1 + w) \quad (4a)$$

$$\text{- Volume fraction of solids: } n_s = \gamma_d / \gamma_s \quad (4b)$$

$$\text{- Volume fraction of water: } n_w = \gamma_d w / \gamma_w \quad (4c)$$

$$\text{- Void volume fraction (gas): } v = 1 - (n_s + n_w) \quad (4d)$$

The density data refers to the sample under the laboratory conditions. By assuming that the measured water content represents all water present in the undisturbed sample, an adjusted dry density value may be obtained, i.e.:

$$n_w + n_s = 1, \quad (5a)$$

which implies:

$$w \gamma'_d / \gamma_w + \gamma'_d / \gamma_s = 1,$$

i.e.:

$$\text{- Adjusted dry density: } S'_d = 1 / (w / \gamma_w + 1 / \gamma_s) \quad (5b)$$

$$\text{- Adjusted void fraction: } n = 1 - \gamma'_d / \gamma_s \quad (5c)$$

$$\text{- Volume fraction of water: } n'_w = 1 - \gamma'_d / \gamma_s \quad (5d)$$

The thermal conductivities of the different compounds all refer to laboratory conditions, i.e. 20°C and atmospheric pressure. The values applied are given in Table 4.4. Input values to equations 1-5c of composition of each sample are taken from Table 4.3.

Table 4.4 Thermal conductivity of compounds in atmospheric pressure and 20°C.

Compound	Thermal conductivity (W/m K)
Water	(0.599)
Chlorite	3.5
Quartz	7.7
Mineral rest.	2.0

Due to the pressure release from down-hole to the laboratory gas dissolved in the pore water may form isolated gas voids in the sample. The result will be that the sample in the laboratory comprises mineral grains, water and gas voids, while it in situ comprises only grains and water. To arrive at in situ thermal conductivity it may therefore be necessary to correct for the effect of these gas voids. This was controlled by a test based on equations 1 to 5 above in this chapter, which can be summarized as follows.

- The measured thermal conductivity is adjusted to saturation (eq. 3) based on the gas void fraction determined from the density data (eq. 4d).
- The conductivity of the mineral fraction is derived from this saturated conductivity by inverse application of the geometric mean equation (eq. 1).
- The in situ conductivity is determined by the geometric mean equation from this solid conductivity and the volumetric composition corresponding to the adjusted dry density (eq. 5b).

4.4.3 Results

The results from the calculations described above are summarized in Table 4.5 and in Figures 4.2 and 4.3.

In situ values of thermal conductivity are required in order to calculate heat flow. The significant deviations in conditions from in situ to the

laboratory are temperature and pressure. From previous experience we have found the temperature effect to be negligible.

The possibility of presence of undersaturation / gas voids in the samples was checked according to the procedure above, and only in a few occasions a slight apparent undersaturation was found. These values are attributed to uncertainty in average solid density and in the volume determination, and no correction to the measured values is applied.

The indication of a low gas content from the above test is confirmed by measurement of low headspace gas concentrations on 11 samples from various depths and sites.

The details of these results will be included in a separate report. It is however noted that all Quaternary samples had a measured concentration of head space gas between 5 and 31 μl gas/kg dry sediment. (For comparison: The bedrock sample from 32.5 m at site 7227/11-U-01C had a gas concentration of 1020 μl gas/kg dry rock).

The plots of thermal conductivity versus water content also include curves for the theoretical relation between thermal conductivity and water content for different quartz contents (Figure 4.2). In these curves only two mineral compounds are assumed, namely quartz (thermal conductivity 7.7 W/m K) and mineral rest. (The mineral rest includes also in this case 6-10% chlorite. This is accounted for, resulting in an increased thermal conductivity for the mineral rest (2.1 W/m K) compared to the value given in Table 4.4).

The three plots show vertical, weighted and horizontal thermal conductivity versus water content. The actual range in quartz content is 18-39% (mean value 27%) for site 7227/08-U-01, 20-30% (mean value 23%) for site 7227/11-U-01 and 16-35% (mean value 24%) for site 7230/05-U-01.

The weighted thermal conductivity gives the best fit to the trend of the theoretical curves. This data also fits in the scatter in measured thermal conductivity, considering the quartz content given above. The plots of horizontal and vertical thermal conductivity versus water content give a higher scatter and lie above and below the theoretical curves respectively. This would be expected if the thermal conductivity of the soil is anisotropic. (Note however that the latter parameter is a function of the former and the horizontal conductivity and therefore automatically will

plot low on the diagram if the horizontal conductivity plots high.)

A similar relationship is found in the plots of computed, theoretical thermal conductivity versus horizontal-, weighted- and vertical thermal conductivity (Figure 4.3).

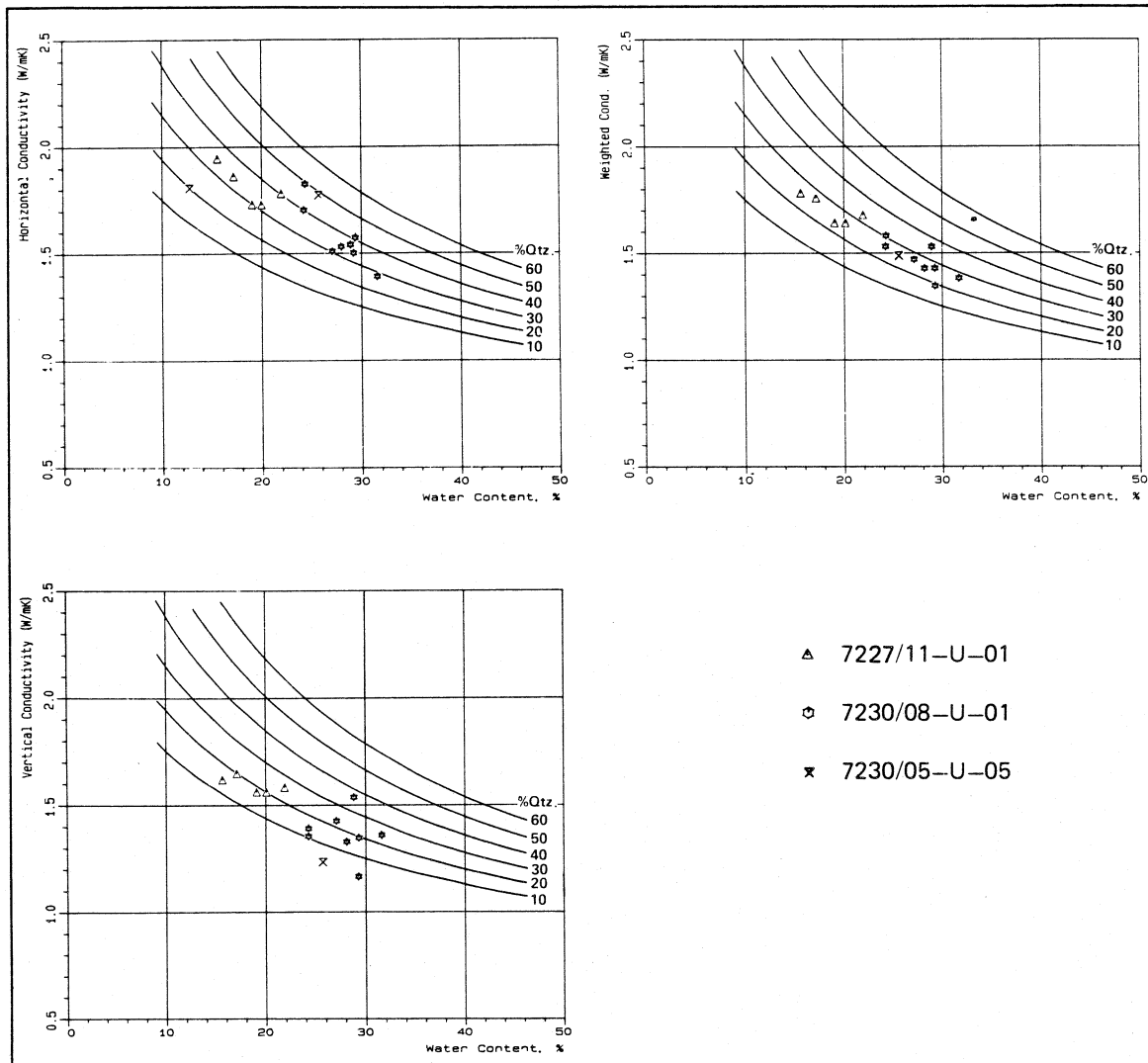


Figure 4.2 Thermal conductivity versus water content. The curves show the theoretical relation for isotropic sediments with different quartz contents.

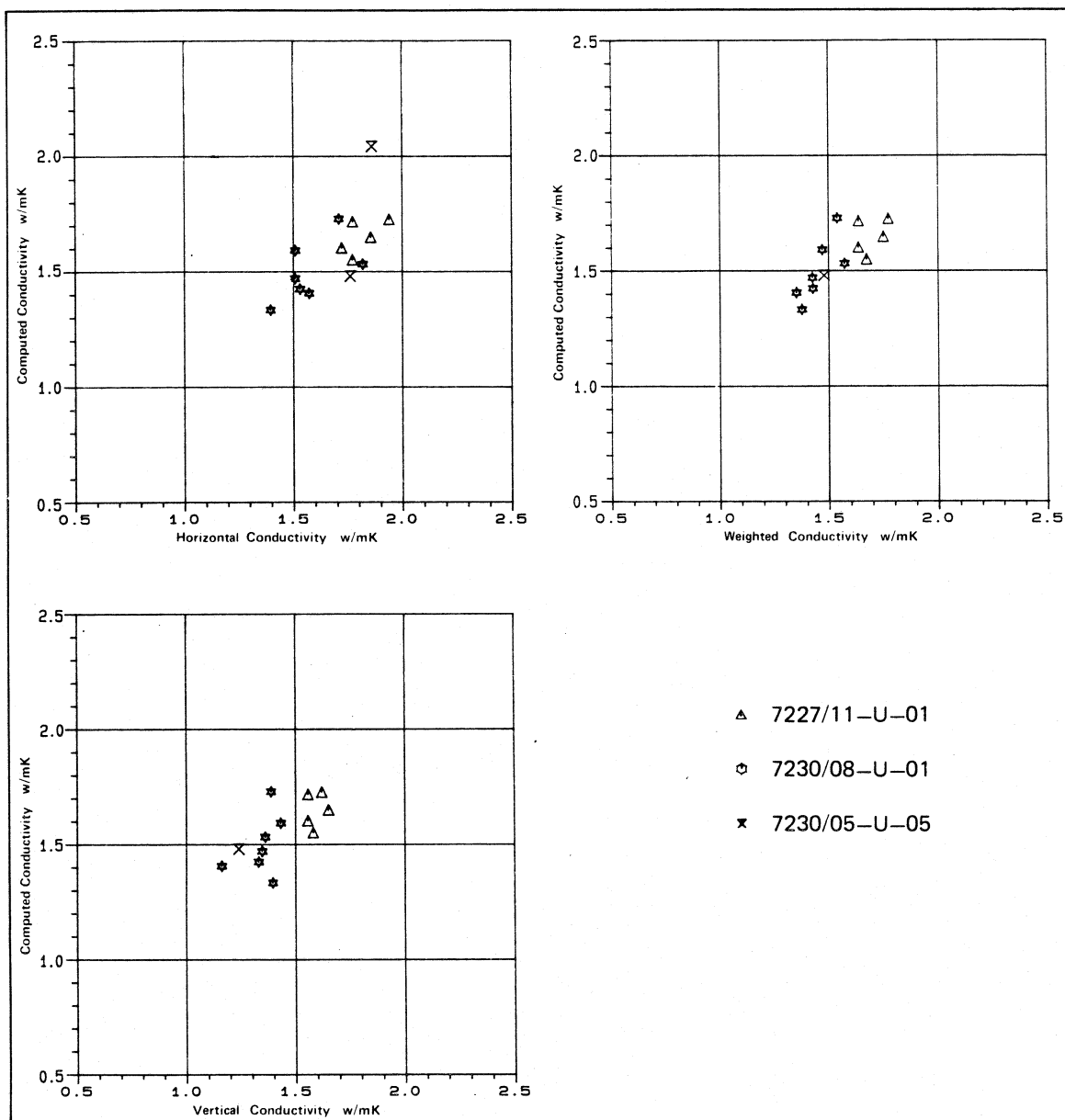


Figure 4.3 Horizontal-, weighted- and vertical thermal conductivity versus theoretical thermal conductivity based on sediment composition.

4.5 Discussion of results and determination of mean vertical thermal conductivity values

4.5.1 Calculation of average thermal conductivity values

In Chapter 3 we established depth intervals across which the temperature gradients were defined for each site. From Tables 4.1 and 4.2 and Figures 4.4, 4.5 and 4.6, thermal conductivity can be determined across the

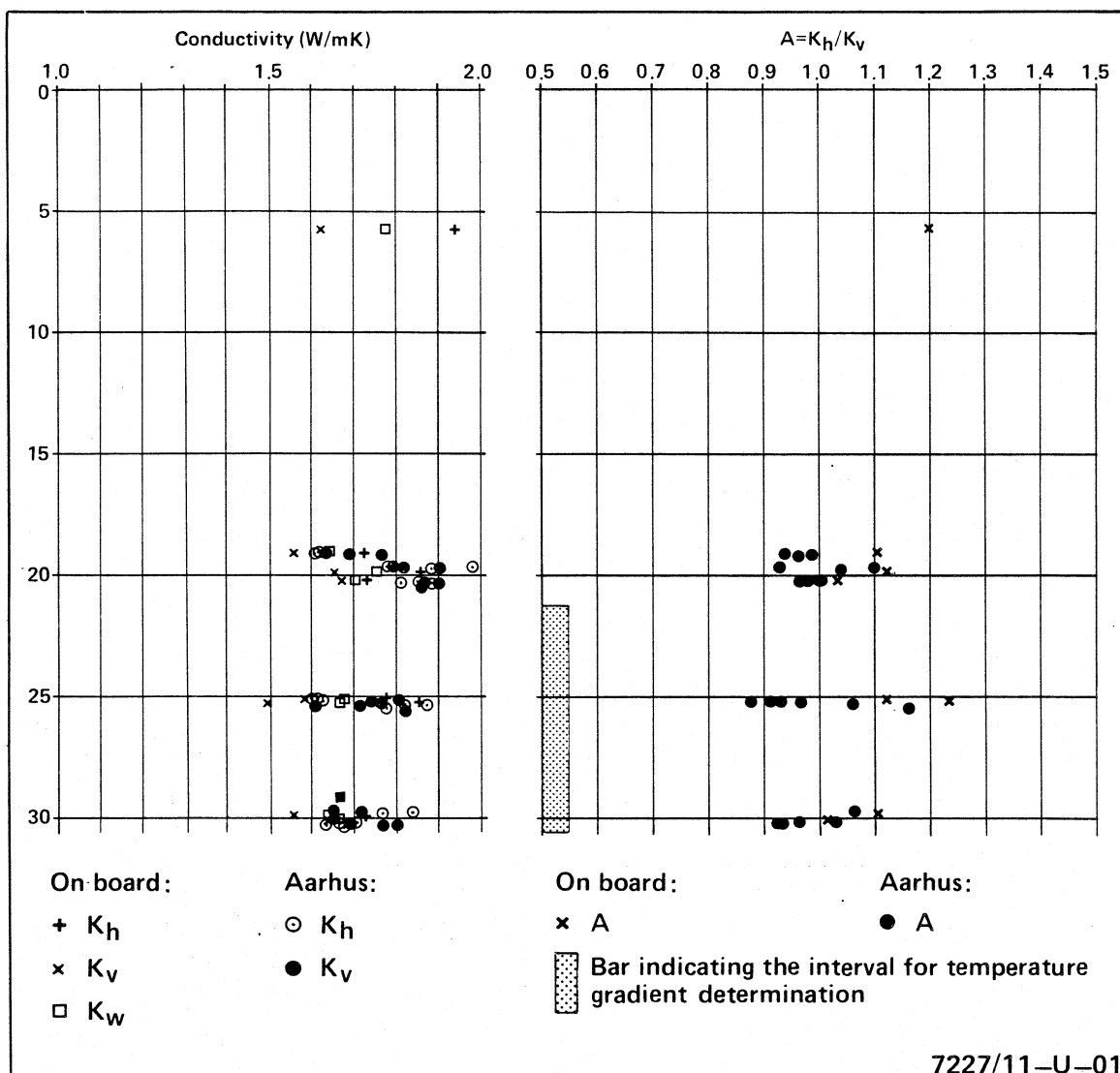


Figure 4.4 Thermal conductivity data from site 7227/11-U-01. Explanation to abbreviations are given in the text.

corresponding depth intervals. The result of this is shown in Table 4.5. Note that the numbers in () here refer to number of datapoints along the depth axis and that in the on board measurements each datapoint is the mean of three readings, whereas the Aarhus data are mean values of 3 - 5 readings. The values influenced by rock fragments or regarded as unreliable are not included in the average values used for heat flow calculation.

From Table 4.5 it is seen that the mean K_h - values from the on board measurements and from Aarhus correspond excellently. The biggest difference

is found in the data from site 7230/05-U-05 and even in this case the mean value from the Aarhus data is less than 2% lower than the mean value from the field data.

Table 4.5 Thermal conductivity data (W/m K) across chosen depth intervals for the 1987 heat flow sites ($A = K_h/K_v$ is dimensionless).

7227/11-U-01 (Depth interval 19.14m - 30.16m)						
Field measurements				Measurements in Aarhus		
K_h	K_v	A	K_i	K_h	K_v	A
1.75 [.07] (11)	1.62 [.05] (5)	1.08 [.04] (5)	--	1.74 [.12] (21)	1.75 [.09] (21)	0.99 [.07] (21)
Including measurements influenced by rock fragments (see text)						
1.76 [.08] (13)	1.59 [.06] (7)	1.11 [.07] (7)				

7230/08-U-01 (Depth interval 14.34 m - 24.90 m)						
Field measurements				Measurements in Aarhus		
K_h	K_v	A	K_i	K_h	K_v	A
1.51 [.05] (19)	1.32 [.09] (8)	1.15 [.10] (8)	1.59 [.02] (2)	1.49 [.04] (12)	1.40 [.07] (12)	1.07 [.07] (12)
Including measurements influenced by rock fragments (see text)						
	1.36 [.11] (10)	1.13 [.11] (10)				

7230/05-U-05 (Depth interval 12.15 m - 17.11 m)						
Field measurements				Measurements in Aarhus		
K_h	K_v	A	K_i	K_h	K_v	A
1.74 [.07] (7)	1.31 [.07] (3)	1.35 [.07] (3)	1.74 [.03] (3)	1.71 [.08] (9)	1.44 [.13] (9)	1.20 [.12] (9)
Including one value regarded as unreliable						
1.79 [.16] (8)						

The values in [] are standard deviation of the datapoint distribution which frequently is used to quantify the scatter in a dataset. In the present case this parameter should, however, be used with caution. None of the datasets from the three sites do necessarily have a standard Gaussian distribution as the main cause for the scatter probably is the internal variability in thermal property of the three sediment columns rather than scatter due to limitation in the measurement technique. In Figure 4.7 the distribution in the datasets is shown by plotting histograms of number of datapoints within 0.05 W/m K intervals for each site. This illustrates the correlation found between K_h - values from on board measurements and values from Aarhus. The K_v - values do, however, differ somewhat. This difference is further discussed below.

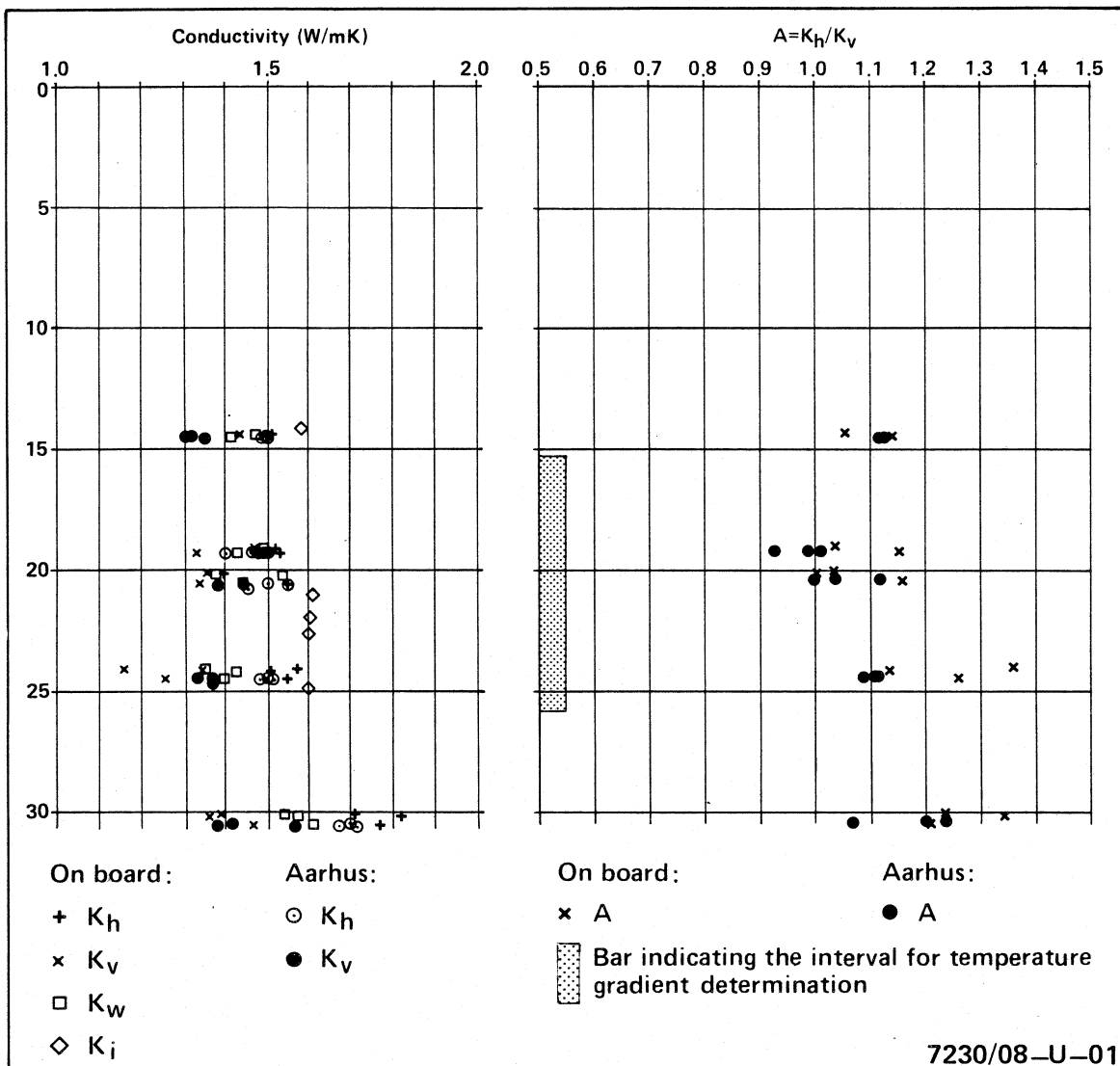


Figure 4.5 Thermal conductivity data from site 7230/08-U-01. Explanation to abbreviations is given in the text.

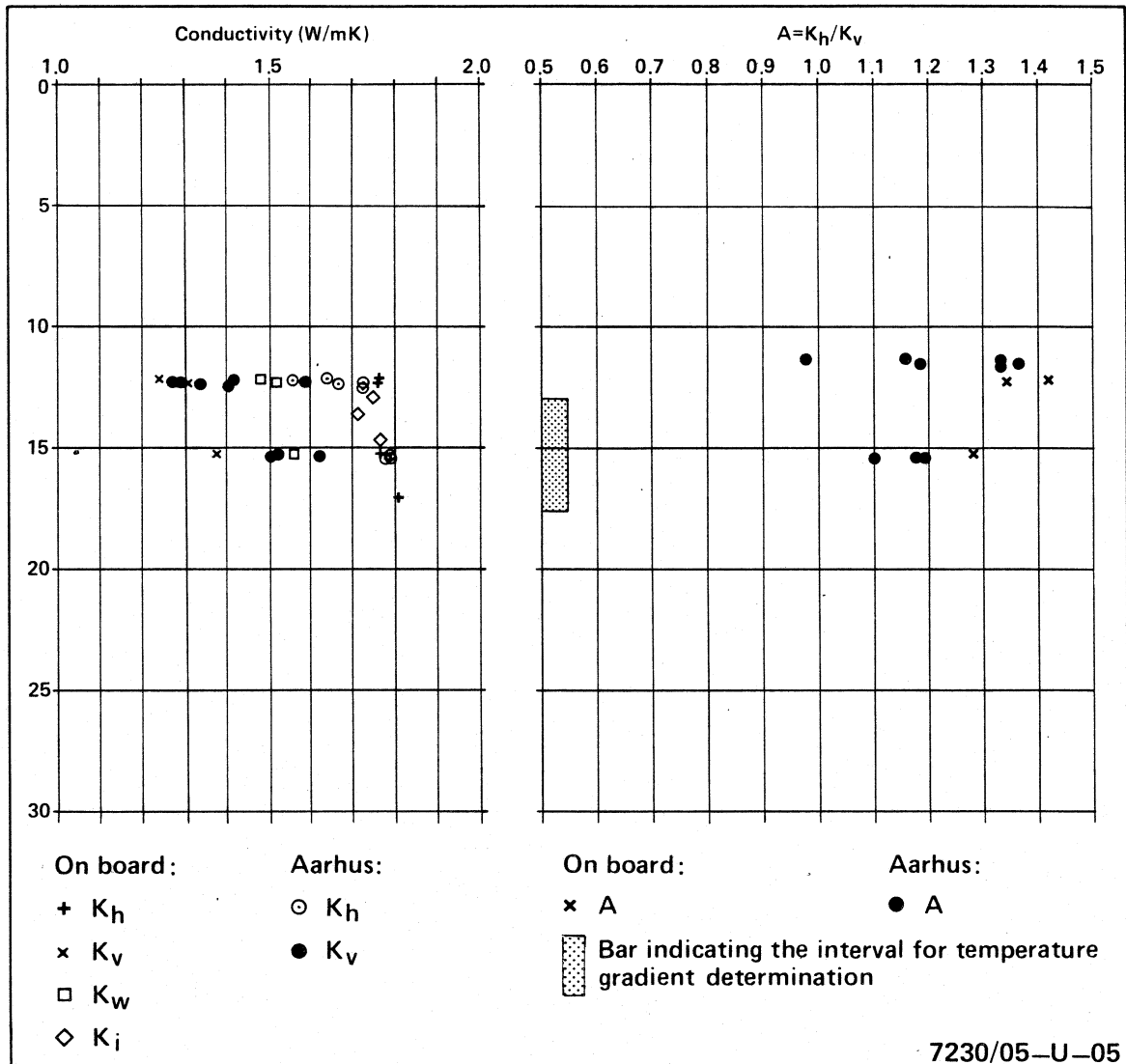


Figure 4.6 Thermal conductivity data from site 7230/05-U-05. Explanation to abbreviations is given in the text.

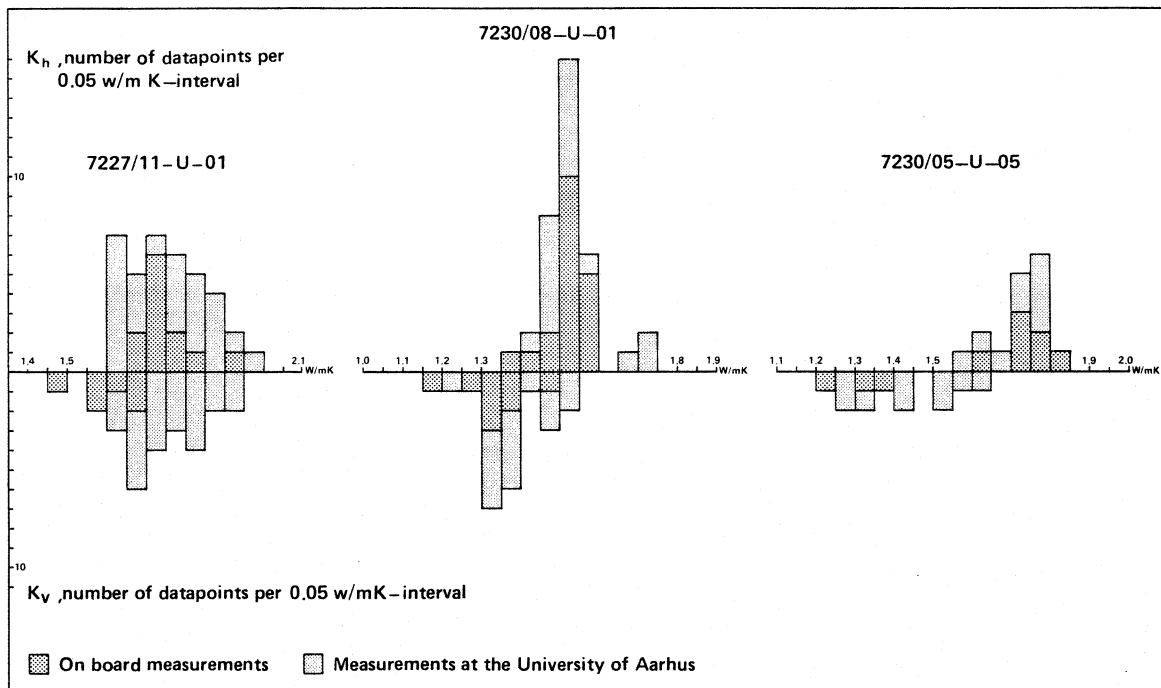


Figure 4.7 Histograms showing number of datapoints within 0.05 W/m K - intervals for the different K_h and K_v - datasets. Unreliable datapoints are omitted (see text).

4.5.2 Anisotropy of thermal conductivity

Numerous papers and reports describe anisotropy of the thermal conductivity of sedimentary rocks. The possible presence of this effect in Quaternary sediments has, however, generally been neglected (Balling pers. comm. 1986).

Penner (1963) has described anisotropic thermal conductivity in Cretaceous marine shales and in postglacial marine and lacustrine clays from Canada. In the marine postglacial clay (which would correspond closest to the sediments in the Barents Sea) he found a coefficient of anisotropy of 1.05 - 1.20 with an average value of 1.13. This also relates well with previous experience from IKU heat flow studies in the Barents Sea, indicating presence of variable degree of anisotropy, but with a typical value of K_h/K_v between 1.0 and 1.1 (e.g. Sættem 1988).

The values from the measurements on this years samples made on board by Fugro-McClelland, and later in the laboratory in Aarhus, show a systematic difference in the coefficient of anisotropy, the former values being 7 - 10% higher. We attribute this to an unfavourable geometry during the

measurement with the needle perpendicular to the sample axis in the on board tests. Boundary effects from part of the needle being in air when the perpendicular measurement were made have caused too low values in these measurements. The effect of this may be most significant for site 7227/11-U-01 where the Quaternary samples have a diameter of 63 mm. At sites 7230/05-U-05 and 7230/08-U-01 all the samples have a diameter of 71 mm. This is further discussed in Appendix I, and we conclude that the vertical thermal conductivity calculated from the on board data should be increased by approx. 8% for site 7227/11-U-01 and by 4% for sites 7230/08-U-01 and 7230/05-U-05.

Application of these corrections to the datasets from the three sites gives values that correspond to the results from Aarhus within 0.5%, 2% and 5.5% respectively.

4.5.3 Mean vertical thermal conductivity

From the results discussed above we conclude that anisotropy in the thermal conductivity is present in the samples from the two sites in block 7230 whereas the samples from site 7227/11-U-01 have isotropic thermal conductivity. The mean thermal conductivity values found for the three sites is summarized in Table 4.6.

When evaluating the confidence of the data three factors must be considered, namely:

- accuracy and resolution of the needle probes,
- variability in the soil properties and sample representativity,
- confidence in the determination of the anisotropy.

An important question is whether the sample representativity and datapoint density is sufficient to precisely define a correct average thermal conductivity value for the three sediment columns. We believe that the fairly high number of measurements and the good correlation between K_h measured on board and in Aarhus, which were done on two different selections of samples, positively verifie this.

The accuracy of the needle probe method is discussed in Appendix I. In the literature the precision of this method is evaluated to be within $\pm 5\%$,

probably better than $\pm 3\%$.

The thermal conductivity values presented in Table 4.1 are mean values of three measurements with the probe in the same position. The maximum difference within each set of readings is typically less than 3% of the absolute value but may occasionally be as high as 13%. We conclude that in general the given individual value in Table 4.1 is correct within $\pm 5\%$, and for most of the data to within $\pm 3\%$.

Systematic errors (i.e. calibration errors) are concluded to be insignificant due to the favourable comparison of K_h -values from the different datasets, and of K_w -values to the theoretical conductivity.

The variability in the thermal conductivity of the soil can be evaluated from the tables and figures given in this chapter. The bulk part of the datapoints generally plots within $\pm 5 - 10\%$ of the average value for each site (Figure 4.7).

A scatter in the order of $\pm 10-15\%$ from the mean horizontal thermal conductivity is expected from the theoretical relations between sediment composition and conductivity given in Figure 4.2, given the measured variation in water content in the samples and if the quartz content is allowed to vary between 20% and 30%. If the quartz content is kept fixed at 25% the expected scatter is reduced by 50%.

The uncertainties in the calculation of K_v is discussed extensively in Section 4.5.2 and in Appendices I and II. From this discussion we conclude that boundary effects during the on board tests should be accounted for. This gives agreement also in the K_v -values from two of the sites whereas the K_v -value from Aarhus for site 7230/05-U-05 is approx. 5.5% higher than the K_v -value calculated from on board measurements. The K_v -values from Aarhus are used in Table 4.6.

Table 4.6 Mean vertical thermal conductivity for calculation of heat flow and mean horizontal thermal conductivity at the 1987 IKU heat flow sites. K_h is the average from both on board values and values from Aarhus. A and K_v is based only on the values from Aarhus. The numbers in parenthesis indicate the interval defined by $\pm$ the standard deviation of mean values. The confidence in the K_h values are discussed in the text.

Site	Thermal conductivity		
	K_h (W/m K)	$A = K_h/K_v$	K_v (W/m K)
7227/11-U-01	1.75	0.99	1.75 (1.73-1.77)
7230/08-U-01	1.50	1.07	1.40 (1.38-1.42)
7230/05-U-05	1.73	1.2	1.44 (1.40-1.48)

The uncertainty of the average values is given as $\pm$ the standard deviation of the mean values (calculated as $s/n^{\frac{1}{2}}$, s and n are the values in [] and () brackets respectively in Table 4.5). The confidence intervals are given in Table 4.6. Similar confidence intervals are also calculated for the K_h -values (± 0.02 W/m K for sites 7227/11-U-01 and 7230/05-U-05 and ± 0.01 W/m K for site 7230/08-U-01). As discussed previously the standard error of the K_h -values (Table 4.5) is, however, rather an expression of the variability in the soil more than of measurement uncertainties, and we find this uncertainty insignificant.

5. FINAL HEAT FLOW VALUES

5.1 Temperature gradient data

5.1.1 Corrections for perturbations in measured temperatures due to the late Quaternary history

Supracrustal geological processes and climatic changes will cause variations in the boundary conditions for heat flow through the earth's crust.

The transient effect on the present vertical heat flow from previous climatic changes will vary with depth as a function of the time span since the events occurred and of the actual temperature amplitudes involved.

Therefore, in order to be able to compare the heat flow data collected in the present project (15-40 m below the seabed) with similar data from exploration wells (2000-4500 m below the seabed) it is necessary to apply a correction model which implies none or negligible corrections at an average well depth of 2000-3000 m.

Werner (1985) related a time span of 200 000 years to a depth range of 10 km. Nielsen & Balling (1985) showed an example where the effects from a temperature change of 10°C 10 000 years ago are totally damped at 2000 m. With the temperature amplitudes and the combinations of different temperature events through time that are used in our models, the deduced corrections to be applied at 2000-3000 m can be neglected.

Conclusively, the shallow heat flow data should be comparable to exploration well data if they are corrected for late Quaternary climatic changes according to the models below.

This effect has been studied in the heat flow investigations done by IKU in the Barents Sea since 1985, and based on inferred temperature fluctuations during the last 250 000 years, different amount of climatic transient effects have been calculated. The calculations are performed at the Geophysical Laboratory, Department of Geology at the University of Aarhus in Denmark.

The inferred temperature fluctuations are deduced from assumptions about periods of glaciations in the area alternating with periods with temperature conditions similar to the present. The present temperature is found by extrapolating the measured temperatures in the boreholes to the seabed, and the temperatures during glaciations are found by inferring realistic average ice sheet thicknesses for each site and assuming that the ice sheet at the base were at the melting point.

Two alternative models have been considered, one resulting in believed maximum effect on the measured temperature gradients and one resulting in believed minimum effect on the measured temperature gradients. The two models assume different duration of each glaciation and different ice sheet thickness. These two variables are combined to obtain maximum and minimum effect. A complete description and discussion of the temperature models is not included here. The corrections given in Table 5.1 are, however, based on the models and work described above and the actual present mean annual seabed temperature at each site is considered in the suggested corrections.

There are considerable uncertainties both in ice sheet thickness, basal temperatures and ice sheet extent during the glaciations. We have furthermore not accounted for episodes of erosion and deposition within the temperature history time interval. Until the knowledge about the Quaternary history for the region is improved, however, the recommended corrections are realistic approximations.

Furthermore, the assumptions behind the estimated corrections may be equally valid for the different sites, and therefore the uncertainty in the corrections can be neglected when comparing data from the different sites.

Table 5.1 Suggested corrections for transient effects on the present temperature gradient based on two alternative glaciation models.

Site	Correction 10^{-3} K/m	
	Minimum glaciation model	Maximum glaciation model
7227/11-U-01	3.4	6.2
7230/08-U-01	3.1	5.4
7230/05-U-05	2.7	4.8

5.1.2 Final temperature gradients

From a combination of Table 3.1 and Table 5.1 we arrive at the corrected final temperature gradient values given in Table 5.2.

We recommend that the minimum climatic correction model is applied. If, however, the maximum correction model is chosen, it should be used for all sites.

Table 5.2 Final temperature gradients for the 1987 heat flow sites corrected for climatic perturbations based on the recommended minimum correction model. The values in brackets are corrected by the maximum correction model.

Site	Temperature gradient (10^{-3} K/m)		
	Recommended value	Lower limit	Upper limit
7227/11-U-01	26.2 (29.0)	24.1 (26.9)	28.3 (31.1)
7230/08-U-05	38.7 (41.0)	38.3 (40.6)	39.6 (41.9)
7230/05-U-01	72.0 (74.1)	68.7 (70.8)	75.4 (77.5)

5.2 Thermal conductivity data

Table 4.6, Section 4.5.3 summarizes the results of the thermal conductivity investigations.

The thermal conductivity is calculated as the arithmetic mean across the same intervals that the temperature gradients are determined for.

Vertical thermal conductivity at site 7227/11-U-01 is 1.75 W/m K (1.73-1.77 W/m K).

Vertical thermal conductivity at site 7230/08-U-01 is 1.40 W/m K (1.38-1.42 W/m K).

Vertical thermal conductivity at site 7230/05-U-05 is 1.44 W/m K (1.40-1.48 W/m K).

5.3 Heat flow calculation

Final heat flow values are calculated from the thermal conductivity data summarized in Section 5.2 and the temperature gradients given in Table 5.2. The values in Table 5.3 are all based on the recommended minimum climatic correction model.

Table 5.3 Final heat flow values for the 1987 IKU heat flow sites. Upper and lower limits are obtained by combining upper and lower limits of both thermal conductivity and temperature gradient simultaneously. Minimum model of climatic correction is assumed.

Site	Heat flow (mW/m ²)		
	Recommended value	Lower limit	Upper limit
7227/11-U-01	45.9	41.7	50.1
7230/08-U-01	54.2	52.9	56.2
7230/05-U-05	104	96.2	112

The uncertainty intervals given in Table 5.3 are calculated from the most unfavourable combinations of uncertainties in upper and lower temperature/depth points in the temperature gradient data together with upper and lower boundaries in the thermal conductivity values. The boundaries are therefore at a fairly high level of confidence.

6. HEAT FLOW MODELLING

6.1 Introduction

Shallow heat flow measurements on top of salt structures are expected to show high values due to focusing of heat flow caused by the high thermal conductivities of salt compared to sediments, particularly at shallow depths. In order to derive the undisturbed heat flow, i.e. the heat flow at more than 25 km depth, the heat flow anomaly caused by the salt structure must be modelled. Ideally heat flow caused by convection and conduction should be modelled in three dimensions, but for the elongated structure on which the heat flow measurements has been performed, modelling of heat flow in two dimension (horizontal and vertical) is sufficiently accurate. Heat transfer caused by convection is not possible to model within the scope of this project.

A model of salt geometry is constructed from seismic interpretation. Properties (density contrasts) of the model are deduced from gravity modelling. The density contrasts are used to infer the thermal conductivity distribution for the model. Thus, the heat flow anomalies can be modelled and compared to the measured shallow heat flow.

6.2 Mapping of salt structures

6.2.1 Seismic Interpretation

The Nordkapp Basin is described on several occasions in literature (Rønnevik et al. 1982; Faleide et al. 1984 and others). So far no decisive answer is given to the age of the salt in the Nordkapp Basin. Ages ranging from Carboniferous to Lower Permian are the most common suggestions. There has also been speculated in whether salt occurs in more than one level. On the eastern/southern side of the basin one can observe features looking like salt pillows in the Lower Permian section. This is indicated by an "A" in Figure 6.1, where a schematic cross section of line NPD 3030-76 is shown. Below this interval several sequences that change rapidly in thickness are seen. Some of these might be associated with salt intervals ("B" and "C" in Figure 6.1). Closer to the salt dome there can be seen some strongly divergent reflections ("D"). It is reasonable to assume that the

interval between these two reflections is the main source for the salt.

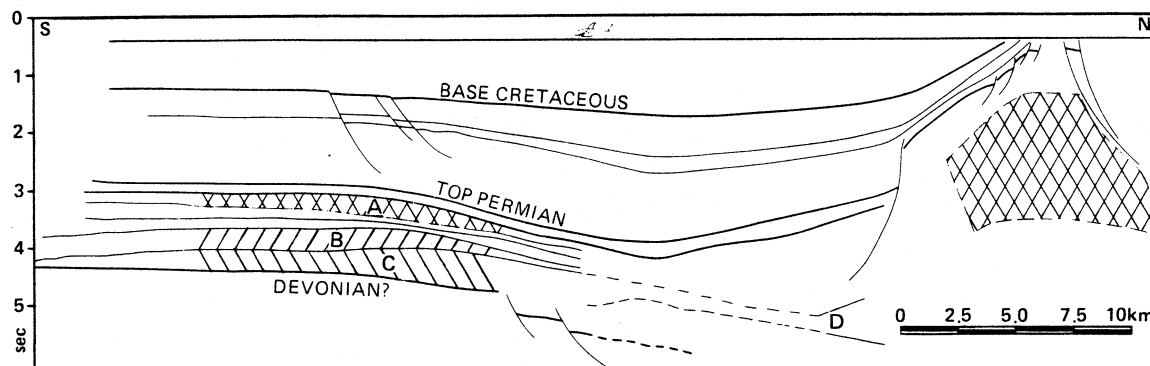
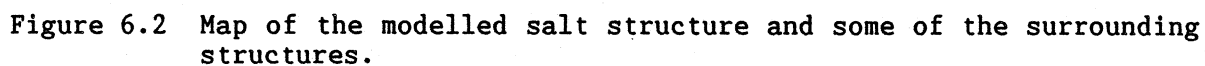


Figure 6.1 Schematic cross section from line NPD 3030-86.

Because of limitations in data quality it is difficult to comment on the age of this interval, but it seems quite obvious that it must be older than the salt pillow observed on the flank. The lowermost reflection which might coincide with the horizon H mapped by Rønnevik et al. (1982), seems to be faulted down in several steps into the basin, leaving space for the increased thickness in the Carboniferous and Permian sediments. Consequently, one might conclude that if the salt in the Nordkapp Basin salt structures is sourced from only one interval, this interval must be older than the pillow-like features that we can observe on the flank of the basin, and therefore of Carboniferous rather than Permian age.

Across the salt structure where the heat flow site 7230/05-U-05 is located, a substantial throw at the Upper Jurassic level is observed. This indicates that faulting occurred in association with the salt movements (line IKU 302230-87, Figure 2.4). Further, it is possible that the fault plane constitutes a boundary for the salt body on the northern flank. On other flanks the extent of the salt body is set to where the reflections seem to terminate. This must be considered as the maximum extent of the salt body. The map in Figure 6.2 shows the width of the salt body. Comparing with some of the surrounding structures, the faulting seems to have made the main structure more complicated than the others. The fault seems to split the structure in two parts, one N-S trending and one SW-NE trending part. The main fault seems to turn north between line 3030 and 303730, as there on line 303730 is no difference in the Jurassic level on the two sides of the



structure. The fault pattern seen on this line looks more like a collapse structure.

The base of the salt is not simple to identify, but there is, at a certain level some change in the energy pattern that might be caused by reflections from below the salt. In this case the salt body is detached from the original salt interval, while some salt may still be left at the original level; a possibility that is indicated in the interpreted section used for gravimetric modelling (Figure 6.4).

Another remarkable feature that is observed on many of the salt structures, is the pronounced asymmetry. On one side of the salt domes, a "shoulder"-like feature is present. On the updip side of this "shoulder", the Triassic sequence thickens, suggesting that the "shoulder" may have been the crest of a salt dome in Triassic time (Figure 6.3). It is an accepted theory that the salt has moved in two distinct phases (Triassic and Late Cretaceous/Tertiary) (Jensen and Sørensen 1988) and that the last phase was initiated by a major tectonic event. This event may have caused faulting along a zone of weakness at the flank of the original salt domes. The salt movements will then be associated with the fault planes, and explain the present geometry of the salt structures.

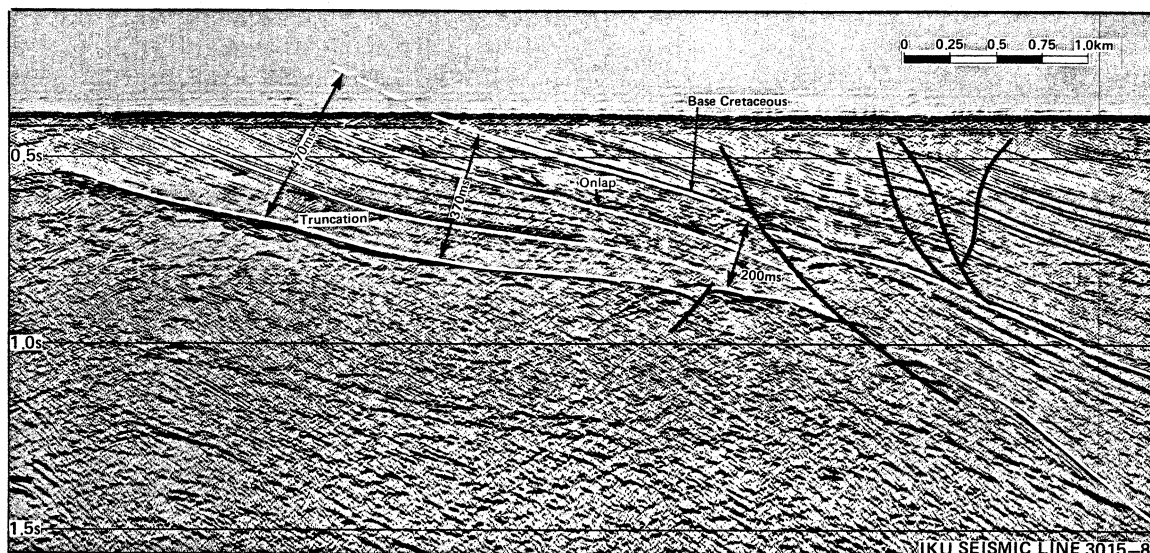


Figure 6.3 Part of line IKU-3015-87 indicating the thickness of the Triassic section towards the crest of the salt structure.

6.2.2 Gravity modelling

From the seismic interpretation, two depth converted cross-sections along lines 302230 and 3015 are constructed (Figure 6.4 and Figure 6.5). A number of bodies with density contrasts to an assumed "regional density model" are used as input to the gravity modelling. The regional model is constructed by extrapolation of the geological conditions from outside the basin.

The salt pushes up denser material and therefore the geometry consists of a mixture of bodies with positive and negative density contrasts. The local gravity anomaly is computed by extrapolation of the regional trend from undisturbed strata away from the salt and subtraction of this from the measured values.

The gravity anomalies caused by the salt-induced structures are calculated by means of a 2.5 dimensional (2.5D) gravity modelling program (Enmark 1981) modified to run on the VAX computers at IKU. In 2.5D modelling, the structure is modelled in the vertical cross-section on which the gravity anomaly has been measured. The anomalous densities are specified as a set of bodies, each consisting of a polygon in the cross-section and a width

associated with the third dimension. A gravity anomaly can be caused by an infinite number of structures in the subsurface, hence gravity is only used to check and calibrate the model obtained from interpretation of the reflection seismics. The properties assigned to the bodies of the two seismic lines on which gravity has been modelled, are shown in Table 6.1.

Figures 6.6 and 6.7 show the modelled gravity anomalies and those deduced from gravity measurements. Several attempts were made to increase the density contrasts in the shallower parts of the salt bodies. However, a shallow increase in density contrasts causes the gravity anomalies to be much more pronounced whereas the width of the anomaly is reduced. It is therefore concluded that the amount of salt present cannot be increased significantly beyond the masses proposed here if the constraints imposed by the observed gravity anomaly is not to be violated.

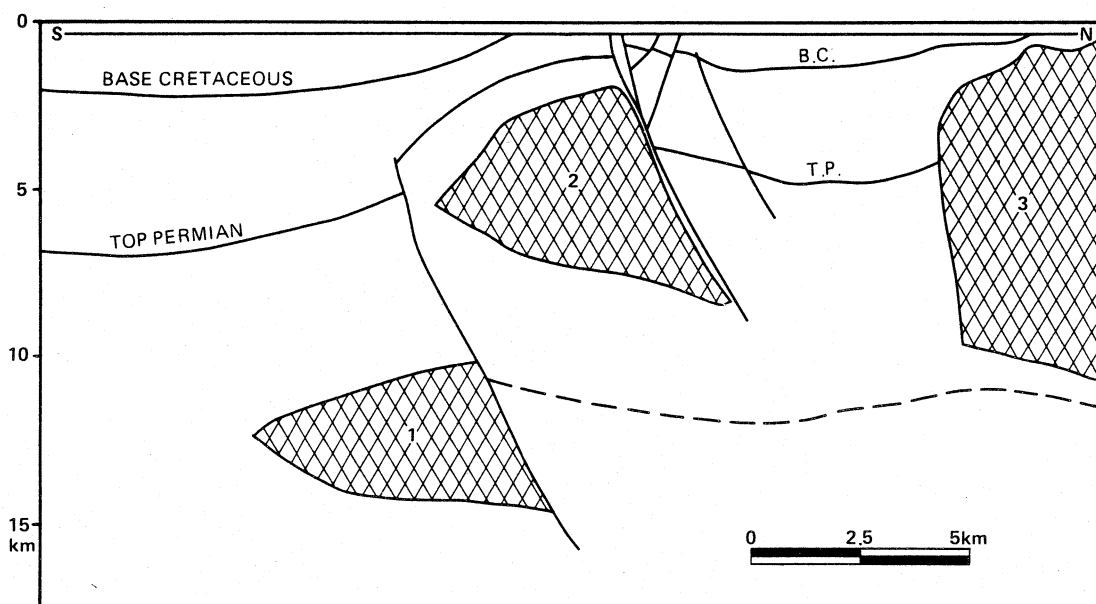


Figure 6.4 Depth converted section from line NPD 302238-86 used as input to gravimetric modelling. 1: Volume of remaining salt in the original salt level. 2: Main salt body. 3: Salt dome north of the modelled structure.

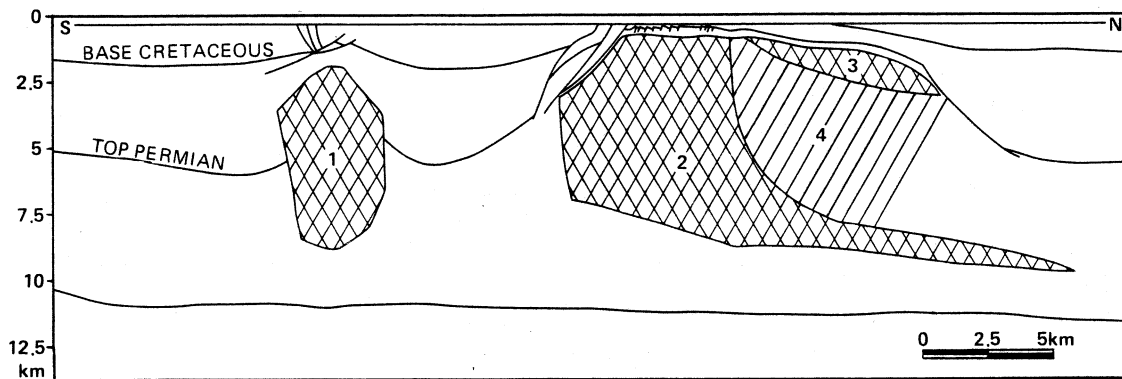


Figure 6.5 Depth converted section from line NPD 3015-85. 1. Small salt dome south of main structure. 2: Main salt body (could be detached from original deposition level). 3: "Shoulder" - remnant of Triassic salt dome? 4: Body with probably less salt than main body (more reflection energy).

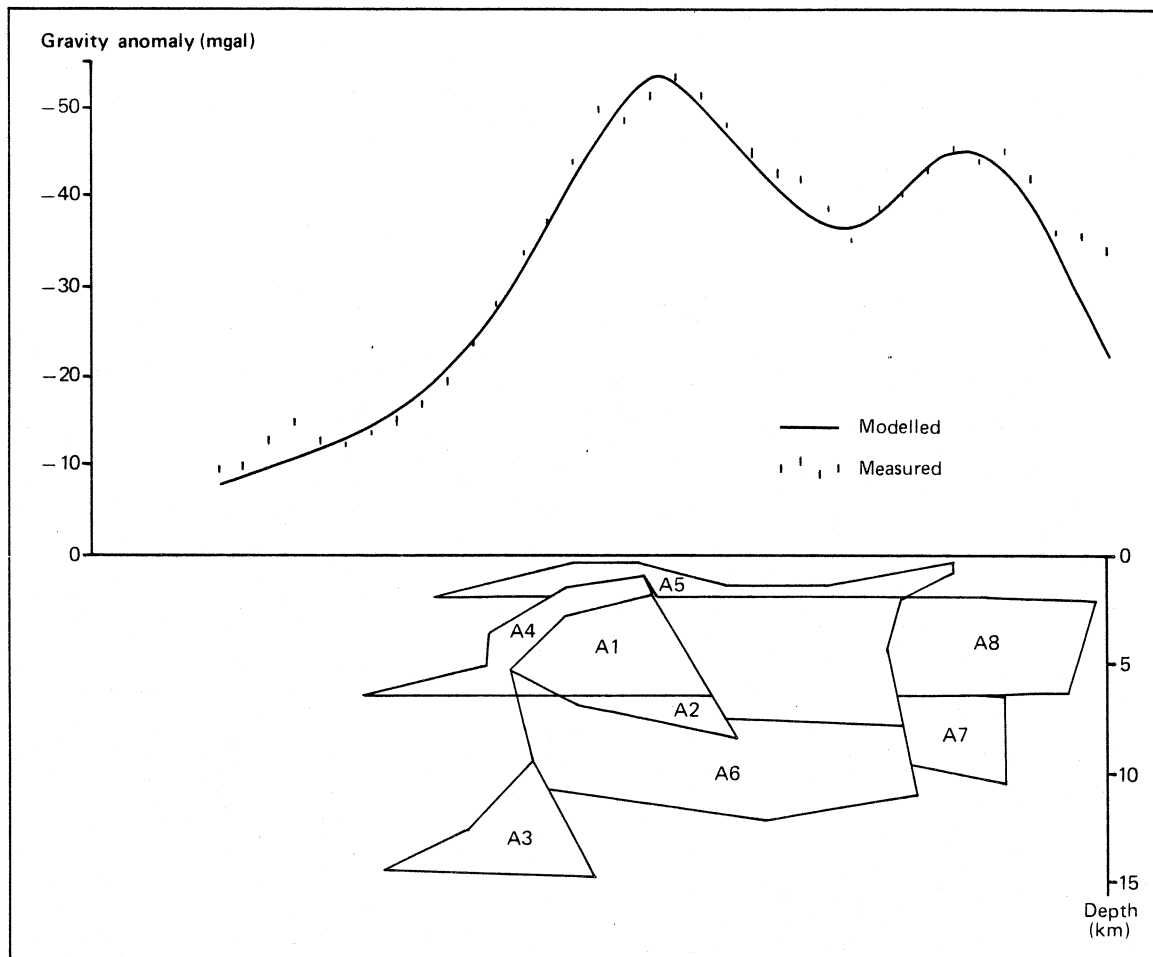


Figure 6.6 Modelled gravity anomaly along seismic line 302230 based on the seismic interpretation shown in Figure 6.4. Properties assigned to the bodies termed A1 - A8 are given in Table 6.1.

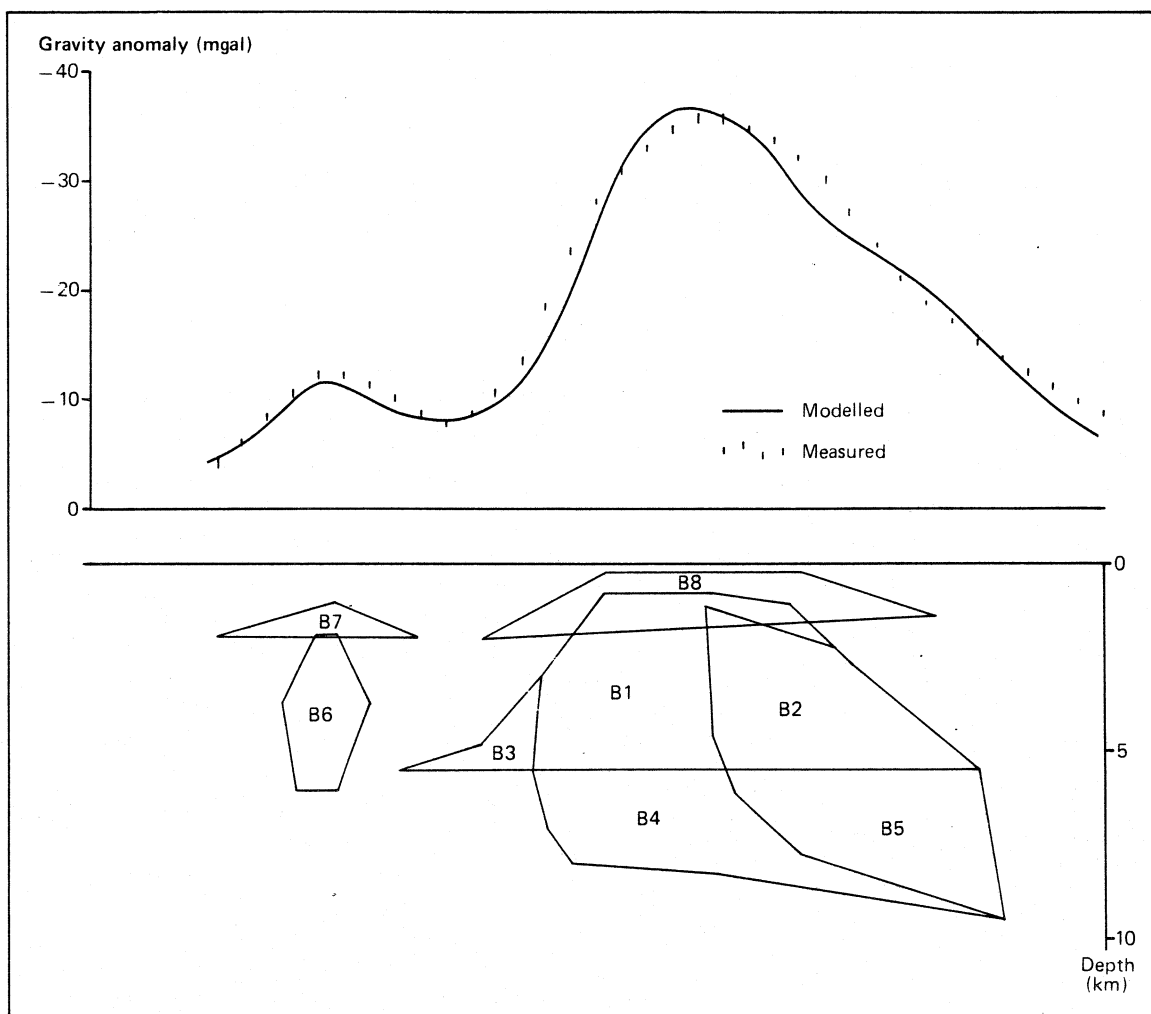


Figure 6.7 Modelled gravity anomaly along seismic line 3015 based on the seismic interpretation shown in Figure 6.5. Properties assigned to the bodies termed B1 - B8 are given in Table 6.1.

Table 6.1 Body definitions for gravity modelling.

Body	Width (m) *		Density Contrast (kg/m ³)	Comments
	From	To		
A1	-4000	6000	-80	Salt used in heat flow modelling
A2	-4000	6000	-100	
A3	-4000	6000	-160	
A4	-5000	7000	60	
A5	-5000	7000	10	
A6	-2000	4000	-60	
A7	-3000	5000	-30	
A8	-4000	6000	-60	
B1	-1000	500	-100	
B2	-1000	1000	-60	
B3	-1000	1000	120	
B4	-1000	500	-250	
B5	-2000	1000	-220	
B6	-1000	1000	-230	
B7	-2000	2000	80	
B8	-2000	2000	25	

* width is perpendicular to the seismic section (total width of body is 10 000 m).

A: line 302230 (Heat flow is measured on this line)

B: line 3015

From the map in Figure 6.2 it is easily understood that the widths of the salt bodies caused by line 3015 are significantly less than the ones mapped by line 302230. The salt boundary is not very well defined to the west due to lack of data. Thus the larger apparent density contrasts inferred for line 3015 may be due to inaccurate mapping. A doubling of the width of the salt bodies along line 3015 would compensate for halving the density contrasts. The definition of the width of the salt bodies along line 302230 is made with a much higher confidence due to better seismic coverage.

The density of salt is set to 2.15 g/cm³ (Figure 6.8), whereas for the sediments a minimum and a maximum density-versus-depth function is used.

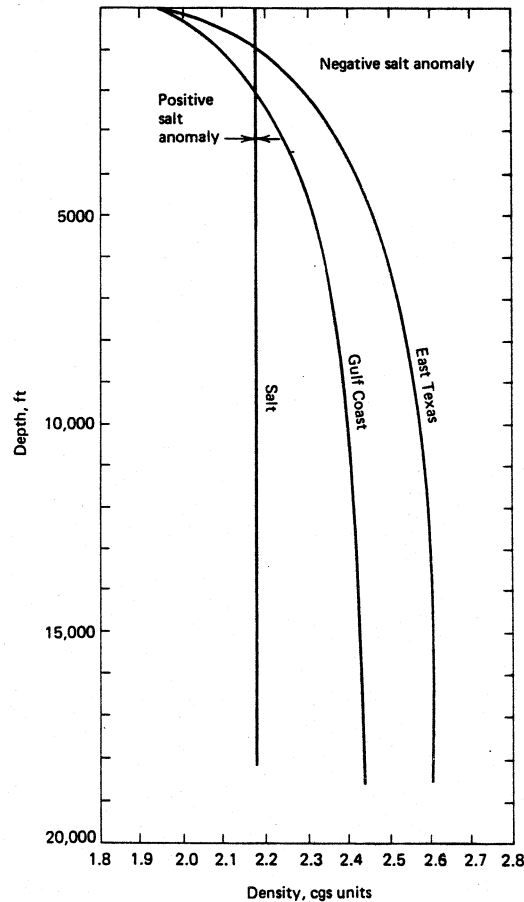


Figure 6.8 Density versus depth for sediments in Gulf coast and east Texas (from Dobrin 1983, p. 460).

For the maximum sediment density, the east Texas curve in Figure 6.8 is used.

A minimum density versus depth curve is obtained by extrapolating measured porosity data from shallow drilling in the Nordkapp Basin into the deeper parts around the salt domes. Measured porosities average approximately 30% for Mesozoic sediments. In the rim synclines, these sediments are at an average depth of 3 km. The center of the salt body A1 (Figure 6.6), is at a depth of 4.5 km. Extrapolation of the porosity from 3 km to 4.5 km can be achieved by means of a standard porosity versus depth curve. For sandstones, the relationship

$$\Theta = \Theta_0 e^{-0.39(z-z_0)}$$

can be used.

$$\Theta = \text{porosity [0.01\%]}$$

$$z = \text{depth (km)}$$

$$z_0 = \text{depth at which } \Theta_0 \text{ is measured.}$$

Then, porosity at 4.5 km becomes 17%. A sediment grain density of 2.7 g/cm³ and 17% porosity results in a bulk sediment density of 2.41 g/cm³ (see Table 6.2).

The two density versus depth curves apply only to the depth interval of the shallow salt structure (body A1 + A2). The deeper salt bodies are located in denser Palaeozoic rocks, for which a bulk sediment density of 2.55 g/cm³ (see Figure 6.8) is appropriate. In the Nordkapp Basin no samples of these rocks are available.

The gravity modelling results (Table 6.1) can be used to calculate the amount of salt present in each of the mapped bodies on line 302230 with importance to the heat flow assessment i.e. body A1 + A2 (= body A1 + body A2), A3 and A6. These "salt bodies" are believed to consist of a mixture of salt (density 2.15 g/cm³) and Palaeozoic rocks (density 2.55 g/cm³). For body A1 + A2, a minimum and a maximum amount of salt is deduced from the two density versus depth curves. The amount of salt is computed from:

$$\rho_b = (1-p)\rho_{sed} + p \rho_{salt}$$

where

$$\begin{aligned} \rho_b &= \text{bulk density,} \\ \rho_{sed} &= \text{sediment density,} \\ \rho_{salt} &= \text{salt density,} \\ p &= \% \text{ salt,} \end{aligned}$$

resulting in:

$$p = \frac{\rho_b - \rho_{sed}}{\rho_{salt} - \rho_{sed}} = \frac{\rho_b - 2.55}{2.15 - 2.55}$$

The resulting salt percentages are shown in Table 6.2.

Table 6.2 Amount of salt in "salt-bodies" determined from gravity modelling and density assumptions.

Body	Density anomaly (kg/m ³)	Background density (g/cm ³)	Bulk body density (g/cm ³)	% salt
A1 + A2	-80	2.55	2.47	25
		2.41	2.33	55
A3	-160	2.55	2.39	40
A6	-60	2.55	2.49	15

Thus, for the proposed sediment density distribution, the shallow salt structure (A1 + A2) is estimated to contain from 25% to 55% salt, mixed with heavy Palaeozoic material, whereas body A3 contains 40% and body A6 contains 15% salt. For further discussions of the somewhat low amounts of salt in the structures, see Section 6.4.

6.3 Modelling of temperature and heat flow

6.3.1 Procedure

The static temperature field in the salt structure is calculated on the basis of a number of assumptions:

1. Existence and position of material boundaries.
2. Different thermal conductivity in different bodies within the structure.
3. Fixed sea bottom temperature at 6°C. (Inferred surface temperature at heat flow site is 3.2°C but the actual temperature does not influence heat flow calculations.)

4. Vertically directed, constant heat flow is 60 mW/m^2 at a depth of 25 km.
5. Vertically directed heat flows along both vertical boundaries. The horizontal distance of the model (Figure 6.9) is 24 km.

The accuracy of the calculations are with significance only limited by the geometry partition into finite elements (mesh) (Figure 6.9) used by the calculation program. Estimation of the accuracy is normally based on making finer or coarser partitions. The time will not allow for this. Previous experience, however, indicates that the absolute accuracy of the modelled heat flows are within $\pm 5\%$ whereas errors in the sensitivity analyses are less than $\pm 1\%$.

The program used is called NRAD and is a general program for calculating two-dimensional transient heat flow in solids (Frivik et al. 1977; Frivik and Thorbergesen 1981; Thorbergesen 1986). Thus, it is not the perfect program for static problems but still applicable for these tasks, using low heat capacity values. The number of time steps needed is kept at a minimum.

Three cases have been modelled in order to define the range of possible surface heat flow that can be expected. In the modelling 60 mW/m^2 is used as heat flow at 25 km. The heat flows resulting from the modelling are normalized to this base values. This is possible due to the dimensionless form of the model being considered, i.e. the heat flow anomaly is linearly dependent on the base heat flow.

The calculations were initiated with a constant temperature gradient field of 20 K/km corresponding to the heat flow 60 mW/m^2 and a thermal conductivity of 3 W/m K . Approximately 100 time steps were needed to obtain static conditions. (Case A - see next section). The final temperature field of one case was each time used as basis for the next case, obtaining the new solutions in some 30 time steps (10 time steps were run at a time, inspecting the static convergence).

Case A is defined to give a minimum modelled heat flow anomaly using the smallest possible thermal conductivity contrasts. In case B the orientation of the bedding planes (assuming salt and other sediments to occur interbedded) was changed from being perpendicular to the heat flow (using the weighed sum of resistivities) to being parallel (using the weighted sum of conductivities). In case C the conductivity of the Palaeozoic basis

material was increased from 3.0 to 3.5 W/m K. The salt concentration of body A1 + A2 was increased to 55%.

For complete description of the cases, see Section 6.3.2.

Figure 6.9 shows the finite element mesh used. The numerical location of nodes and the composition of these into elements are listed in Appendix III.

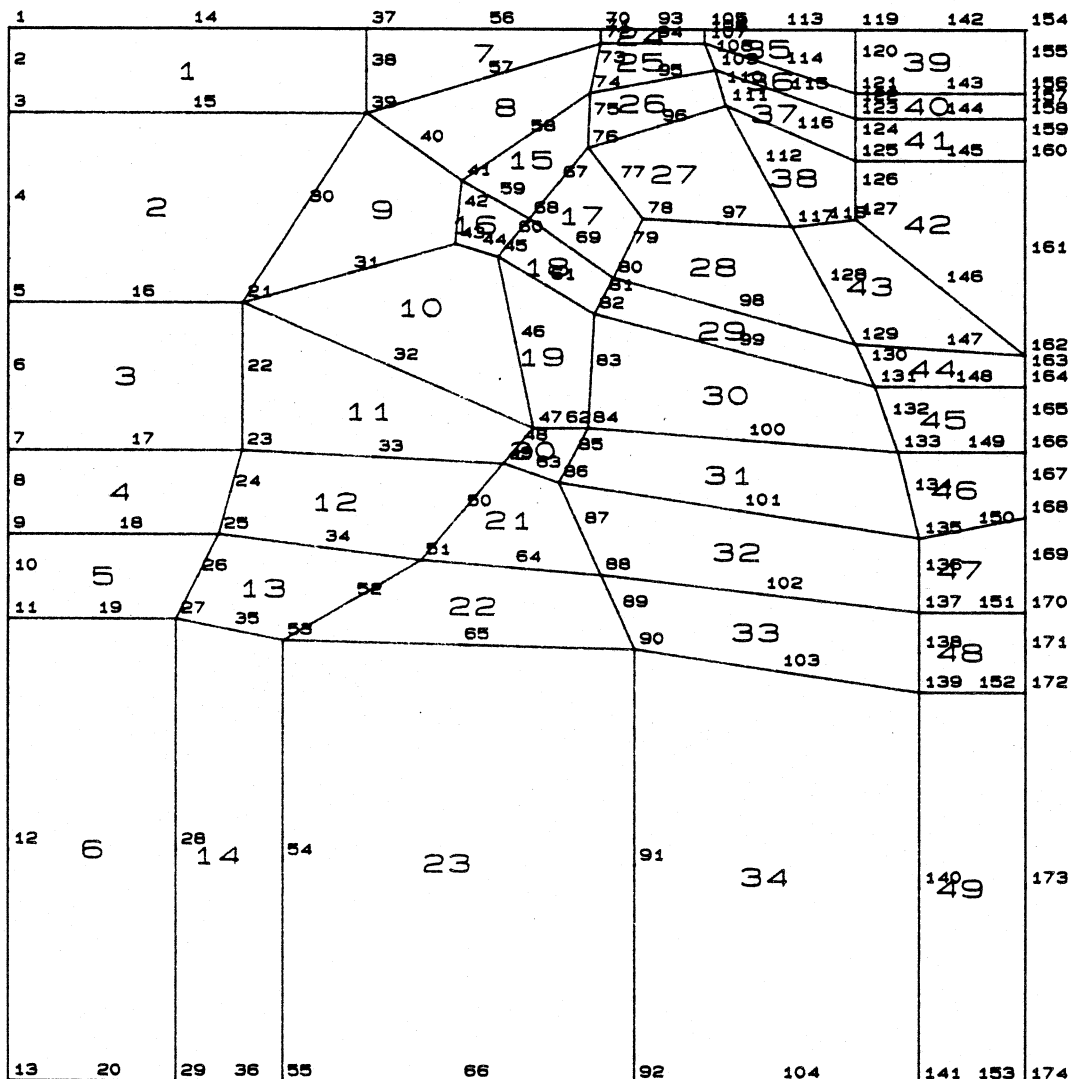


Figure 6.9 Finite Element Partition.

6.3.2 Input parameters - thermal conductivities

Thermal conductivities for rocks are mainly dependent on lithology, porosity, stratification (anisotropic effect) and temperature. From IKU shallow drilling in the Barents Sea, including the Nordkapp Basin, some knowledge of the lithology is available, in particular for the Mesozoic sediments.

Due to the large contrasts in thermal conductivity between the salt and the other sediments, particularly in the shallower sequences, the required accuracy of the thermal conductivity assessment is in the 10% range. Hence the use of constant thermal conductivities within each lithologic unit is acceptable.

The Cretaceous sediments are expected to consist of fairly uncompacted shales and sandstones and a thermal conductivity of 1.5 W/m K is used. The Mesozoic sediments, for which shallow drilling samples are available, are more compacted, but porosities in the drilled section average 30% (see section 6.2.2). Thermal conductivity measurements on these samples are not yet available, but using data from Balling et al. (1981) for sandstones, shales and siltstones a conductivity of 2.0 W/m K is chosen.

The Palaeozoic sequence consists of rocks which yield significantly higher conductivities due to a higher degree of cementation and loss of pore space. The conductivity is set to 3 W/m K in models A and B and 3.5 W/m K in model C. This corresponds to porosities from 25% to 15% for sandstones and 7% to 0% for claystones. A mixture of dense shales, sandstones and limestones/dolomites are expected to be present in the Palaeozoic.

The salt is mixed with Palaeozoic rocks, and therefore the bulk thermal conductivities of the salt structures depend both on the salt properties and on the properties of other sediments present. The thermal conductivity of salt is, as demonstrated in Figure 6.10, dependent on temperature more than composition.

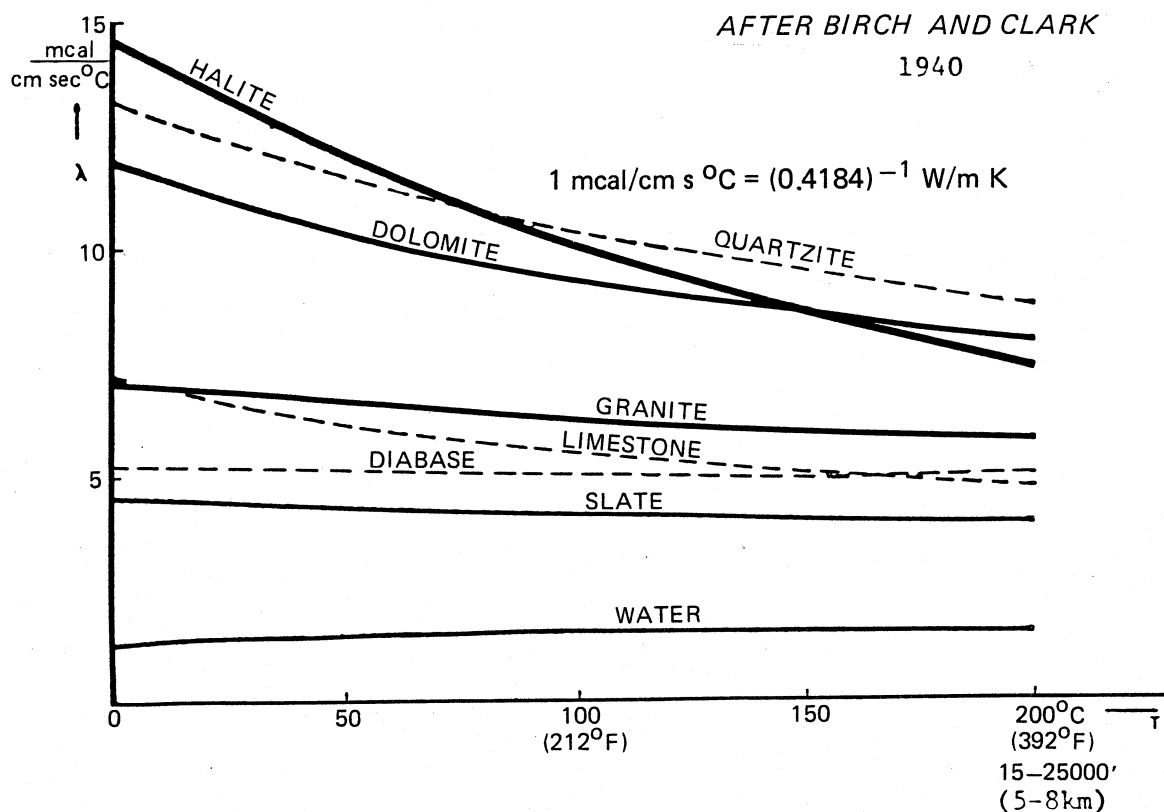


Figure 6.10 Variation of thermal conductivity with temperature (from Gretener 1981).

The salt is experiencing a higher temperature than 60°C in the modelled structures and therefore the upper limit of the salt conductivity is 5 W/m K (12 mcal/cm s °C) (Figure 6.10). At a temperature of 150°C, the thermal conductivity of Halite (salt) is reduced to 8.5 mcal/cm s °C (~ 3.5 W/m K). However, since no samples of the salt are available and the conductivity anomalies in the upper parts of the salt domes are expected to contribute the most to the modelled heat flow anomalies, a value of 5 W/m K is chosen as representative for the thermal conductivity of the salt. The resulting body conductivities are listed in Table 6.3.

Due to the interbedding of salt and other sediments in the salt structures, a method of computing the average bulk thermal conductivity is needed. The choice is between horizontal layering, in which case the averaging of thermal resistivities (1/conductivities) is appropriate, and vertical layering caused by the tendency for the salt to push and tilt sediments towards the vertical position during salt flowing, in which case the average of conductivities is appropriate. Cases A and B are equal except for the method used to calculate bulk conductivities in the salts:

Case A: Average of thermal resistivities

Case B: Average of thermal conductivities.

Table 6.3 Salt body thermal conductivities.

Body	% salt	Thermal conductivity (W/m K)		
		Case A	Case B	Case C
A1 + A2	25/25/55 (*)	3.33	3.5	4.325
A3	40	3.57	3.8	4.1
A6	15	3.19	3.3	3.725
(*) % salt in case A/B/C				

Case A and B will show the sensitivity of the modelling with respect to methods of thermal conductivity averaging in the mixed salt/sediment bodies whereas case A and C will define the maximum and minimum heat flow anomalies to be expected on top of the modelled structure.

6.3.3 Results

Results from the three simulation cases are given in Figure 6.11, and details are listed in Appendix III. Figure 6.11 shows the resulting isotherm distribution for an input heat flow of 60 mW/m² at the base of the model and using the thermal conductivity distribution of case C. The relative surface heat flow distribution is also shown for the cross-section. Note that case C, due to its larger conductivity contrasts, results in the most extreme heat flow distribution. The maximum heat flow increase over the top of the structure is 32% (case A), 33% (case B) and 42% (case C). Note also that the surface heat flow is reduced with from 10% (case A) to 13% (case C) above the rim synclines. Thus the maximum surface heat flow is 63% higher than the minimum surface heat flow.

The sensitivity of the surface heat flow with respect to different methods of computing the average thermal conductivity of the salt structures is low, (minimum anomaly computed is 32% and 33%) i.e. not more than 3% of the

modelled anomaly.

The minimum and maximum modelled surface heat flow anomaly of 32% and 42% is compared to the measured surface heat flow at site 7230/05-U-05 that lies in the range 96.2 mW/m² to 112 mW/m². Combining these results leads to a regional heat flow at the base of the model ranging from 68 mW/m² to 85 mW/m². If also the uncertainty of $\pm 5\%$ in the modelling program is accounted for the values for minimum and maximum surface heat flow anomaly becomes 27% and 47% and the range in heat flow at the base of the model becomes 65 mW/m² - 88 mW/m².

The most likely heat flow is thought to be closer to case C than case A because the sediment-depth curve used to derive case C is based more upon the porosity data from the IKU shallow drilling within the basin. Thus a heat flow anomaly of 40% is taken as the most probable from the heat flow modelling. The measured surface heat flow at site 7230/05-U-05 is reported to have a most likely value of 104 mW/m² (Table 5.3). Then the most probable heat flow at 25 km in this area becomes 74 mW/m² (= 104/1.4), see also Table 6.4.

Table 6.4 Measured and modelled heat flow at site 7230/05-U-05. Numbers in paranthesis account also for the $\pm 5\%$ uncertainty in the used finite element model.

	Recommended	Lower limit	Upper limit
Measured (mW/m ²)	104	96.2	112
Modelled anomaly (%)	40	32 (27)	42 (47)
Heat flow at 25 km (mW/m ²)	74	68 (65)	85 (88)

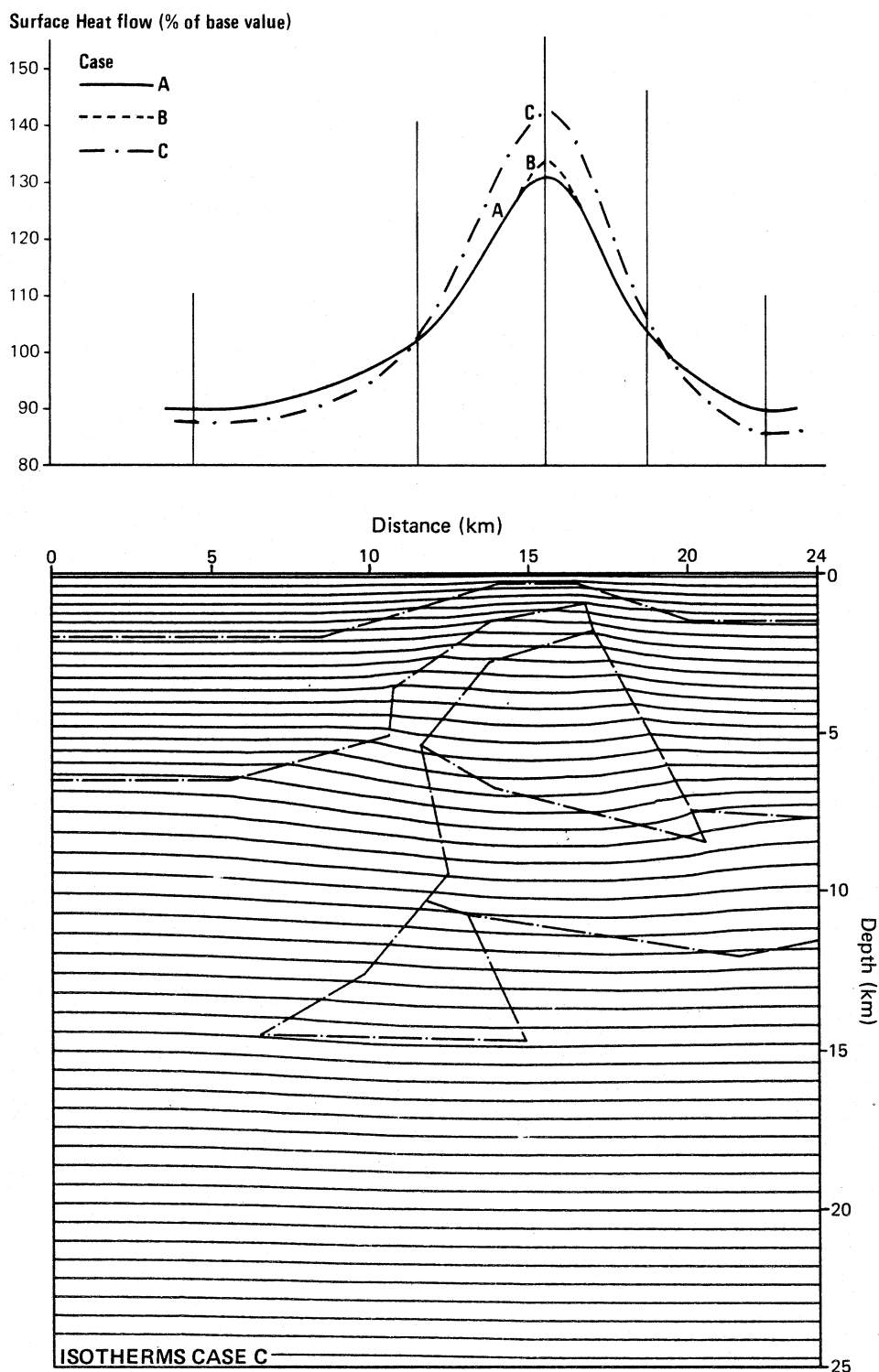


Figure 6.11 Isotherms of case C and surface heat flow of all cases.
The temperature difference between isotherm lines depends linearly on the heat flow input at 25 km.
Heat flow = 60 mW/m²: isotherm spacing = 10 K
Heat flow = 74 mW/m²: isotherm spacing = 12.3K

6.4 Discussion

6.4.1 Modelling input

The possibility of having less than 50% salt in a salt dome may be raised as an objection to the work described in this chapter. The gravity anomaly can also be explained by shallower salt bodies containing 100% salt. The total amount of salt must then be reduced and the horizontal extent of the salt bodies must be increased. This is not supported by the seismic interpretation. Therefore we were not able to create a model with close to 100% salt in the salt structures. Because of the change in horizontal extent of the salt structures that is required if the salt content is increased and salt is modelled at a shallower depth, it not known whether the resulting modelled heat flow anomaly will increase or decrease. For such a consideration to be worthwhile, a new consistent salt body model has to be put forward.

The results of this heat flow modelling may be more constrained once the thermal conductivity measurements now being performed on the IKU Nordkapp Shallow drilling cores are completed. Data on the Palaeozoic section will also be useful for this purpose. If the thermal conductivity of the Palaeozoic section (including Palaeozoic in salt bodies) is increased 10%, an increase in heat flow anomaly of 2% is obtained.

6.4.2 Comparison to shallow measurements

The modelled undisturbed heat flow (74 mW/m^2) at location 7230/05-U-05 is significantly higher than the other 1987 shallow heat flow measurements: 45.9 mW/m^2 in site 7227/11-U-01 and 54.2 mW/m^2 in site 7230/08-U-01.

The observed heat flow distribution in the Nordkapp Basin may be caused by:

- tertiary tectonics,
- large-scale heat flow focusing caused by thermal conductivity contrasts due to salt bodies,
- fluid flow caused by compaction.

If compaction of the Mesozoic sediments currently is an active process, then additional heat transfer by convection of water must be considered. Water will escape along permeable carrier beds and updip the salt dome flanks where it can escape into the seawater through the Quaternary sediments. However, subsidence has not been significant in this basin during late Tertiary times, and it therefore seems unlikely that the required overpressure can be maintained for such a long time. Without overpressure, there will be no fluid flow by convection. Thus, a mechanism for producing very late overpressure would be required.

Further modelling is required to solve these problems, and the heat flow measurement on top of the salt dome does suggest that the solution to this problem may be vital to the maturation and hydrocarbon generation distribution within the basin.

7. BEDROCK SAMPLE AT SITE 7227/11-U-01

7.1 Introduction

At site 7227/11-U-01 top bedrock was penetrated at 32.5 m. The drilling was stopped after about one hour drilling with insignificant penetration. Then the bit was plugged and the drilling was terminated.

From the deep towed boomer data top bedrock should be expected at 39 ms which would equal 32.5 m if a sound velocity of 1670 m/s is assumed. Sound velocity is measured on sediment samples from the lower 15 m of the Quaternary overburden, and the average vertical sound velocity is found to be 1827 m/s. If this is representative for the whole Quaternary column, a thickness of 35.6 m would be expected. A more realistic sound velocity for the whole column would probably be about 1750 m/s giving a depth of about 34 m. This is 1.5 m deeper than the TD-depth.

Taking into account the possibility of local seabed irregularities, however, we conclude that the bedrock plug at 32.5 m was cut in in situ bedrock or in a large boulder close to bedrock and therefore represents the local lithology.

7.2 Lithology

One sample is analysed by X-ray diffraction (XRD) analysis. The sample consists of fragments of a greenish grey claystone. The colour on dry weathered surfaces is pale greyish green. The rock is slightly micaceous and silty (quartz). Scattered black fragments are probably of organic origin.

The X-ray diffraction analysis (Figure 7.1) shows that cristobalite is the major mineral of this sample, and that clay minerals are present only in small amounts. Cristobalite, which is a silica polymorph, may be indicative of either the presence of recrystallized amorphous silica from skeletons of microorganisms or of volcanic activity.

Table 7.1 Mineralogy (semi-quantitative wt%) of rock sample from 7227/11-U-01, 32.5 m based on XRD analysis.

Mineral	Content (wt %)
Quartz	13
Cristobalite	78
Albite	3
K-feldspar	tr
Mica/illite	3
Kaolinite	2
Chlorite	1
Pyrite	tr

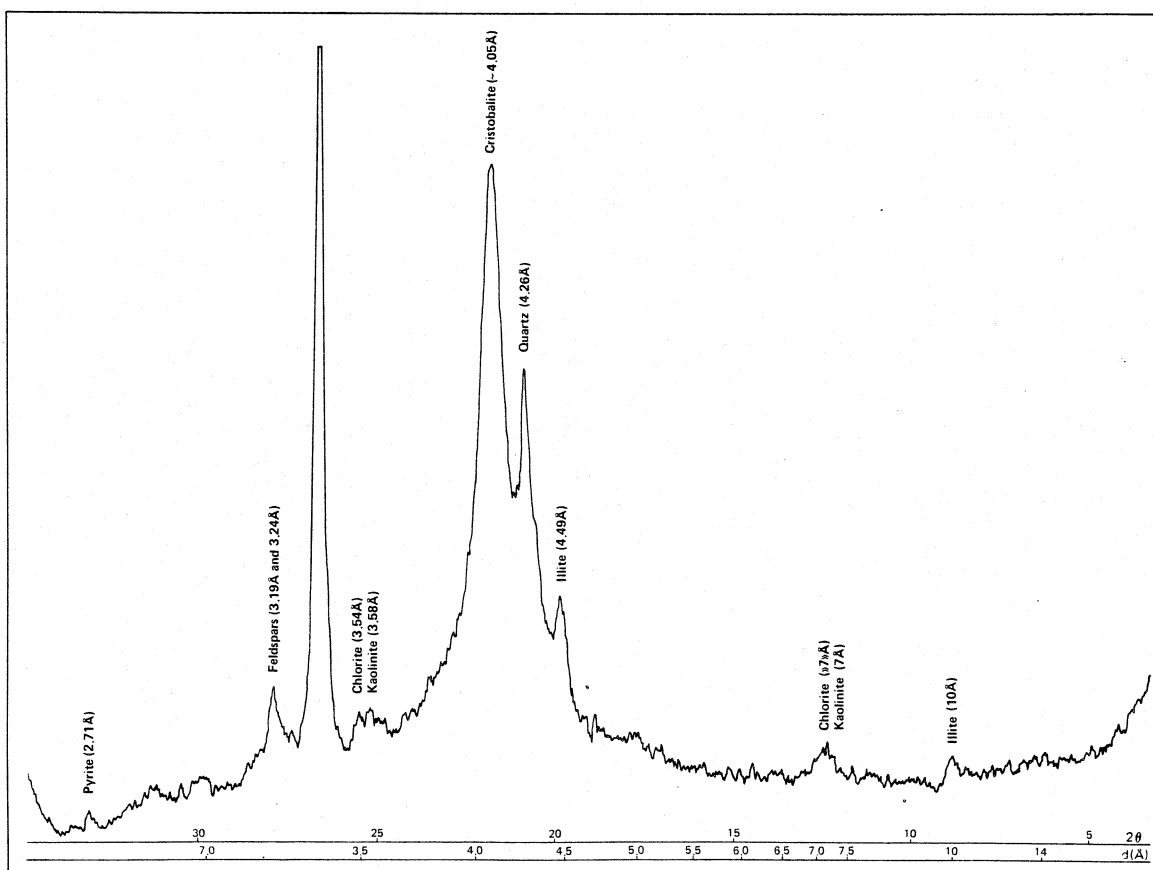


Figure 7.1 X-ray diffraction of rock sample from 7227/11-U-01.

7.3 Biostratigraphy

An organic residue from a sample at 32.50 m contains a moderately diverse dinoflagellate cyst assemblage. The cooccurrence of *Deflandrea oebisfeldensis* and *Areoligera* cf. *senoensis* points to a Late Paleocene age. *Thalassiphora delicata*, *Palaeostonocystis laevigata*, *Comotodinium* sp. and a few other species have also been recorded. Heilmann-Clausen (1985) distinguished 8 palynozones in a latest Danian to Ypresian section in a Danish borehole, and our sample may be referred to his zone 5 (which mainly consists of a dark grey noncalcareous clay in the uppermost part of the Selandian).

The microfauna was only represented by some few, poorly preserved *Bathysiphon* spp., *Saccamina* and *Trochamina* sp. of little stratigraphical significance.

7.4 Organic geochemistry

The hydrocarbons obtained from the headspace gas show a relatively low yield of ca. 1000 µl/kg dry rock (Table 7.2). Methane is the dominating compound, while C2-C5-hydrocarbons occur only in trace concentrations. The ratio i-C4/n-C4 of 1.2 may suggest that the gas derives from an immature source, however the ratio should be considered with caution because of the low concentration level.

The total organic carbon (TOC) content of different subsamples shows values of 0.4, 1.0 and 1.1 % (Table 7.3). The large spread may be explained by lithological inhomogeneities of the canned sample (C-7025). The Rock-Eval data of the two carbon-rich subsamples are, however, consistent (Table 7.4), and the low hydrogen index (<50 mg HC/g TOC) indicates that the organic material is hydrogen-poor and has no significant potential for the generation of hydrocarbons. The T_{max} values of 427 and 421°C suggest that the organic material is immature, although they appear somewhat high in comparison with the vitrinite reflectance of 0.33% R_o (Table 7.5). Both this and the hydrogen-poor character of the organic matter may in part reflect the high proportion of reworked and oxidised organic material which was observed under the microscope.

The vitrinite reflectance data obtained from this sample are considered to be rather poor. This is largely due to the fact that most of the few

vitronite particles present in the sample tended to be reworked. A few lower reflectivity vitronite particles were present which may be relatively indigenous to the rock, but these tended to be very small and of variable quality.

The fluorescence of the few sporinite particles present was green to greenish-yellow (1-2) which is consistent with the lowest population of the reflectance data (mean 0.33 %R_o), suggesting that the organic matter in the rock is immature.

Table 7.2 Data from headspace gas analysis. Concentration (µl gas / kg dry rock) of C₁ - C₅₊ hydrocarbons in headspace gas.

Site	IKU no.	Depth (m)	C1	C2	C3	iC4	nC4	C5+	SUM C1-C4	SUM C2-C4	WET-NESS (%)	iC4 ----- nC4
7227/11-U-01	C 7025	32.50	947	26	23	14	12	29	1020	73	7.20	1.18

Table 7.3 Total carbon (TC) and total organic carbon (TOC) content.

Site	IKU no.	Depth (m)	TC (wt% of dry sediment)	TOC	CaCO ₃
7227/11-U-01C	C-6761	32.50	--	0.96	--
7227/11-U-01C	C-7025	32.50	1.80	0.35	12.09
7227/11-U-01C	C-7025 *)	32.50	--	1.14	--
*) different fractions of same sample					

Table 7.4 Data from Rock-Eval pyrolysis.

Site	IKU No.	DEPTH m	S1 (mg/g ROCK)	S2 (mg/g ROCK)	S3 (mg/g ROCK)	TOC (%)	HYDR. INDEX (mg/g TOC)	OXYGEN INDEX (mg/g TOC)	PETR. POT. S1+S2	PROD. INDEX S1 ----- S1+S2	TEMP. MAX (°C)
7227/11 -U-01	C 6761	32.5	0.10	0.47	0.64	0.96	49	64	0.57	0.18	427
7227/11 -U-01	C 7025	32.5	0.15	0.49	0.52	1.14	43	46	0.64	0.23	421

Table 7.5 Vitrinite reflectance data.

Site	IKU no.	Depth (m)	Vitrinite Reflectance (O/O R _o), No of meas.	Rel. Rat.	Standard Deviation	Fluorescence
7227/11-U-01	C-6761	32.5	0.33 (7) 0.57 (5)	P R	0.06 0.08	1-2
Rel. Rat. (Reliability Rating): P - poor, R -reworked						

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A P P E N D I X I**FIELD OPERATIONS AND INSTRUMENTATION**

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AI 1. SUMMARY OF FIELD OPERATIONS

AI 1.1 General

The heat flow sites 7227/11-U-1, 7230/05-U-05 and 7230/08-U-01 were drilled as part of a field work joint drilling cruise of several IKU projects in the southern Barents Sea during July through September 1987. A shallow seismic survey was carried out in May 1987 for the purpose of selecting drill sites and to be able to correlate the shallow data to conventional seismic in the area.

The shallow seismic profiling was carried out by Master Surveys A/S and comprised collection of data using analog sleeve airgun, digital airgun, deep tow boomer and side-scan sonar. Bentech A/S was sub-contracted for the positioning and Geophysical Service International processed the digital seismic data.

The drilling cruise was performed by the Norwegian drillship M/S Bucentaur which was contracted from Offshore Support Services A/S.

Diamant Boart a/s was sub-contracted for the bedrock drilling and have also delivered the diamond drilling rig that was used for the job (type DBH 1500S).

Fugro-McClelland Engineers B.V., The Netherlands were sub-contracted to perform the down-hole sampling and temperature and on board thermal conductivity measurements. The down-hole probes for temperature measurements are designed and manufactured jointly by Fugro-McClelland Engineers B.V. and Omegalink International Ltd, whereas the combined probes measuring both temperature and thermal conductivity are made by Fugro-McClelland Engineers B.V.

Bentech A/S was responsible for positioning on the drilling cruise as on the seismic cruise.

The drilling cruise for the present project was carried out in combination with several other cruises and therefore benefitted considerably on fixed expences like mob / demob, sailing to and from the area etc.. The time consumption is summarized in Table AI 1.1.

Table AI 1.1 Summary of time consumption of drilling operations related to the project HEAT FLOW MEASUREMENTS BARENTS SEA 1987.

Site	Time consumption (on site work, hours)	Comments
7227/11-U-01	59.5	Redrilling necessary stony, stiff soil
7230/08-U-01	18.9	Good conditions
7230/05-U-05	18.5	Stiff - hard soil below 12m. TD due to swell and hard soil.
Total time consumption (hours):		
On site work	97	
Weather standby	9	
Sailing	8	

An outline of the heat flow measurement procedure at a drilling site will be as follows (Figure AI 1.1).

- a) The drillship moved into position and lowered the seabed guide frame.
- b) Drill pipes were run until the seabed frame was entered and the bit touched the seabed. Then an accurate reference depth measurement on the drill string was made.
- c) The drilling commenced and from about 10 m below the seabed and downwards the drilling was stopped every 3-5 m for temperature measurement.
- d) At each testing depth, a sediment sample was first obtained with a thin-walled, hydraulically operated push sampler (WIP) or a hammer sampler. If the sampling was successful and the obtained material showed no significant content of gravel or pebble that might be

hazardous to the probes, a temperature measurement was carried out.

Due to the difficult soil conditions / thin overburden at two of the locations the possibility was limited for refusing any sampled depth for temperature measurement due to gravel content.

- e) The temperature probe was mounted on a hydraulically operated device normally used for cone penetrometer testing (WISON), and pushed into the undisturbed sediment below the cavity created by the push sampling.

Alternatively a combined temperature and in situ thermal conductivity probe could be used. This probe made it possible to measure in situ the two parameters needed for calculation of heat flow (temperature and thermal conductivity).

- f) After the completion of a measurement, the equipment was retrieved and the drilling proceeded another 3-5 m.
- g) Thermal conductivity was measured on the recovered core material as soon as equilibrium with the on board temperature was obtained.

The working conditions varied from excellent to difficult with respect to soil conditions, weather and seastate.

On site 7227/11-U-01 fairly stiff sediment was encountered below approx. 5 m. This, in combination with content of coarse fragment in the sediments, made redrilling necessary two times before sufficient data was obtained (after 59.5 hours on site operation). Two thermistor needles were broken on this site. The wind force and sea state varied within respectively 2 - 5 and 3 - 4 on the Beaufort scale.

On site 7230/08-U-01 fairly soft sediments were encountered. One thermistor needle was broken. Wind and sea state were 3 - 4 on the Beaufort scale during the whole operation.

On site 7230/05-U-05 the soil conditions were similar to on site 7227/11-U-01. The weather conditions were however more difficult. The operations started after a period of weather stand by, and one needle was broken as the direct result of heavy swell. Wind and sea state at the beginning of

the operation was 4 - 5 and 5, but increased to respectively 7 and 6 on the Beaufort scale. Additional sample data for thermal conductivity measurements were obtained in borehole 7230/05-U-05A which were obtained a few m away from the first hole.

The data recovery is summarized in Table AI 1.2.

Table AI 1.2 Data recovery from the 1987 IKU heat flow sites.

Site	Quaternary samples		Temperature measurements	In situ thermal conductivity measurements
	No	Acc. length (m)		
7227/11-U-01	11	4.21	6	0
7230/08-U-01	5	3.52	22	7
7230/05-U-05	4	1.66	10	3

Some of the measurements in the table above have less reliability than the other. This is discussed further in the main report. Selected results from the sample analysis is given in Chapter 4 in the main report as a background for an evaluation of the thermal conductivity data. A detailed sample description will be given in a separate report.

AI 1.2 Positioning

Bentech A/S in Tromsø was operator for the navigation chains and provided equipment and personnel for positioning of the drilling vessel.

Hyperfix was used as the main system. Syledis was used as a reference system for Hyperfix calibration. Final positions for the drill sites are based on Hyperfix, range-range.

In the beginning of the cruise there were some problems with some of the instruments on board and with the performance of hyperfix calibration. After this phase both systems worked well during the rest of the cruise.

Table AI 1.3 Final position of the 1987 heat flow sites.
 Coordinates in brackets are UTM CM 27deg east.

Site	Seis. line	SP	Coordinates	
			N	E
7227/11 -U-01	C/D 86-6	300	72°01'15.81'' (7991570.4	27°29'59.31'' 517219.9)
-U-01C	----"----	299.9	72°01'15.86 (7991571.9	27°29'56.75'' 517195.3)
7230/08 -U-01-	IKU 302230- 87	2500	72°25'45.59 (8040236.9	30°22'34.38'' 613712.2)
7230/05 -U-05-	IKU 302230- 87	604	72°42'07.14'' (8070607.9	30°22'32.09'' 611981.7)
-U-05A	-----"-----	606.3	72°42'6.00'' (8070571:8	30°22'31.64'' 611979.5)

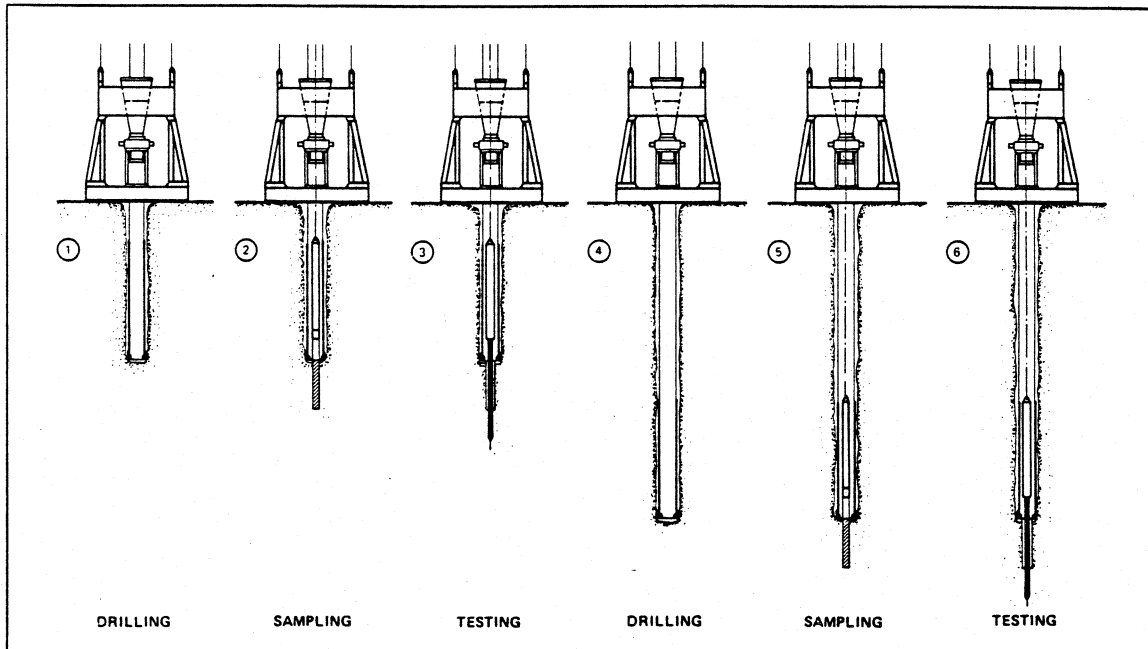


Figure AI 1.1 Summary of heat flow measurement procedure during shallow drilling (From Zielinski et al. 1986).

AI 2. INSTRUMENTS, DESIGN AND OPERATION

AI 2.1 General

A brief description of the design and operation of the main instruments that were used in connection with the heat flow measurements is given below. The instruments are:

- The WISON system
- The WIP system
- The down-hole temperature probe
- The needle probe
- The combined down-hole temperature and thermal conductivity probe.

AI 2.2 The WISON

The WISON system is a hydraulically operated system normally used for geotechnical testing (cone penetration tests). The system was lowered inside the API drill string and latched in with its lower end at drill bit level (see Figure AI 2.1). The cone with the temperature probe mounted at the end was then pushed into the underground. Maximum pushing force is 9 tons. Normal pushing speed is 2 cm/sec. This was modified for the heat flow testing and the pushing could be performed in increments of a few millimetres.

AI 2.3 The WIP

This system comprises a thin-walled push sampler designed and operated in a similar fashion as the WISON system. The WIP system used during the cruise had 2" thin-walled sample tubes which obtained samples of good quality of sufficient size for thermal conductivity measurements. However, for soil mechanical testing with standard laboratory equipment this diameter is regarded as a minimum for the types of sediment encountered.

AI 2.4 The down-hole temperature probe

AI 2.4.1 Probe description

The down-hole temperature probe was operated by the WISON system as shown in Figure AI 2.1. The controlled push-in-operation made possible by use of the WISON system kept the frictional heat to a minimum. In order to transmit the thermistor output up to the surface vessel without loss of accuracy and resolution, a temperature stable amplifier was built into a pressurized compartment in the WISON. Thereby the thermistor output was transmitted via the WISON umbilical cable as amplified voltages to a precision strip chart recorder on board the vessel. Two amplifier channels were simultaneously monitored, one wide range, low resolution channel and one narrow range, high resolution channel. The latter was capable of resolving temperature changes as small as 0.001°C with negligible influence of the umbilical or slip-ring connectors on the primary signal.

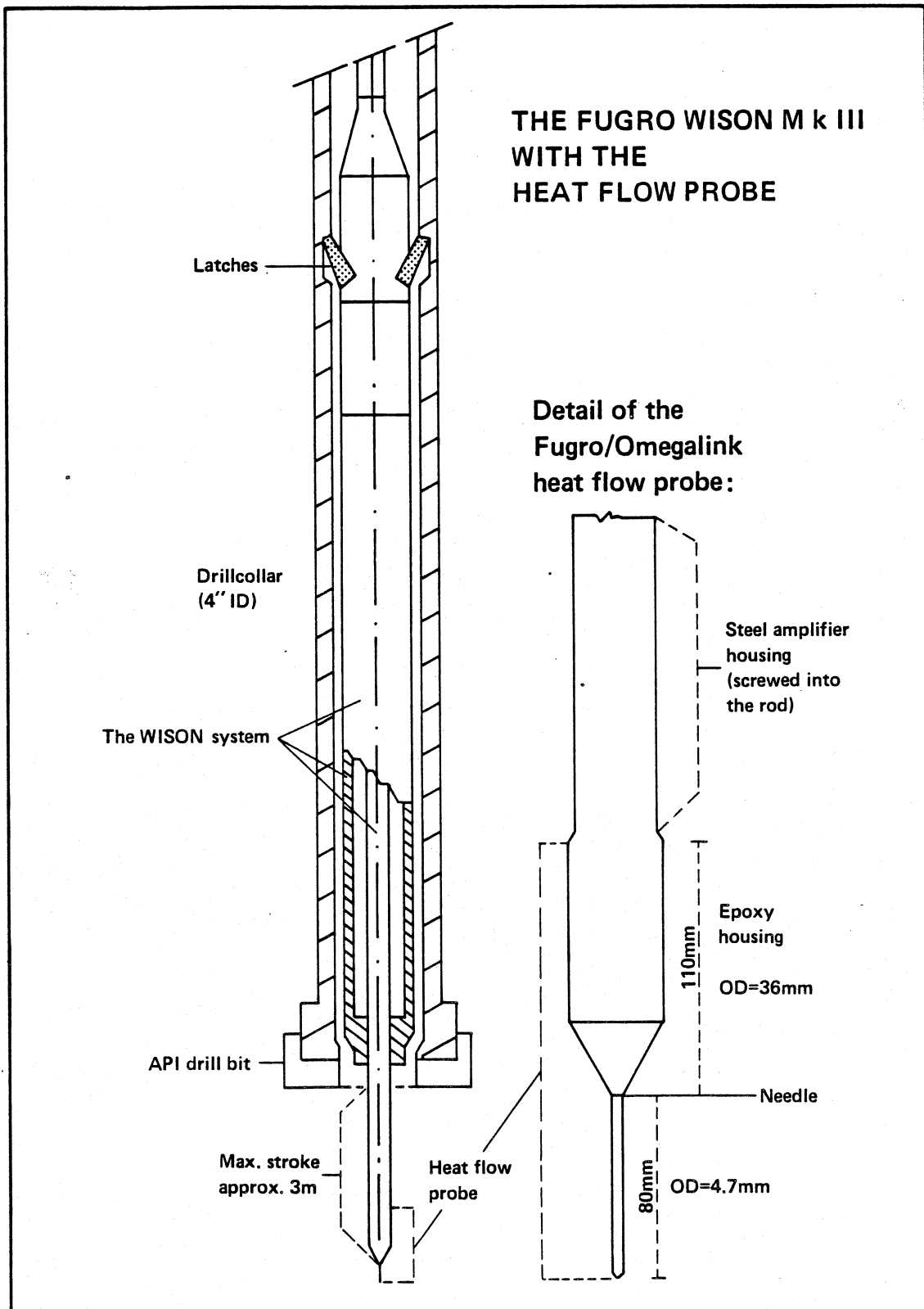


Figure AI 2.1 The combined temperature and thermal conductivity probe mounted in the Fugro WISON Mk III system.

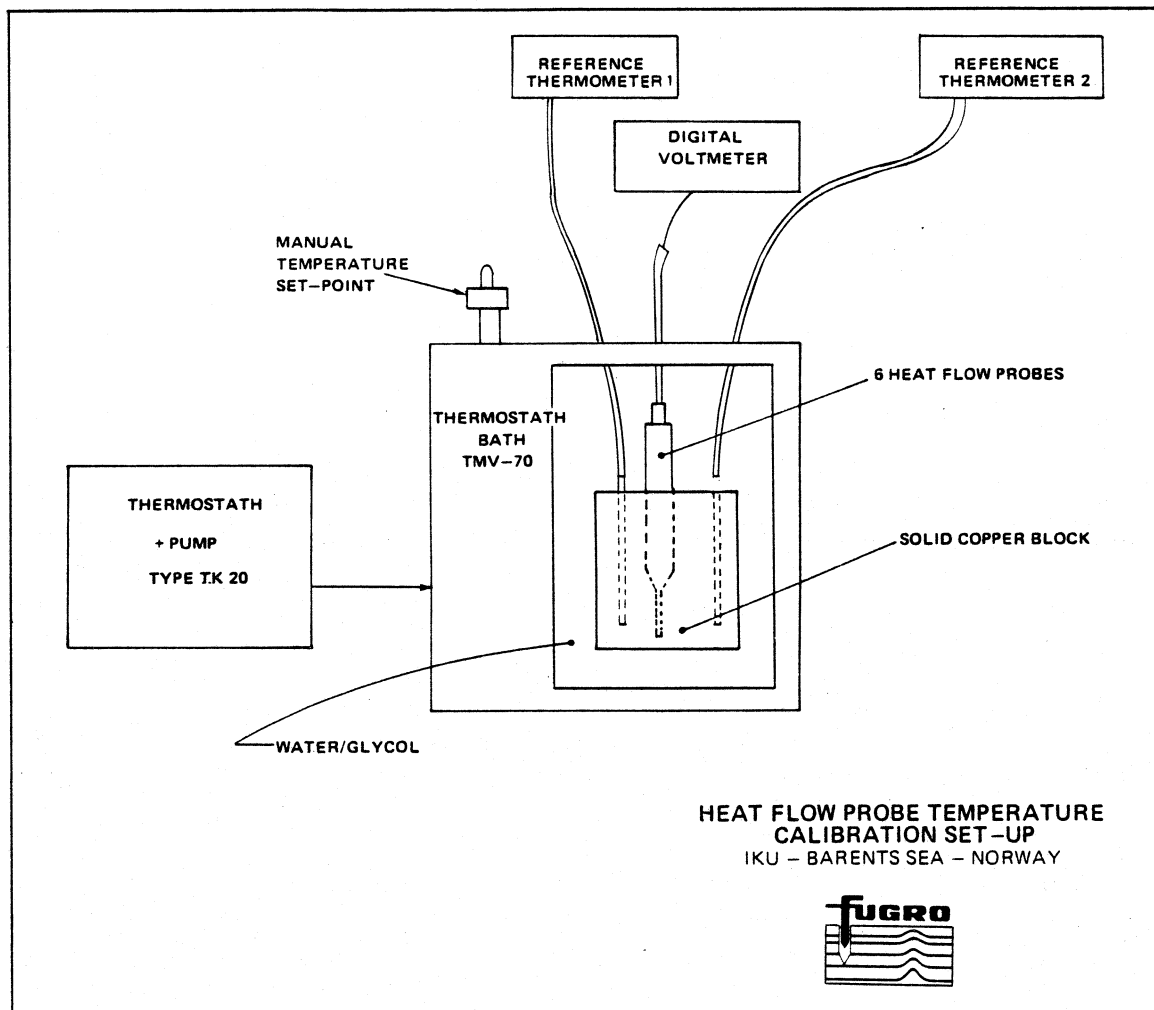


Figure AI 2.2 Temperature calibration set up. (Due to malfunction of reference thermometer 2, only one reference thermometer was used).

AI 2.4.2 Calibration

The temperature calibration of the temperature probes (FT-probes) and combined probes (FHT-probes) was performed by Fugro in co-operation with the Dutch Calibration Organization.

Some of the probes were damaged during the tests and therefore no comparison of pre- and post cruise calibration is possible in these cases. These probes are FHT2 and FT20 on site 7230/08-U-01, FHT7 on site 7230/08-U-01 and FHT4, FHT6 and FT15 on site 7230/05-U-05. The remaining probes were post cruise calibrated in order to quantify any drifting in the instruments.

The calibration was based on comparison with reference thermometers and followed the set up shown in Figure AI 2.2. The main calibration instruments had the following specifications:

- 1 Guildline Digital Platinum Resistance Thermometer Model 9540
Basic absolute accuracy $\pm 0.01^{\circ}\text{C}$.
Resolution 0.001°C .
- Tamson Thermostath Bath type TMV 70
Microprocessor controlled
Control accuracy $\pm 0.005^{\circ}\text{C}$.
Temperature range 0 to 100°C .
- 1 Tamson Thermostath Pump type TK-20
Control accuracy $\pm 0.002^{\circ}\text{C}$.
Temperature Range -30°C . to $+30^{\circ}\text{C}$.

The calibration set up allows calibration of six probes simultaneously. The pre- and post cruise calibration dates given in the table below shows which probes that were calibrated simultaneously and also which of these that were used in the same borehole.

Table AI 2.1 Pre- and post cruise calibration dates for different temperature probes.

Site	Probe	Pre cruise calibr.date	Post cruise calibr.date
7227/ 11-U-01	FHT2	09.06.87	
	FT13	30.06.87	11.09.87
	FT20	30.06.87	11.09.87
	FT11	30.06.87	11.09.87
7230/ 08-U-01	FHT4	09.06.87	
	FHT7	09.06.87	
	FHT9	09.07.87	11.10.87
	FHT5	09.07.87	11.10.87
	FHT6	09.06.87	
7230/ 05-U-05	FHT5	09.07.87	
	FHT4	09.06.87	
	FT15	30.06.87	11.09.87

AI 2.4.3 Calibration results

The calibration are made in steps of about 1 K from -5°C to $+10^{\circ}\text{C}$. The polynome factors in the equation giving temperature from measured voltage from each individual probe is then adjusted to give an optimum fit to the reference thermistor. The same procedure is used in the post cruise calibrations.

Neither the reference thermistors nor the temperature probe thermistors are stable as a function of time. This drifting will affect the accuracy of individual probes and therefore the relative resolution between individual probes (i.e. what may be the difference in recorded temperature by different probes if the real temperature is constant).

This uncertainty is influenced by the following effects:

- resolution of the reference,
- drifting (time stability) of the reference,
- resolution of the thermistor probes,
- drifting of the probes.

The resolution of the reference is ± 0.001 K.

The resolution of the probes is probably best evaluated from the results in borehole 7230/08-U-01 (Chapter 3 in the main report). In this case 8 sets of 2 or 3 temperature/depth-datapoints from individual probes give almost exactly the same gradient, although there is a slight sidetracking between the different segments (Figure 3.3). It is seen that exactly the same gradient (although at different absolute temperature levels) can be achieved by adjusting individual temperatures approx. ± 0.002 K. Thus, we conclude that individual temperature probes have a short term resolution of ± 0.002 K in undisturbed measurements.

The drifting in the calibration equipment and the probe thermistors can not be directly evaluated separately from the calibration that has been performed.

Such a separation would be necessary in order to be able to quantify the uncertainty introduced by:

- 1) comparing sensors calibrated simultaneously,
- 2) comparing sensors not calibrated simultaneously.

The total relative drifting in reference and probe thermistors can be evaluated from the data in Table AI 2.2. In this table temperature is calculated by use of the polynomials determined during pre- and post cruise calibration for a number of given voltage outputs. The difference between the two sets of temperatures expresses a combination of resolution uncertainties and drifting of the sensors.

Table AI 2.2 indicate that the drifting is dependent on the absolute temperature level. The actual temperature range for the heat flow measurements is 3°C-5°C. Within this temperature interval the average drifting is found to be 0.0051 K (standard deviation 0.0094 K). Probe FT11 is omitted from this statistics as it was reported to behave unstable during post cruise calibration.

The mean value of 0.0051 K probably expresses the drifting component from the reference, and may indirectly be used to separate reference and probe drifting.

AI 2.4.4 Probe evaluation

Based on the results from the field measurements, the calibration results and the above consideration, our evaluation of the reliability of the probes is as follows:

- the resolution of individual probes is better than ± 0.005 K, probably in the order of ± 0.002 K for undisturbed measurements,
- independent drifting of probes and reference from pre- to post calibration may be in the order of 0.005 K,
- two thermistors calibrated simultaneously may give a total relative difference of ± 0.01 K,
- two thermistors calibrated individually may give a total relative difference of ± 0.015 K.

The above estimates are probably conservative and may result in a slight overestimate in the calculated temperature gradient. For future projects the calibration procedures will be improved to reduce the above uncertainties.

Data from mid- and tip point thermistors should be combined with caution as the mid point thermistor gives slightly different absolute temperatures (Ref. Figure 3.3). This is possibly due to a less favourable position of this thermistor during calibration and field measurement.

AI 2.5 The needle probe

Thermal conductivity measurements were performed on core samples in the on board laboratory via the standard needle probe method (Von Herzen and Maxwell 1959). After waiting for temperature equilibration to shipboard conditions, a 10 cm long, 3 mm diameter "hypodermic-like" probe was inserted into sediment samples. Visibly disturbed samples were not measured. A calibrated quantity of heat was introduced into each sample via a heater wire located in the needle probe while the rise in sample temperature was recorded digitally via a thermistor head, also located in the needle probe. The normal duration of these measurements was three minutes, which ensures that the usual infinite line source theory can be used to arrive at thermal conductivity values.

The precision of the needle probe is judged by von Herzen and Maxwell (1959) to be 3 - 4% when accounting both for calibration errors and random errors in repeated measurements. They suggested that the random error contribution to this probably is in the order of 1 - 2%. This compare well with the opinion of Woodside and Messmer (1961) who claim a reproducibility of better than 2.5%. Beck et al (1971), however, evaluate absolute values to be accurate to "something like $\pm 5\%$. 5% accuracy is also claimed by Matshuda and von Herzen (1985) and Balling et al (1981). Balling et al (1981) however explicitly include the effect of varying sample quality in this accuracy interval.

Kristiansen (1982) has performed a detailed study of the needle probe method, and has plotted relative error in recorded temperature rise for needle probes of different diameters and lenght/diameter ratio. His plot is shown in Figure AI 2.3. This figure illustrates the influence both of probe lenght and lenght /diameter ratio on the precission of the method and

Table AI 2.2 Comparison of temperatures resulting from pre- and post cruise calibration polynomials calculated.

Probe name : FHT A 5
Date : 13 Oct 1987

Voltage	Temperature pre CAL	Temperature post CAL	Deviation (pre-post)
-4.495	-4.975	-4.972	-.003
-3.345	-3.464	-3.46	-.004
-1.195	-2.039	-2.035	-.003
-.045	-.695	-.69	-.005
.105	.572	.577	-.005
.255	1.778	1.777	0
.405	2.933	2.93	.004
.555	4.039	4.035	.004
.705	5.098	5.091	.007
.855	6.113	6.107	.006
1.005	7.09	7.088	.002
1.155	8.029	8.016	.014
1.305	8.938	8.919	.019
1.455	9.82	9.864	-.045

Probe name : FHT B 5
Date : 13 Oct 1987

Voltage	Temperature pre CAL	Temperature post CAL	Deviation (pre-post)
-.516	-4.971	-4.972	.001
-.366	-3.45	-3.45	-.001
-.216	-2.017	-2.016	-.002
-.066	-.666	-.663	-.003
.084	.61	.611	-.001
.234	1.823	1.819	.004
.384	2.984	2.977	.007
.534	4.096	4.087	.009
.684	5.158	5.148	.01
.834	6.178	6.169	.008
.984	7.16	7.154	.006
1.134	8.103	8.084	.019
1.284	9.016	8.996	.021
1.434	9.902	9.935	-.032

Probe name : FHT A 9
Date : 13 Oct 1987

Voltage	Temperature pre CAL	Temperature post CAL	Deviation (pre-post)
-.502	-4.988	-4.972	-.016
-.352	-3.451	-3.444	-.007
-.202	-2.017	-2.01	-.008
-.052	-.668	-.655	-.014
.098	.61	.623	-.013
.248	1.829	1.831	-.003
.398	2.991	2.989	.002
.548	4.104	4.101	.003
.698	5.174	5.163	.01
.848	6.198	6.186	.012
.998	7.174	7.173	.001
1.148	8.12	8.105	.015
1.298	9.031	9.018	.013
1.448	9.909	9.955	-.046

Probe name : FHT B 9
Date : 13 Oct 1987

Voltage	Temperature pre CAL	Temperature post CAL	Deviation (pre-post)
-.518	-4.968	-4.972	.004
-.368	-3.423	-3.442	.018
-.218	-1.993	-2.006	.011
-.068	-.645	-.65	.005
.082	.638	.628	.01
.232	1.854	1.838	.015
.382	3.017	2.997	.019
.532	4.134	4.109	.026
.682	5.201	5.173	.028
.832	6.217	6.196	.022
.982	7.195	7.178	.017
1.132	8.137	8.106	.03
1.282	9.048	9.022	.026
1.432	9.93	9.956	-.026

Probe name : FT 11
Date : 13 Oct 1987

Voltage	Temperature pre CAL	Temperature post CAL	Deviation (pre-post)
-3.141	8.276	9.585	-1.31
-2.591	7.528	7.324	.205
-2.041	6.755	6.855	-.1
-1.491	5.958	5.975	-.016
-.941	5.137	5.098	.039
-.391	4.284	4.271	.013
.159	3.395	3.397	-.002
.709	2.468	2.266	.202
1.259	1.507	.889	.618
1.809	.511	-.268	.779
2.359	-.529	-.992	.463
2.909	-1.626	-2.026	.4
3.459	-2.785	-3.569	.784
4.009	-4	-4.873	.873

Probe name : FT 13
Date : 13 Oct 1987

Voltage	Temperature pre CAL	Temperature post CAL	Deviation (pre-post)
-4.434	9.979	9.967	.012
-3.754	9.109	9.104	.004
-3.074	8.204	8.205	-.001
-2.394	7.269	7.269	0
-1.714	6.296	6.296	-.001
-1.034	5.284	5.279	.005
-.354	4.225	4.221	.005
.326	3.111	3.111	-.001
1.006	1.941	1.939	.002
1.686	.718	.705	.013
2.366	-.569	-.581	.012
3.046	-1.944	-1.946	.001
3.726	-3.412	-3.423	.012
4.406	-4.996	-4.983	-.013

Probe name : FT 15
Date : 13 Oct 1987

Voltage	Temperature pre CAL	Temperature post CAL	Deviation (pre-post)
-4.109	9.534	9.967	-.433
-3.449	8.666	8.646	.021
-2.789	7.777	7.786	-.009
-2.129	6.851	6.857	-.006
-1.469	5.89	5.893	-.004
-.809	4.892	4.893	-.002
-.149	3.846	3.849	-.002
.511	2.746	2.753	-.006
1.171	1.595	1.598	-.002
1.831	.394	.387	.007
2.491	-.873	-.875	.002
3.151	-2.228	-2.219	-.008
3.811	-3.665	-3.67	.005

Probe name : FT 20
Date : 13 Oct 1987

Voltage	Temperature pre CAL	Temperature post CAL	Deviation (pre-post)
-4.475	9.974	9.967	.007
-3.785	9.095	9.1	-.004
-3.095	8.177	8.184	-.007
-2.405	7.232	7.241	-.009
-1.715	6.242	6.249	-.007
-1.025	5.217	5.219	-.001
-.335	4.147	4.149	-.002
.355	3.015	3.023	-.008
1.046	1.826	1.831	-.005
1.736	.586	.58	.005
2.426	-.724	-.727	.003
3.115	-2.127	-2.118	-.009
3.805	-3.618	-3.622	.004

suggests a relative error of 1 - 3% for the needle probes used with lengths of 5 - 10 cm and length / diameter ratios of 33 - 60 (8 - 10 cm and 13 - 16 in the case of the in situ probe (described below)). The figure also indicates that the length of the probe rather than the length / diameter ratio is the most critical factor to the precision of a probe - particularly for needles shorter than 5 cm.

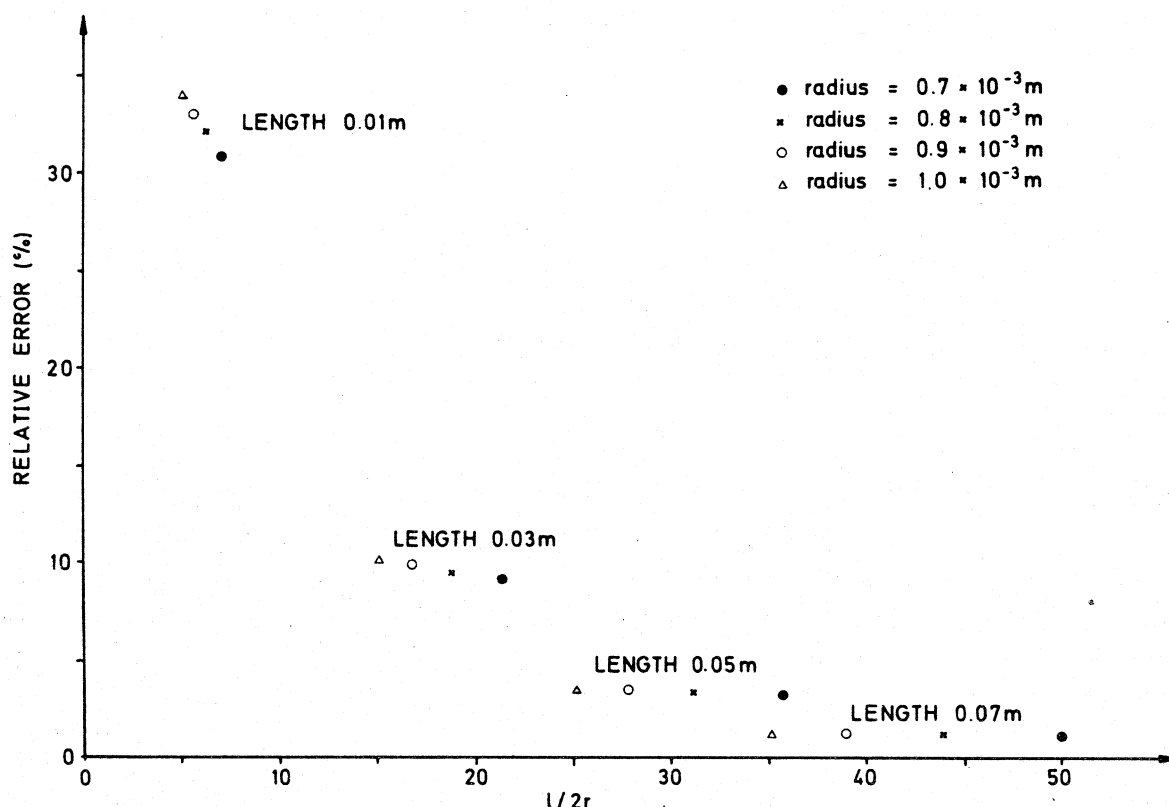


Figure AI 2.3 Relative error (in %) of temperature rises of the finite line source (compared to the infinite line source) as a function of the length/diameter ratio (Kristiansen, 1982).

For the on board laboratory measurements the intention was to use 6 cm long, 1 mm diameter needles, as the samples to be tested had a diameter of 63 mm or 72 mm. This was however not possible due to delay from the manufacturer. The measurements were done with the needle both parallel and perpendicular to the sample axis, and in the latter case the needle was not fully embedded in the sample.

After the cruise smaller needles were available and comparison tests were done using both 10 cm and 6 cm needles on the same 72 mm soil samples. During these tests the samples unfortunately were lowered into water to keep stable temperatures. In this case part of the long needles had direct contact with free water during the perpendicular measurement. This

situation may cause heat transfer by convection during heating of the needle, and recording of a too high conductivity will result.

Of five test series, four resulted in a 0% - 7% higher anisotropy measured with a 6 cm long needle than with the 10 cm long needle (average 4%). Approximately 20% higher anisotropy was found by use of the short needle in one of the test sets. This test set was however believed to comprise unreliable data.

The fact that opposite results were found in this laboratory investigation compared to the difference between the on board data and the results from Aarhus is most likely a result of heat transfer due to convection in the laboratory tests. Convection around the needle segments in free water would increase the measured K_w and thereby reduce the calculated anisotropy. The actual effect on the on board measurements can, however, not be determined from this test.

A second test was performed to achieve this. Only 10 cm needles and 50 mm and 75 mm samples were used, and measurements were only performed perpendicular to sample axis.

The steps in each test sequence was as follows:

1. Needle ends in free air, five repeated measurements.
2. Needle ends covered by extra sample material, five repeated measurements.
3. Needle ends in free air, five repeated measurements.

One test sequence was run on a 50 mm sample and two sequences on 75 mm samples. Table AI 2.3 gives the average result from steps 1, 2 and 3 in each test sequence. Both the average of all five tests and three tests (neglecting 2 extreme values) of each step is given.

The results in Table AI 2.3 concur with the other data indicating that boundary effects occur when the needle probe is longer than the sample diameter.

The effect on the coefficient of anisotropy is approximately two times the deviation given in Table AI 2.3. By interpolating, we conclude that the effect on A and K_v in the laboratory measurement would be

Table AI 2.3 Comparison of thermal conductivity measured by a 100 mm needle probe with the probe ends in free air (1 and 3) and covered by sample material (2). Further explanation is given in the text.

Sample diameter	Tests	Thermal conductivity W/m K			Deviation %	
		Step 1	Step 2	Step 3	$\frac{2-1}{1}$	$\frac{2-3}{3}$
50 mm	3	1.308	1.365	1.264	4.4	8.0
	5	1.301	1.366	1.263	5.0	8.2
75 mm	3	1.385	1.389	1.379	0.3	0.7
	5	1.404	1.396	1.389	(-0.6)	0.5
75 mm	3	1.218	1.223	1.213	0.4	0.8
	5	1.234	1.242	1.215	0.6	2.2

5-10% on 63 mm samples and 2-5% on 72 mm samples. The thermal conductivity is, however, slightly higher in the samples from the heat flow sites than in the samples from the laboratory and this may also increase the above effect slightly. We therefore choose to apply a correction of 8% and 4% respectively.

AI 2.6 Combined down-hole temperature and thermal conductivity probe

The combined in situ temperature and thermal conductivity tool was designed and built by Fugro. This tool is based on a needle with dimensions 100 mm by 6 mm which is connected to the WISON deploying system via an epoxy amplifier housing similarly as the temperature probe.

The probe comprises two thermistors, one at the tip of the probe and one at the center of the probe. In addition a heating wire follows the entire probe similarly as for a standard needle probe.

The diameter/length ratio of the in situ probe is about 1:16.7 which is higher than the often used ratios of 1:30 - 1:40 for needle probes. Thus the in situ probe deviates more from the ideal infinite line source than a standard needle probe. This is, however, not found to affect the results (see also Figure AI 2.3).

The reliability of the thermal conductivity values obtained by the in situ probe can also be evaluated from the plot in Figure AI 2.4 where the result

from one of the Fugro 100 mm by 6 mm in situ needle probes is cross-plotted with corresponding values obtained by a 125 mm by 3 mm standard probe from Geotherm in Canada. This plot shows good correlation.

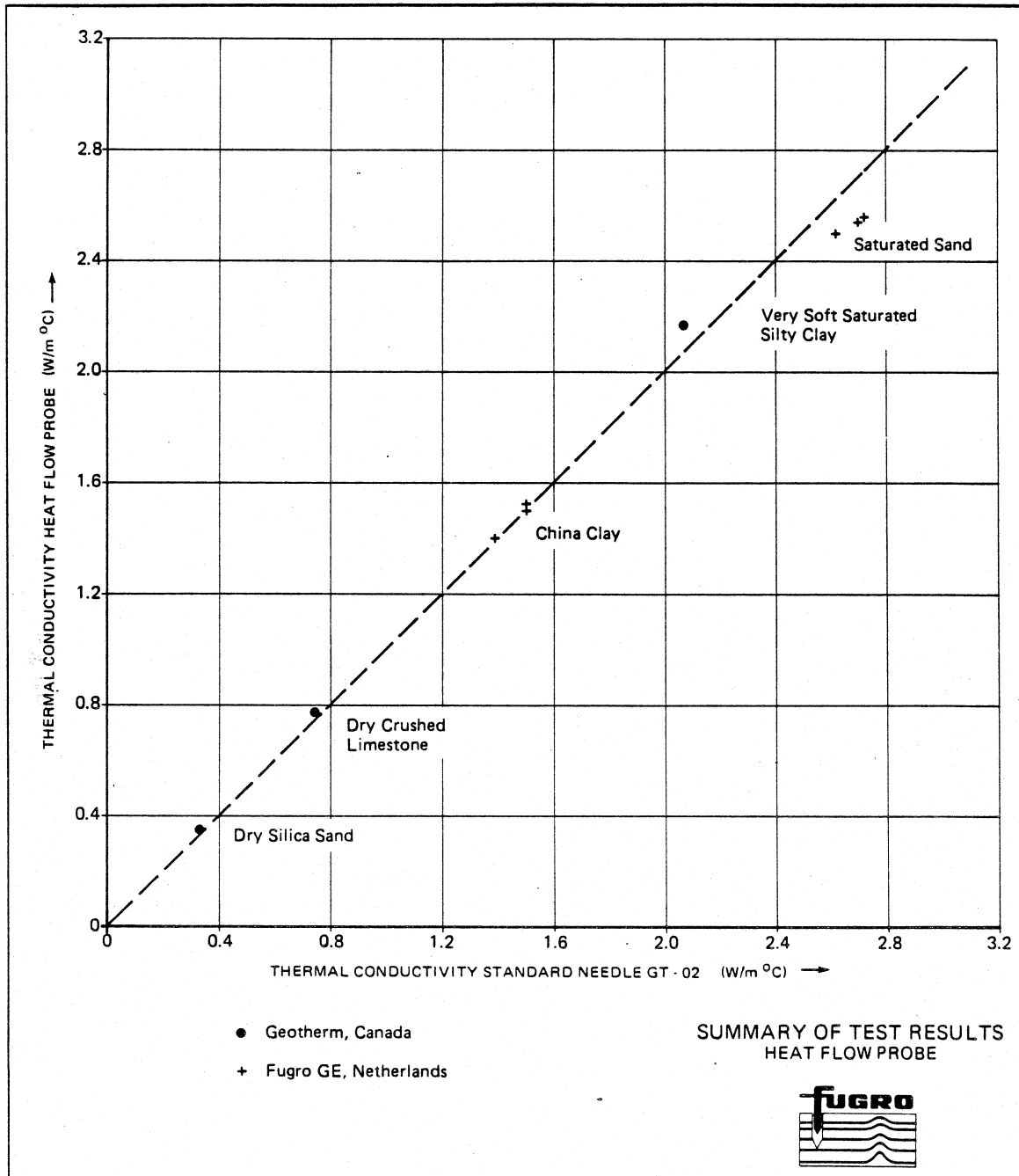


Figure AI 2.4 Comparison of thermal conductivity measured by the Fugro in situ probe and a standard probe from Geotherm, Canada. (The plot is shown by permission from Fugro-McClelland Engineers B.V., The Netherlands, for restricted use and must not be reproduced without their written permission).

A P P E N D I X I I

REPORT FROM THERMAL CONDUCTIVITY ANALYSIS IN AARHUS, DENMARK.

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AII 1. INTRODUCTION

In the present Appendix we enclose a brief report by N. Balling, University of Aarhus about the analyses of thermal conductivity that were done on Quaternary samples from the 1987 heat flow sites.

We note that the average values for thermal conductivity given in the present appendix are not restricted to the depth intervals that the temperature gradients are calculated for.

THERMAL CONDUCTIVITY - 15 QUATERNARY SAMPLES - BARENTS SEA 1987

Introduction

Thermal conductivity has been measured on 15 core samples of Quaternary rocks from the IKU-1987 cores. Thermal conductivity anisotropy is measured on all samples. Measurements were carried out at room temperature ($\sim 20^{\circ}\text{C}$) and at pressure 1 bar. No significant drying of cores was observed. In addition to these measurements further measurements were carried out on 6 samples to test for pressure dependence on conductivity and the coefficient of conductivity anisotropy within a low pressure range of 1 to 10 bar. All measurements were taken by the needle probe method. The probes used have a length of 50 mm and an outer diameter of 1.5 mm.

Thermal conductivity and conductivity anisotropy

For the "15 cores, 20°C , 1 bar" data-set, 5 single measurements were taken in each sample (fig. 1). Measuring results are summarized in table 1. For each sample, 3 data-sets are given, "top", "bottom", and "mean", each containing horizontal conductivity (kh), vertical conductivity (kv) and coefficient of conductivity anisotropy ($A = kh/kv$). The "mean" values result from using all 5 measurements combined. (The central measurement is neither used in "top" nor "bottom" sets).

For the data-set as a whole also average values (kav), standard deviation (s), and standard error of mean ($s.err. = s/\sqrt{n}$) are given. Since the A-values are determined as a squared ratio of observations ($A = kh^2/km^2$, $km = (kh \cdot hv)^{1/2}$) some variability is to be expected due to the combined effect of experimental uncertainty and local conductivity variability not necessarily associated with well defined conductivity anisotropy. From experience experimental uncertainty is likely to be about $\pm 5\%$ on single values. However, as will appear also from the present data-set, mean values resulting from averaging over 5-10 samples normally yield well defined mean values and a low degree of anisotropy ($< 10\%$) may thus be extracted. The mean values of table 1 clearly show a high degree of internal consistency and accuracy. We find kh-values of 1.67, 1.66, and 1.67 $\text{W m}^{-1} \text{K}^{-1}$ for "mean", "top", and "bottom", respectively. The equivalent values for kv are 1.56, 1.59, and 1.58 $\text{W m}^{-1} \text{K}^{-1}$, and for A, 1.07, 1.05, and 1.07. The associated standard errors are 0.03 to 0.05 for conductivity and 0.02 to 0.04 for the coefficient of anisotropy.

We observe, as to be expected, a slightly higher standard deviation and standard error for kv as compared to kh; kv is determined as a ratio (km^2/kh) of measured values, and "accumulated experimental uncertainty" is included.

The data-set seems sufficiently large to reveal on an average lower vertical conductivity as compared to horizontal conductivity and thus a significant, although small, conductivity anisotropy. The average value of A of 1.07 for the 15 "sample mean values" and the associated standard error of 0.03 are considered as well defined.

Thermal conductivity as a function of pressure (1 to 10 bar)

From the above set of cores, 6 samples were selected for conductivity-pressure measurements, to test for any minor effects resulting from unloading, transportation etc.

Measurements were taken with the needle placed as usual in the two mutually perpendicular directions at 9 different (vertical) pressure levels between 1 and 10 bar (1, 2, 3, 4, 5, 1, 7, 10 and 1 bar). The 1 bar measurements after 5 and 10 bar were taken to test for conductivity hysteresis.

The measurements were carried out with the core samples placed in a cylinder of 50 mm diameter and height 60 mm, through which the needle probe used could be inserted into the sample from bottom to yield k_h and from side to yield k_m . The samples were "surrounded by" quartz sand filling the space between the measuring cylinder and rock sample. The pressure was supplied hydraulically to a cylindrical dish on top of the quartz sand, thus resulting in a dominating vertical pressure component but with significant horizontal components. The single pressure values are read from a stressmeter with digital display. Inaccuracy of pressure is generally less than 5%.

The measuring results are summarized in table 2. Conductivity values are normalized to conductivity at 1 bar (first measurement) to emphasize relative variations. (For one sample (No. 5) results are normalized to the values of 2 bar due to rather high uncertainty of the 1 bar results). Average values, standard deviation and standard error of average value are calculated. A few data showing higher than normal experimental uncertainty (values in brackets) are omitted from averaging. Although only 6 samples are measured, the data set shows a high degree of accuracy and seems sufficiently large to yield well defined average values. Within the pressure range 1 to 5 bar we resolve no conductivity nor conductivity anisotropy variations. Around 7-10 bar a small ($\leq 5\%$) increase in vertical conductivity and decrease in anisotropy may be indicated, but not defined. Although minor unwanted sample deformations cannot generally be excluded and some of the deviations from mean values may be due to such effects, the average values are sufficiently well defined to exclude a significant effect of pressure on conductivity and conductivity anisotropy for the present core materials with the pressure range of 1 to 5 bar.

General

From the two data-sets we observe that if conductivity anisotropy is to be resolved to an accuracy better than 5-10% on core materials of the present (quite homogeneous) conductivity structure, generally some averaging of single measuring values is necessary. Single observations of A may be "in error" by, i.e. deviate from sample representative values by, up to 10 to 15%, resulting from combined local conductivity variations and experimental uncertainty. Thus unaveraged needle probe data should generally not be used to extract vertical conductivity to be used in heat flow determination and thermal modelling

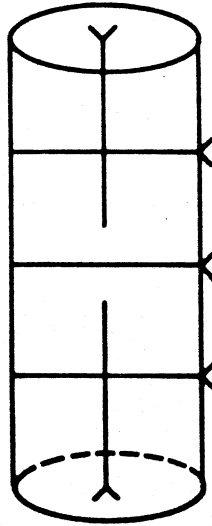


Fig. 1.

Table 1

kh - normalized data

Pressure (bar) :			1	2	3	4	5	1	7	10	1
1	-7230/05-U-05	12.26	1.00	0.97	0.97	0.99	1.02	1.02	1.04	1.05	1.08
2	-7230/05-U-05	15.17	1.00	0.93	0.93	0.96	0.96	(0.73)	(0.82)	0.93	0.92
3	-7227/11-U-01C	19.84	1.00	1.00	1.01	1.01	1.01	1.02	(1.07)	1.01	1.01
4	-7230/08-U-01	20.49	1.00	0.99	1.01	1.01	1.01	1.00	1.01	1.01	1.02
5	-7227/11-U-01C	25.08		1.00	0.99	0.98	0.96	0.97	0.96	0.99	0.97
6	-7230/08-U-01	30.50	1.00	0.98	0.95	1.01	1.01	1.00	1.01	1.02	0.99
kav :			1.00	0.98	0.98	1.00	1.00	1.00	1.01	1.00	1.00
s :			0.00	0.02	0.03	0.02	0.02	0.02	0.02	0.03	0.05
s.err. :			0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02

kv - normalized data

Pressure (bar) :			1	2	3	4	5	1	7	10	1
1	-7230/05-U-05	12.26	1.00	(0.87)	0.93	1.00	1.00	0.97	1.12	1.07	1.01
2	-7230/05-U-05	15.17	1.00	0.92	0.99	0.98	0.96	(1.23)	(1.18)	1.08	1.05
3	-7227/11-U-01C	19.84	1.00	0.97	0.96	0.96	0.96	0.91	(0.88)	0.94	0.96
4	-7230/08-U-01	20.49	1.00	0.93	0.92	0.98	0.99	1.00	0.99	1.07	1.06
5	-7227/11-U-01C	25.08		1.00	1.02	0.99	1.01	(0.88)	0.99	1.01	1.00
6	-7230/08-U-01	30.50	1.00	1.02	1.07	1.06	1.09	1.15	1.12	1.07	1.08
kav :			1.00	0.97	0.98	1.00	1.00	1.01	1.05	1.04	1.03
s :			0.00	0.03	0.05	0.03	0.04	0.08	0.06	0.04	0.04
s.err. :			0.00	0.01	0.02	0.01	0.02	0.03	0.02	0.02	0.01

km - normalized data

Pressure (bar) :			1	2	3	4	5	1	7	10	1
1	-7230/05-U-05	12.26	1.00	(0.92)	0.95	1.00	1.01	0.99	1.08	1.06	1.05
2	-7230/05-U-05	15.17	1.00	0.93	0.96	0.97	0.96	0.95	0.98	1.00	0.98
3	-7227/11-U-01C	19.84	1.00	0.98	0.98	0.99	0.99	0.96	0.97	0.98	0.98
4	-7230/08-U-01	20.49	1.00	0.96	0.97	1.00	1.00	1.00	1.00	1.04	1.04
5	-7227/11-U-01C	25.08		1.00	1.00	0.99	0.99	(0.92)	0.98	1.00	0.99
6	-7230/08-U-01	30.50	1.00	1.00	1.01	1.04	1.05	1.07	1.06	1.04	1.03
kav :			1.00	0.97	0.98	1.00	1.00	1.00	1.01	1.02	1.01
s :			0.00	0.03	0.02	0.02	0.02	0.04	0.04	0.03	0.03
s.err. :			0.00	0.01	0.01	0.01	0.01	0.02	0.02	0.01	0.01

A = kh/kv (nonnormalized A)

Pressure (bar) :			1	2	3	4	5	1	7	10	1
1	-7230/05-U-05	12.26	1.17	(1.31)	1.23	1.16	1.20	1.23	1.09	1.15	1.26
2	-7230/05-U-05	15.17	1.19	1.20	1.11	1.17	1.18	(0.71)	(0.83)	1.02	1.05
3	-7227/11-U-01C	19.84	0.85	0.88	0.89	0.90	0.90	0.96	(1.03)	0.91	0.89
4	-7230/08-U-01	20.49	1.17	1.24	1.28	1.20	1.20	1.17	1.19	1.10	1.12
5	-7227/11-U-01C	25.08	(0.73)	0.93	0.90	0.92	0.89	(1.03)	0.91	0.92	0.91
6	-7230/08-U-01	30.50	1.17	1.12	1.04	1.11	1.08	1.01	1.05	1.10	1.07
kav :			1.11	1.08	1.07	1.08	1.08	1.09	1.06	1.03	1.05
s :			0.12	0.13	0.13	0.11	0.12	0.10	0.09	0.08	0.12
s.err. :			0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.03	0.05

Table 2

Quaternary samples :

Nr. :		kh	Mean		A	kh	Top		A	kh	Bottom		A
			kv				kv				kv		
1	-7227/11-U-01C 19.08	1.62	1.63	0.99		1.61	1.71	0.94		1.62	1.68	0.97	
2	-7227/11-U-01C 19.84	1.88	1.81	1.04		1.78	1.90	0.93		1.98	1.79	1.10	
3	-7227/11-U-01C 20.14	1.85	1.90	0.97		1.89	1.86	1.01		1.81	1.85	0.98	
4	-7227/11-U-01C 25.08	1.61	1.74	0.93		1.62	1.76	0.92		1.60	1.81	0.88	
5	-7227/11-U-01C 25.23	1.82	1.71	1.06		1.87	1.61	1.16		1.77	1.82	0.97	
6	-7227/11-U-01C 29.89	1.77	1.65	1.07		1.83	1.71	1.07		1.70	1.65	1.03	
7	-7227/11-U-01C 30.04	1.66	1.76	0.94		1.63	1.69	0.97		1.68	1.80	0.93	
8	-7230/08-U-01 14.42	1.50	1.32	1.13		1.50	1.31	1.14		1.49	1.35	1.11	
9	-7230/08-U-01 19.05	1.46	1.47	0.99		1.52	1.51	1.01		1.40	1.50	0.93	
10	-7230/08-U-01 20.49	1.50	1.44	1.04		1.55	1.38	1.12		1.45	1.45	1.00	
11	-7230/08-U-01 24.43	1.50	1.37	1.09		1.49	1.33	1.12		1.51	1.37	1.11	
12	-7230/08-U-01 30.50	1.70	1.41	1.20		1.68	1.57	1.07		1.71	1.38	1.24	
13	-7230/05-U-05 12.10	1.64	1.41	1.16		1.55	1.58	0.98		1.72	1.27	1.36	
14	-7230/05-U-05 12.26	1.72	1.29	1.33		1.66	1.40	1.19		1.77	1.33	1.33	
15	-7230/05-U-05 15.17	1.79	1.52	1.18		1.79	1.50	1.19		1.78	1.62	1.10	
kav :		1.67	1.56	1.07		1.66	1.59	1.05		1.67	1.58	1.07	
s :		0.13	0.18	0.10		0.13	0.17	0.09		0.15	0.20	0.14	
s.err. :		0.03	0.05	0.03		0.03	0.04	0.02		0.04	0.05	0.04	

Table 2

Quaternary samples :

Nr. :		kh	Mean		A	kh	Top		A	kh	Bottom		A
			kv				kv				kv		
1	-7227/11-U-01C 19.08	1.62	1.63	0.99		1.61	1.71	0.94		1.62	1.68	0.97	
2	-7227/11-U-01C 19.84	1.88	1.81	1.04		1.78	1.90	0.93		1.98	1.79	1.10	
3	-7227/11-U-01C 20.14	1.85	1.90	0.97		1.89	1.86	1.01		1.81	1.85	0.98	
4	-7227/11-U-01C 25.08	1.61	1.74	0.93		1.62	1.76	0.92		1.60	1.81	0.88	
5	-7227/11-U-01C 25.23	1.82	1.71	1.06		1.87	1.61	1.16		1.77	1.82	0.97	
6	-7227/11-U-01C 29.89	1.77	1.65	1.07		1.83	1.71	1.07		1.70	1.65	1.03	
7	-7227/11-U-01C 30.04	1.66	1.76	0.94		1.63	1.69	0.97		1.68	1.80	0.93	
kav :		1.74	1.74	1.00		1.75	1.75	1.00		1.74	1.77	0.98	
s :		0.10	0.08	0.05		0.11	0.09	0.08		0.11	0.06	0.06	
s.err. :		0.04	0.03	0.02		0.04	0.03	0.03		0.04	0.02	0.02	
8	-7230/08-U-01 14.42	1.50	1.32	1.13		1.50	1.31	1.14		1.49	1.35	1.11	
9	-7230/08-U-01 19.05	1.46	1.47	0.99		1.52	1.51	1.01		1.40	1.50	0.93	
10	-7230/08-U-01 20.49	1.50	1.44	1.04		1.55	1.38	1.12		1.45	1.45	1.00	
11	-7230/08-U-01 24.43	1.50	1.37	1.09		1.49	1.33	1.12		1.51	1.37	1.11	
12	-7230/08-U-01 30.50	1.70	1.41	1.20		1.68	1.57	1.07		1.71	1.38	1.24	
kav :		1.53	1.40	1.09		1.55	1.42	1.09		1.51	1.41	1.08	
s :		0.08	0.05	0.06		0.06	0.09	0.04		0.09	0.05	0.09	
s.err. :		0.03	0.02	0.03		0.03	0.04	0.02		0.04	0.02	0.04	
13	-7230/05-U-05 12.10	1.64	1.41	1.16		1.55	1.58	0.98		1.72	1.27	1.36	
14	-7230/05-U-05 12.26	1.72	1.29	1.33		1.66	1.40	1.19		1.77	1.33	1.33	
15	-7230/05-U-05 15.17	1.79	1.52	1.18		1.79	1.50	1.19		1.78	1.62	1.10	
kav :		1.72	1.41	1.22		1.67	1.49	1.12		1.76	1.41	1.26	
s :		0.05	0.08	0.06		0.08	0.06	0.08		0.02	0.12	0.09	
s.err. :		0.03	0.04	0.04		0.05	0.03	0.05		0.01	0.07	0.05	

Data-set averages :

kav :	1.67	1.56	1.07	1.66	1.59	1.05	1.67	1.58	1.07
s :	0.13	0.18	0.10	0.13	0.17	0.09	0.15	0.20	0.14
s.err. :	0.03	0.05	0.03	0.03	0.04	0.02	0.04	0.05	0.04

A P P E N D I X I I I

DETAILS OF HEAT FLOW MODELLING RESULTS.

	Page
Case A: Minimum Heat Flow Anomaly (including mesh and start temperatures)	2
Case B: Case A with summation of conductivities instead of resistivities	9
Case C: Maximum Heat Flow Anomaly	10

Case A.

```

*****
* NRAD-system initiated at 8:56:48 on 18/ 1-1988 *
* Version: 1-88 *
*****
  
```

```

*****
  
```

```

* Input data *
  
```

```

*****
  
```

Salt structure geometry and input data.

```

* Control data *
  
```

```

    1    1    1    1    1    1
    1    0
  
```

Continued simulation

```

    1-0.100E+01 0.100E+19 0.200E+21 0.100E+19
    1.00000    4.00000    0.00000
  
```

IKU

```

* Material data *
  
```

```

    6    0    0
  
```

Material number 1: Conductivity = 1.5 W/mK

```

    2    0    2    0
    -100.0000 1000.0000
    0.150E+01 0.150E+01
    -100.0000 1000.0000
    0.100E+07 0.100E+07
  
```

Material number 2: Conductivity = 2 W/mK

```

    2    0    2    0
    -100.0000 1000.0000
    0.200E+01 0.200E+01
    -100.0000 1000.0000
    0.100E+07 0.100E+07
  
```

Material number 3: Conductivity = 3 W/mK

```

    2    0    2    0
    -100.0000 1000.0000
    0.300E+01 0.300E+01
    -100.0000 1000.0000
    0.100E+07 0.100E+07
  
```

Material number 4: 15 % Salt (3.19 W/mK)

```

    2    0    2    0
    -100.0000 1000.0000
    0.319E+01 0.319E+01
    -100.0000 1000.0000
    0.100E+07 0.100E+07
  
```

Material number 5: 25 % Salt (3.33 W/mK)

```

    2    0    2    0
    -100.0000 1000.0000
    0.333E+01 0.333E+01
    -100.0000 1000.0000
    0.100E+07 0.100E+07
  
```

Material number 6: 40 % Salt (3.57 W/mK)

```

    2    0    2    0
    -100.0000 1000.0000
    0.357E+01 0.357E+01
    -100.0000 1000.0000
    0.100E+07 0.100E+07
  
```

```

* Geometry data *
  
```

```

    174    49    63    1    0
  
```

Scale factors and inner radius:

```

    1000.00000    1000.00000    0.00000
  
```

Node coordinates:

1	0.00000	0.00000	61	12700.00000	-6075.00000
2	0.00000	-1000.00000	62	13050.00000	-9450.00000
3	0.00000	-2000.00000	63	12342.45000	-10525.00000
4	0.00000	-4250.00000	64	11875.00000	-12772.20000
5	0.00000	-6500.00000	65	10650.00000	-14600.00000
6	0.00000	-8250.00000	66	10650.00000	-25000.00000
7	0.00000	-10000.00000	67	13000.00000	-3650.00000
8	0.00000	-11000.00000	68	12300.00000	-4500.00000
9	0.00000	-12000.00000	69	13300.00000	-5200.00000
10	0.00000	-13000.00000	70	14000.00000	0.00000
11	0.00000	-14000.00000	71	14000.00000	-162.50000
12	0.00000	-19500.00000	72	14000.00000	-325.00000
13	0.00000	-25000.00000	73	13875.00000	-912.50000
14	4225.00000	0.00000	74	13750.00000	-1500.00000
15	4225.00000	-2000.00000	75	13725.00000	-2150.00000
16	2775.00000	-6500.00000	76	13700.00000	-2800.00000
17	2775.00000	-10000.00000	77	14350.00000	-3650.00000
18	2500.00000	-12000.00000	78	15000.00000	-4500.00000
19	2000.00000	-14000.00000	79	14650.00000	-5200.00000
20	2000.00000	-25000.00000	80	14300.00000	-5900.00000
21	5550.00000	-6500.00000	81	14075.00000	-6325.00000
22	5550.00000	-8250.00000	82	13850.00000	-6750.00000
23	5550.00000	-10000.00000	83	13775.00000	-8100.00000
24	5275.00000	-11000.00000	84	13700.00000	-9450.00000
25	5000.00000	-12000.00000	85	13350.00000	-10100.00000
26	4500.00000	-13000.00000	86	13000.00000	-10750.00000
27	4000.00000	-14000.00000	87	13500.00000	-11847.20000
28	4000.00000	-19500.00000	88	14000.00000	-12944.40000
29	4000.00000	-25000.00000	89	14400.00000	-13822.20000
30	7000.00000	-4250.00000	90	14800.00000	-14700.00000
31	8050.00000	-5800.00000	91	14800.00000	-19850.00000
32	8975.00000	-7975.00000	92	14800.00000	-25000.00000
33	8617.45000	-10150.00000	93	15225.00000	0.00000
34	7375.00000	-12300.00000	94	15225.00000	-325.00000
35	5250.00000	-14250.00000	95	15225.00000	-1225.00000
36	5250.00000	-25000.00000	96	15325.00000	-2300.00000
37	8450.00000	0.00000	97	16750.00000	-4585.50000
38	8450.00000	-1000.00000	98	17150.00000	-6675.00000
39	8450.00000	-2000.00000	99	17150.00000	-7600.00000
40	9575.00000	-2800.00000	100	17350.00000	-9725.00000
41	10700.00000	-3600.00000	101	17250.00000	-11400.00000
42	10625.00000	-4350.00000	102	17750.00000	-13372.20000
43	10550.00000	-5100.00000	103	18150.00000	-15200.00000
44	11050.00000	-5250.00000	104	18150.00000	-25000.00000
45	11550.00000	-5400.00000	105	16450.00000	0.00000
46	11975.00000	-7425.00000	106	16450.00000	-162.50000
47	12400.00000	-9450.00000	107	16450.00000	-325.00000
48	12042.45000	-9875.00000	108	16575.00000	-637.50000
49	11684.90000	-10300.00000	109	16700.00000	-950.00000
50	10717.45000	-11450.00000	110	16825.00000	-1375.00000
51	9750.00000	-12600.00000	111	16950.00000	-1800.00000
52	8125.00000	-13550.00000	112	17725.00000	-3235.50000
53	6500.00000	-14500.00000	113	18225.00000	0.00000
54	6500.00000	-19750.00000	114	18225.00000	-912.50000
55	6500.00000	-25000.00000	115	18350.00000	-1525.00000
56	11225.00000	0.00000	116	18475.00000	-2450.00000
57	11225.00000	-1162.50000	117	18500.00000	-4671.00000
58	12225.00000	-2550.00000	118	19250.00000	-4585.50000
59	11500.00000	-4050.00000	119	20000.00000	0.00000
60	11925.00000	-4950.00000	120	20000.00000	-750.00000

121	20000.00000	-1500.00000
122	20000.00000	-1800.00000
123	20000.00000	-2100.00000
124	20000.00000	-2600.00000
125	20000.00000	-3100.00000
126	20000.00000	-3800.00000
127	20000.00000	-4500.00000
128	19250.00000	-6060.50000
129	20000.00000	-7450.00000
130	20225.00000	-7950.00000
131	20450.00000	-8450.00000
132	20725.00000	-9225.00000
133	21000.00000	-10000.00000
134	21250.00000	-11025.00000
135	21500.00000	-12050.00000
136	21500.00000	-12925.00000
137	21500.00000	-13800.00000
138	21500.00000	-14750.00000
139	21500.00000	-15700.00000
140	21500.00000	-20350.00000
141	21500.00000	-25000.00000
142	22000.00000	0.00000
143	22000.00000	-1500.00000
144	22000.00000	-2100.00000
145	22000.00000	-3100.00000
146	22000.00000	-6100.00000
147	22000.00000	-7575.00000
148	22225.00000	-8450.00000
149	22500.00000	-10000.00000
150	22750.00000	-11800.00000
151	22750.00000	-13800.00000
152	22750.00000	-15700.00000
153	22750.00000	-25000.00000
154	24000.00000	0.00000
155	24000.00000	-750.00000
156	24000.00000	-1500.00000
157	24000.00000	-1800.00000
158	24000.00000	-2100.00000
159	24000.00000	-2600.00000
160	24000.00000	-3100.00000
161	24000.00000	-5400.00000
162	24000.00000	-7700.00000
163	24000.00000	-8075.00000
164	24000.00000	-8450.00000
165	24000.00000	-9225.00000
166	24000.00000	-10000.00000
167	24000.00000	-10775.00000
168	24000.00000	-11550.00000
169	24000.00000	-12675.00000
170	24000.00000	-13800.00000
171	24000.00000	-14750.00000
172	24000.00000	-15700.00000
173	24000.00000	-20350.00000
174	24000.00000	-25000.00000

Elements:

1	1	2	3	15	39	38	37	14	1
2	3	4	5	16	21	30	39	15	2
3	5	6	7	17	23	22	21	16	3
4	7	8	9	18	25	24	23	17	3
5	9	10	11	19	27	26	25	18	3
6	11	12	13	20	29	28	27	19	3

7	37	38	39	57	72	71	70	56	1
8	39	40	41	58	74	73	72	57	2
9	21	31	43	42	41	40	39	30	2
10	21	32	47	46	45	44	43	31	3
11	21	22	23	33	49	48	47	32	3
12	23	24	25	34	51	50	49	33	3
13	25	26	27	35	53	52	51	34	3
14	27	28	29	36	55	54	53	35	3
15	41	59	68	67	76	75	74	58	3
16	41	42	43	44	45	60	68	59	3
17	68	69	80	79	78	77	76	67	5
18	45	61	82	81	80	69	68	60	5
19	45	46	47	62	84	83	82	61	4
20	47	48	49	63	86	85	84	62	4
21	49	50	51	64	88	87	86	63	6
22	51	52	53	65	90	89	88	64	6
23	53	54	55	66	92	91	90	65	3
24	70	71	72	94	107	106	105	93	1
25	72	73	74	95	109	108	107	94	2
26	74	75	76	96	111	110	109	95	3
27	76	77	78	97	117	112	111	96	5
28	78	79	80	98	129	128	117	97	5
29	80	81	82	99	131	130	129	98	5
30	82	83	84	100	133	132	131	99	4
31	84	85	86	101	135	134	133	100	4
32	86	87	88	102	137	136	135	101	3
33	88	89	90	103	139	138	137	102	3
34	90	91	92	104	141	140	139	103	3
35	105	106	107	114	121	120	119	113	1
36	107	108	109	115	123	122	121	114	2
37	109	110	111	116	125	124	123	115	2
38	111	112	117	118	127	126	125	116	2
39	119	120	121	143	156	155	154	142	1
40	121	122	123	144	158	157	156	143	2
41	123	124	125	145	160	159	158	144	2
42	125	126	127	146	162	161	160	145	2
43	117	128	129	147	162	146	127	118	2
44	129	130	131	148	164	163	162	147	4
45	131	132	133	149	166	165	164	148	4
46	133	134	135	150	168	167	166	149	4
47	135	136	137	151	170	169	168	150	3
48	137	138	139	152	172	171	170	151	3
49	139	140	141	153	174	173	172	152	3

Band width: 51 Element no: 28

Node numbering not optimal!

* Initial temperature data *

1		
2	2	1
6.0000	494.0000	
1	154	
13	174	
0.0000	1.0000	
0.0000	1.0000	
1	6.0000	6.0000
2	41.7083	42.3668
3	77.5936	78.9092
4	137.7305	140.1222
5	198.6166	202.0383
6	230.4148	234.3383
7	262.5933	266.9855
8	281.2054	285.8505

9	299.9537	304.8393	71	14.4562	14.6097
10	318.8327	323.9445	72	22.9267	23.2343
11	337.7904	343.1140	73	44.6525	45.3545
12	444.1195	450.3127	74	66.1671	67.2586
13	553.0751	559.5723	75	83.0343	84.4294
14	6.0000	6.0000	76	99.7939	101.4885
15	77.2365	78.5447	77	118.0893	120.1065
16	198.1026	201.5147	78	136.8735	139.2177
17	262.1606	266.5441	79	152.4986	155.1102
18	299.5960	304.4743	80	167.5653	170.4318
19	337.5827	342.9021	81	176.5357	179.5515
20	552.9637	559.4587	82	185.3743	188.5356
21	196.6186	200.0010	83	214.2270	217.8475
22	228.3528	232.2330	84	242.0857	246.1280
23	260.6616	265.0143	85	255.7905	260.0311
24	279.6123	284.2247	86	269.3406	273.7711
25	298.6596	303.5180	87	290.6130	295.3256
26	317.7059	322.7962	88	311.4414	316.4120
27	336.9616	342.2691	89	327.7341	332.8926
28	443.6169	449.8009	90	343.8588	349.1908
29	552.7265	559.2170	91	447.7925	453.9579
30	137.1890	139.5620	92	550.4546	556.8977
31	178.8601	181.9381	93	6.0000	6.0000
32	218.6170	222.3288	94	22.7244	23.0282
33	261.2088	265.5512	95	57.8644	58.8051
34	303.1341	308.0359	96	85.7587	87.2014
35	340.9464	346.2918	97	139.3080	141.6935
36	552.3486	558.8324	98	184.8524	188.0044
37	6.0000	6.0000	99	203.9430	207.4021
38	41.8306	42.4871	100	246.9735	251.0869
39	77.3140	78.6173	101	279.1422	283.7023
40	98.5876	100.2708	102	318.5138	323.5639
41	121.8886	123.9816	103	354.9260	360.3689
42	139.1968	141.5918	104	550.3414	556.7783
43	157.7689	160.4841	105	6.0000	6.0000
44	159.0628	161.7962	106	14.5930	14.7491
45	160.6798	163.4392	107	23.2100	23.5227
46	202.1867	205.6241	108	35.1994	35.7299
47	243.6835	247.7535	109	46.9322	47.6756
48	253.2167	257.4248	110	60.0329	61.0133
49	262.4825	266.8237	111	72.8702	74.0823
50	285.7409	290.4014	112	109.6074	111.4762
51	308.2410	313.1906	113	6.0000	6.0000
52	326.8310	332.0070	114	42.4946	43.1592
53	344.8030	350.1830	115	60.4184	61.4085
54	447.8982	454.0968	116	86.2726	87.7288
55	551.9507	558.4276	117	144.3993	146.8765
56	6.0000	6.0000	118	140.4677	142.8809
57	52.1440	52.9850	119	6.0000	6.0000
58	95.7307	97.3555	120	32.7983	33.2879
59	131.0397	133.2901	121	59.1693	60.1394
60	150.6028	153.1893	122	67.2248	68.3410
61	172.6432	175.5981	123	75.2071	76.4676
62	242.8563	246.9117	124	88.4479	89.9470
63	266.0545	270.4420	125	101.4889	103.2212
64	308.8188	313.7639	126	119.8942	121.9495
65	342.3121	347.6427	127	137.8617	140.2316
66	551.7236	558.1899	128	176.7378	179.7613
67	120.1649	122.2208	129	208.6695	212.2113
68	140.1897	142.5957	130	218.0653	221.7549
69	153.4976	156.1291	131	227.2947	231.1266
70	6.0000	6.0000			

132	241.6914	245.7383
133	255.9068	260.1586
134	274.9192	279.4319
135	293.9188	298.6781
136	311.0091	315.9765
137	328.1775	333.3413
138	346.7621	352.1250
139	365.4853	371.0325
140	457.6140	463.8220
141	550.6106	557.0484
142	6.0000	6.0000
143	58.5693	59.5306
144	74.2821	75.5283
145	100.4087	102.1233
146	177.3032	180.3430
147	214.9514	218.5977
148	230.0306	233.9087
149	257.1870	261.4602
150	289.5631	294.2689
151	328.3592	333.5264
152	365.5908	371.1395
153	550.5507	556.9874
154	6.0000	6.0000
155	32.1042	32.5829
156	58.3574	59.3158
157	66.1837	67.2845
158	74.0298	75.2730
159	86.9509	88.4282
160	99.9055	101.6158
161	159.4819	162.2235
162	219.0588	222.7721
163	225.0197	228.8244
164	231.1841	235.0819
165	244.1932	248.2827
166	257.6700	261.9514
167	271.2665	275.7342
168	285.0958	289.7455
169	306.6220	311.5389
170	328.4104	333.5787
171	346.9894	352.3556
172	365.6175	371.1665
173	457.6771	463.8855
174	550.5223	556.9586

* Boundary condition data *
 Temperature boundary conditions:

1	
2	
0.000E+00	0.100E+19
6.0000	6.0000
11	
1	1
14	1
37	1
56	1
70	1
93	1
105	1
113	1
119	1
142	1
154	1

Heat flow density boundary conditions:

```

1
2
0.000E+00 0.100E+19
-0.0600 -0.0600
5
20 1
36 1
66 1
104 1
153 1

```

Convection boundary conditions:

0

Radiation boundary conditions:

0

* Output data *

```

1
1 1 1
0 0
1
4
70 76 82 92
2
11 1
1 14 37 56 70 93 105 113 119 142 154
11 1
13 20 29 36 55 66 92 104 141 153 174
1

```

IKU

* Start of simulation *

* Time: 0.209497E+18 Number of time steps: 0 Time step: 0.10E+18 *

Temperatures:

```

70 6.0000 76 101.4885 82 188.5356 92 556.8977
1 1
0.0000

```

* Time: 0.313847E+18 Number of time steps: 1 Time step: 0.10E+18 *

Temperatures:

```

70 6.0000 76 101.4885 82 188.5356 92 556.8977

```

Heat flow densities:

```

1, 14, 37: 0.545E-01 37, 56, 70: 0.617E-01 70, 93, 105: 0.790E-01
105, 113, 119: 0.624E-01 119, 142, 154: 0.536E-01

```

Boundary average: 0.597E-01

```

13, 20, 29: -0.600E-01 29, 36, 55: -0.600E-01 55, 66, 92: -0.600E-01

```

```

92, 104, 141: -0.600E-01 141, 153, 174: -0.600E-01

```

Boundary average: -0.600E-01

* Simulation ended *

* Time: 0.3138468E+18 Number of time steps: 1 Time step: 0.104E+18 *

* Total CPU-time: 11.2 sec. Average CPU-time per time step: 6.66 sec. *

* End control data *

0

* NRAD-system terminated at 8:57: 2 *

Case B.

* Material data *

6 0 0
Material number 1: Conductivity = 1.5 W/mK

2 0 2 0
-100.0000 1000.0000
0.150E+01 0.150E+01
-100.0000 1000.0000
0.100E+07 0.100E+07

Material number 2: Conductivity = 2 W/mK

2 0 2 0
-100.0000 1000.0000
0.200E+01 0.200E+01
-100.0000 1000.0000
0.100E+07 0.100E+07

Material number 3: Conductivity = 3 W/mK

2 0 2 0
-100.0000 1000.0000
0.300E+01 0.300E+01
-100.0000 1000.0000
0.100E+07 0.100E+07

Material number 4: 15 % Salt (3.3 W/mK)

2 0 2 0
-100.0000 1000.0000
0.330E+01 0.330E+01
-100.0000 1000.0000
0.100E+07 0.100E+07

Material number 5: 25 % Salt (3.5 W/mK)

2 0 2 0
-100.0000 1000.0000
0.350E+01 0.350E+01
-100.0000 1000.0000
0.100E+07 0.100E+07

Material number 6: 40 % Salt (3.8 W/mK)

2 0 2 0
-100.0000 1000.0000
0.380E+01 0.380E+01
-100.0000 1000.0000
0.100E+07 0.100E+07

* Start of simulation *

* Time: 0.000000E+00 Number of time steps: 0 Time step: 0.50E+18 *

Temperatures:

70 6.0000 76 102.2486 82 186.8387 92 552.6234
1 1
0.0000

* Time: 0.500000E+18 Number of time steps: 1 Time step: 0.50E+18 *

Temperatures:

70 6.0000 76 102.2486 82 186.8387 92 552.6235

Heat flow densities:

1, 14, 37: 0.540E-01 37, 56, 70: 0.617E-01 70, 93,105: 0.799E-01
105,113,119: 0.629E-01 119,142,154: 0.534E-01

13, 20, 29: -0.600E-01 29, 36, 55: -0.600E-01 55, 66, 92: -0.600E-01
92,104,141: -0.600E-01 141,153,174: -0.600E-01

Boundary average: 0.597E-01
Boundary average: -0.600E-01

Case C.

Ground Structure under the Barents Sea - 3.5,55%

* Control data *

```

1 1 1 1 1 1
1 0

```

Continued simulation

```

1-0.100E+01 0.500E+18 0.200E+21 0.100E+20
1.00000 4.00000 0.00000

```

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* Material data *

```

6 0 0

```

Material number 1: Conductivity = 1.5 W/mK

```

2 0 2 0
-100.0000 1000.0000
0.150E+01 0.150E+01
-100.0000 1000.0000
0.100E+07 0.100E+07

```

Material number 2: Conductivity = 2 W/mK

```

2 0 2 0
-100.0000 1000.0000
0.200E+01 0.200E+01
-100.0000 1000.0000
0.100E+07 0.100E+07

```

Material number 3: Conductivity = 3.5 W/mK

```

2 0 2 0
-100.0000 1000.0000
0.350E+01 0.350E+01
-100.0000 1000.0000
0.100E+07 0.100E+07

```

Material number 4: 15 % Salt (3.725 W/mK)

```

2 0 2 0
-100.0000 1000.0000
0.372E+01 0.372E+01
-100.0000 1000.0000
0.100E+07 0.100E+07

```

Material number 5: 55 % Salt (4.325 W/mK)

```

2 0 2 0
-100.0000 1000.0000
0.432E+01 0.432E+01
-100.0000 1000.0000
0.100E+07 0.100E+07

```

Material number 6: 40 % Salt (4.1 W/mK)

```

2 0 2 0
-100.0000 1000.0000
0.410E+01 0.410E+01
-100.0000 1000.0000
0.100E+07 0.100E+07

```

* Start of simulation *

```

* Time: 0.131349E+19   Number of time steps: 0   Time step: 0.33E+18 *
Temperatures:

```

```

70 6.0000 76 102.6984 82 175.3714 92 494.8920
1 1
0.0000

```

```

* Time: 0.164117E+19   Number of time steps: 1   Time step: 0.33E+18 *

```

Temperatures:

70 6.0000 76 102.6984 82 175.3714 92 494.8920

Heat flow densities:

 1, 14, 37: 0.525E-01 37, 56, 70: 0.621E-01 70, 93, 105: 0.854E-01
 105, 113, 119: 0.638E-01 119, 142, 154: 0.514E-01

Boundary average: 0.596E-01

 13, 20, 29: -0.600E-01 29, 36, 55: -0.600E-01 55, 66, 92: -0.600E-01
 92, 104, 141: -0.600E-01 141, 153, 174: -0.600E-01

Boundary average: -0.600E-01

Heat Flow Measurements Barents Sea 1987



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