

REPORT

REPORT TITLE:

HEAT FLOW, CLOSE TO WELL 7120/6-1, BARENTS SEA 19
Report on heat flow calibration site
7120/6-U-1 close to exploration well
7120/6-1.

REPORT NO.: 21.3419.00/05/87

AUTHORS:

J. Sættem, M. Hamborg, Ø. Johansen and
Ø. Sylta



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CLIENT:

BP Petroleum Dev. Ltd., Elf Aquitaine Norge a/s, Esso Norge a.s, Mobil Exploration Norway Inc., Norsk Agip A/S, Norsk Hydro a.s, A/S Norske Shell, Statoil and license holder in block 7120/6-1.

SUMMARY:

As a part of a shallow drilling program in the Nordkapp Basin, heat flow measurements were carried out at two sites, 7227/7-U-1 and 7120/6-U-1. Site 7120/6-U-1 was located close to oil well 7120/6-1 in the Hammerfest Basin in order to compare the two methods of shallow and deep heat flow measurements.

This is a revised version of IKU report 21.3419..00/03/87 made for the licener holder in block 7120/6-1. Only site 7120/6-U-1 and data from well 7120/6-1 are discussed in this revised report.

The temperature measurements have resolution and absolute accuracy of 0.01 and 0.02°C, respectively. The high precision in this data together with a high confidence in the mean thermal conductivity values form a reliable basis for calculation of accurate heat flow values.

The calculated heat flow for site 7120/6-U-1 is close to the corresponding value from deep well 7120/6-1, but has less uncertainty. It is therefore concluded that the results of the comparison test was quite favourable for the relative simple method of shallow heat flow measurements.

KEY WORDS:	
Heat flow	Data comparison
Shallow drilling well 7120/6-U-1	Block 7120/6
Thermal conductivity	Barents Sea

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PREFACE TO REVISED VERSION

The present report is a revised version of IKU report 21.3419.00/03/87, HEAT FLOW MEASUREMENT BARENTS SEA 1986. The report gives the results of a heat flow measurement in shallow borehole 7120/6-U-1, and presents a comparison between this shallow data and heat flow based on data from exploration well 7120/6-1.

The comparison between the results from 7120/6-1 and 7120/6-U-1 has provided a valuable check of the shallow heat flow measurement method, and as the two data sets compare within narrow limits the confidence in both are strengthened.

The permission from the licence holders in block 7120 to use the data and the cooperation with the operator, Norsk Hydro a.s. is appreciated.

PREFACE

This report presents the results of heat flow measurements performed as a part of the IKU project "Nordkapp Basin, shallow seismic, shallow drilling and heat flow measurements 1986". The project was supported by the following companies:

A/S Norske Shell
BP Petroleum Development Ltd. Norway
Den norske stats oljeselskap a.s
Elf Aquitaine Norge a/s
Esso Norge a.s
Mobil Exploration Norway Inc.
Norsk Agip A/S
Norsk Hydro a.s

This participation is gratefully acknowledged.

The field work was carried out on board the M/S Bucentaur. Field work co-ordinators were K.O. Sandvik and J. Sættem. Project responsible has been T. Bugge.

Fugro G.E. BV, The Netherlands together with Omegalink International Ltd., USA performed the temperature measurements and the on board thermal conductivity measurements.

Niels Balling, University of Aarhus, Denmark, has been responsible for additional measurement of thermal conductivity and for calculation of effects from temperature history models.

Soil mechanical testing of selected samples has been carried out at the SINTEF Division of Geotechnical Engineering.

One of the objectives of the project was to perform a comparison between heat flow data collected during shallow drilling and data from an oil well. Well 7120/6-1 was found most suitable for this purpose, and we acknowledge the operator Norsk Hydro a.s and their licence partners on block 7120/6 for giving permission to do this work and for providing the necessary data to perform the work.

The following persons have contributed to the heat flow study:

Field work:	N. Aarhus, P. Chr. Andersen, E. Nesse, L. Rise, K.O. Sandvik, J.G. Verdenius
Laboratory analyses:	V. Fjerdingsstad, E. Sindre, D.A. Westgaard.
Calculation of theoretical thermal conductivity:	Ø. Johansen
Calculation of heat flow from well 7120/6-1:	C.M. Griffiths, Ø. Sylta
Review of late Quaternary history:	M. Hamborg
Drawing:	M.B. Dybvik, B. Fossum
Typing:	M.A. Sagmo
Responsible for reporting and calculation of final heat flow values:	J. Sættem

1. SUMMARY

Heat flow is measured in two shallow boreholes (site 7227/7-U-1 and site 7120/6-U-1) in the southern Barents Sea as part of the IKU project Nordkapp Basin shallow seismic, shallow drilling and heat flow measurements 1986.

The field operation was carried out on board the Norwegian drillship M/S Bucentaur and lasted from 29 July to 15 August 1986. About 66 hours were spent on the heat flow sites.

Steady state heat flow can be calculated from the simple equation

$$Q = K \frac{dT}{dz}$$

where Q is heat flow, K is vertical thermal conductivity and dT is the temperature difference over the depth interval dz .

In our investigation at site 7120/6-U-1 we have measured depth-temperature points within the depth interval 13-31 m below the sea bed. 11 in situ temperature measurements and 3 in situ and 30 on board measurements of thermal conductivity have been carried out. Based on a detailed study of the conductivity of the sediment samples, we conclude that a slight correction due to anisotropy in the thermal conductivity, should be applied.

Correction of the measured temperatures and temperature gradients due to transient effect from late Quaternary climatic changes has been quantified for two alternative glacial history models. At site 7120/6-U-1 the disturbance on the present day gradient is between

$$-4.5 \text{ and } -6.8 \cdot 10^{-3} \text{ } ^\circ\text{C/km}$$

depending on temperature history models.

From the results of the different topics studied we have arrived at the final values of heat flow given in Table 1.1.

Table 1.1 Heat flow data summary. In the final result we have accounted for variation in thermal conductivity with depth, anisotropy in conductivity and late Quaternary climatic effects.
 $1\text{HFU} = 1 \mu\text{cal}/\text{cm}^2 \text{ s}.$

Site	Field result		Final result	
	(mW/m^2)	(HFU)	(mW/m^2)	(HFU)
7120/6-U-1	68.4	1.64	70.1	1.68

The calculated heat flow for site 7120/6-U-1 is within the uncertainty limits of the heat flow calculated from data from the deep well 7120/6-1, but is about 10% higher than the value from this well.

Due to good control on temperature gradient and thermal conductivity in the shallow interval, the shallow measurement seems to be more confident than the value obtained from the deep well.

2. INTRODUCTION

2.1 Previous work

As a part of the IKU Barents Sea Mapping Program, heat flow measurements were carried out at 7 sites in the southwestern Barents Sea during summer 1985.

Accurate temperature measurements and measurements of thermal conductivity from corresponding levels were obtained at six of the seven sites. The data was obtained from depth intervals ranging from 10-34 m to 11-65 m below the sea bed. Based on this data shallow heat flow values were calculated for these sites.

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

2.2 Selection and description of the heat flow site

Based on the good experience in 1985 it was decided to include heat flow measurements also in the IKU project Nordkapp Basin shallow seismic, shallow drilling and heat flow measurements 1986.

Two sites were chosen for heat flow measurements. These sites are 7227/7-U-1 on the northwestern flank of the Nordkapp Basin and 7120/6-U-1 in the Hammerfest Basin.

Due to boulders in the Quaternary overburden two drilling attempts had to be made at both locations in order to obtain sufficient data. The second attempts were termed 7227/7-U-1B and 7120/6-U-1B, respectively and are located within a few metres from the intended positions, and all data are therefore referred to sites 7227/7-U-1 and 7120/6-U-1.

Site 7120/6-U-1 was located close to oil well 7120/6-1 in the Troms I consession area (operator: Norsk Hydro a.s). The purpose of this was to compare the shallow heat flow measurements with heat flow data from the deep

well. Well 7120/6-1 was found to be the best well for this purpose amongst the wells that all the participating companies had access to.

The detailed location of site 7120/6-U-1 was based on shallow seismic profiles shot by Gardline Surveys. This data were kindly made available by Norsk Hydro a.s.

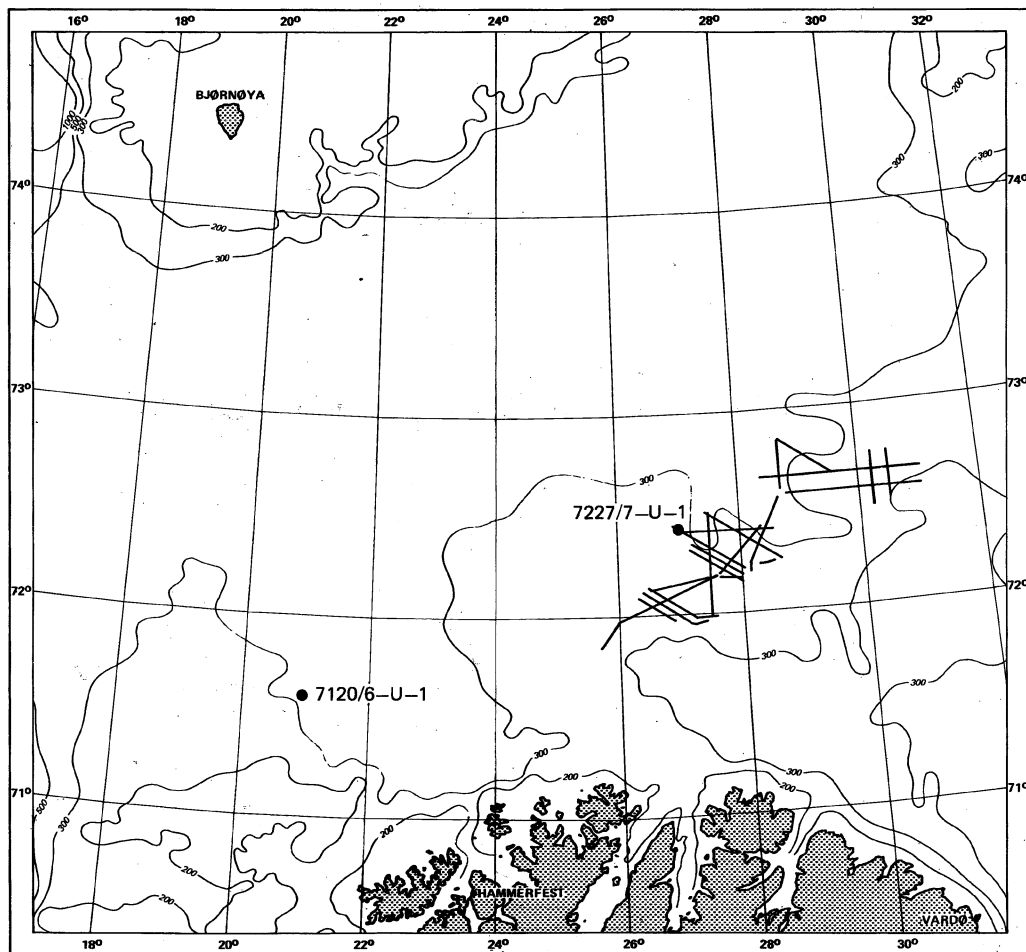


Figure 2.1 Location of the 1986 shallow heat flow sites. (No data from site 7227/7-U-1 is included in the present report.)

At site 7120/6-U-1 the Quaternary sediments comprise an approximately 50 m thick sequence above a seismic reflector which truncates slightly dipping sedimentary rocks of probably Lower Tertiary age (Spencer et al. 1984) on top of a thick sedimentary succession.

Site 7120/6-U-1 is located in the western part of the Hammerfest Basin. This basin had its main subsidence phases during late Jurassic and late Cre-

taceous - early Tertiary and is not affected by salt movements (Gabrielsen et al. 1984).

Table 2.1 Position, water depth and thickness of Quaternary sediment for the 1986 IKU heat flow site in the Hammerfest Basin.

Site	Coordinates				Water depth (m)	Quaternary sediment thickness (m)
	Latitude	Longitude	Northing	Easting		
7120/6-U-1	71°37'12.117"	20°56'30.079"	7946767.6	497947.7	315	50
7120/6-U-1B	71°37'12.117"	20°56'30.079"	7946767.6	497947.7	315	50

Geographical co-ordinates: ED 50 Grid projection: UTM-CM 21° EAST

3. FIELD RESULTS

3.1 Summary

The heat flow measurements were performed as a part of a field work also comprising stratigraphic bedrock drilling. The drillship M/S Bucentaur was contracted for the work. Sediment sampling and temperature measurements were performed by Fugro G.E. B.V., The Netherlands and overall heat flow quality control and on board thermal conductivity measurements were performed by Omegalink International Ltd., USA.

The total drilling period lasted from 29 July to 15 August 1986. The operation was technically very successful and good quality data was collected. Further details about the field work are given in Appendix I.

The measurements at site 7120/6-U-1 comprised 11 depth-temperature points, 3 in situ thermal conductivity measurements and 30 on board conductivity measurements. The temperature data are generally of very good quality, with resolution and absolute accuracy of 0.01 and 0.02°C, respectively. Some data points are less reliable for reasons described below. These data are, however, easy to recognize, and are not included in the calculated heat flow values.

Based on the temperature and thermal conductivity measurements the following heat flow field result for site 7120/6-U-1 is calculated: 68.4 mW/m² (1.64 HFU). 1 HFU = 1 µcal/cm² s.

To obtain the final heat flow values the field results have to be corrected for some secondary effects. These are discussed in Chapters 4 and 5, and the final heat flow values are presented in Chapter 6.

3.2 Summary of field operations

The sediment conditions were fairly good, though pebbles/boulders below the drill-bit necessitated re-drilling before sufficient data was obtained. Undrained shear strength values range within 74-365 kN/m². Due to the hard sediments encountered at 30 m below sea bed no measurements were performed below this depth. As demonstrated below, the data proved, however, sufficient for a reliable calculation of the heat flow.

A summary of the obtained data is given in Table 3.1.

Table 3.1 Number of temperature and thermal conductivity tests carried out at the 1986 IKU heat flow site in block 7120/6.

Site	In situ temperature	In situ thermal conductivity	On board thermal conductivity on sediment samples
7120/6-U-1 and -1B	11	3	30

3.3 Measurements

3.3.1 Down-hole temperature measurements

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 the equation:

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

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 down-hole thermistor is linked to an on board recording unit and a strip chart recorder. These two units are recording voltage output from the thermistor. The voltage is converted to resistance by the equation

$$I/R = C_0 - C_1 (V_{\text{off}} + (V_2/V_F))$$

where

- V_2 = recorded voltage (V)
- R = electric resistance (Ω)
- C_0 = calibration constant (Ω^{-1})
- C_1 = calibration constant ($\Omega^{-1}V^{-1}$)
- V_{off} = calibration constant (V)
- V_F = calibration constant (dimensionless)

Each measurement lasts for about 15 - 30 min (900 - 1800 s) including deployment and insertion of the probe. A typical voltage record is shown in Figure 3.1.

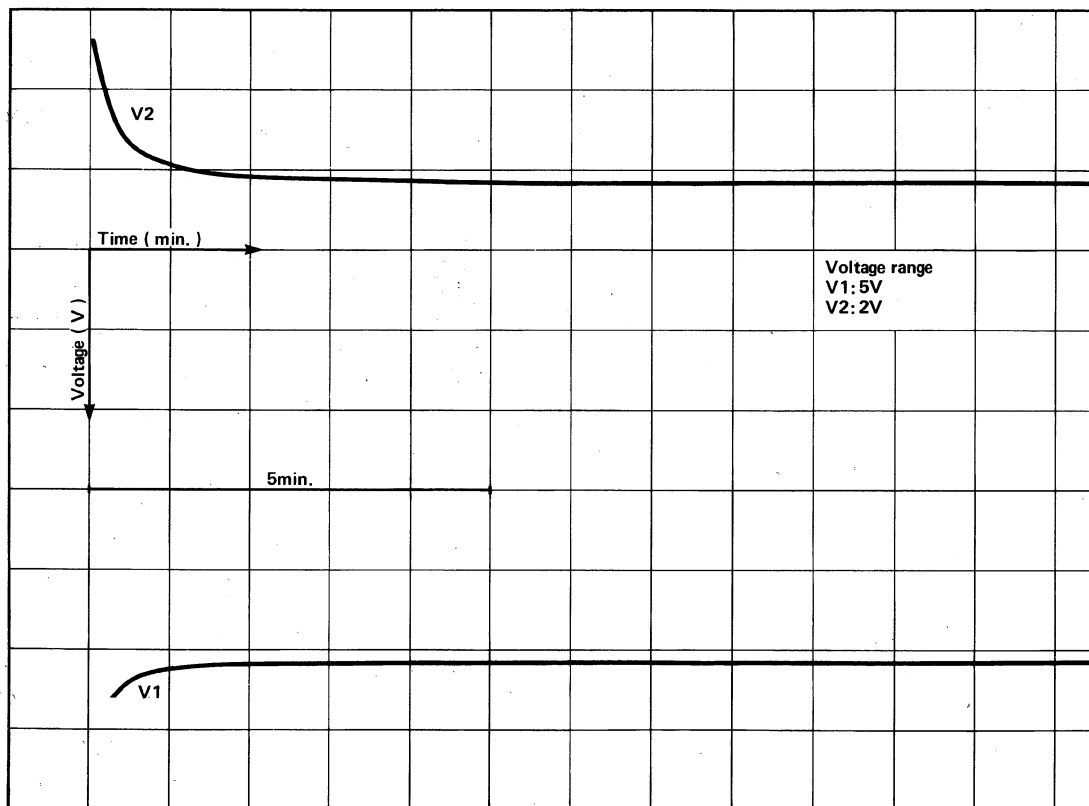


Figure 3.1 Typical voltage output (re-drawn from a strip chart record) from a down-hole temperature measurement.

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 cores 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.

The three deepermost temperature measurements from site 7120/6-U-1B are less reliable than the rest of the given values. This is discussed in detail in Chapter 3.4.1. In Table 3.2 we draw attention to the following:

- The temperature at 26.53 m (WHT5) is lower than at the three neighbouring temperature points above. This would imply a negative gradient, and thus measurement WHT5 should be neglected.
- The measured temperatures at 30.61 and 30.70 m (WT6A and WT6B) are affected by technical problems or down-hole conditions causing the measured temperatures to drift away from in situ. From the plots in Figures 3.5 and 3.6 we suggest that the correct temperature at 30.61 m is between 5.0 and 5.19°C (probably 5.1°C) and at 30.70 m between 4.96 and 5.2°C (probably 5.05°C).

3.3.2 On board thermal conductivity

Thermal conductivity was measured in the on board laboratory using a standard needle probe (Appendix I). This is a standard method for thermal conductivity measurements and will not be further commented here.

The results are given in Table 3.3. Two values are given at each data point. These measurements were performed with the needle vertical and horizontal in the sample. (The use of the two types of data is further described in Chapter 4.5).

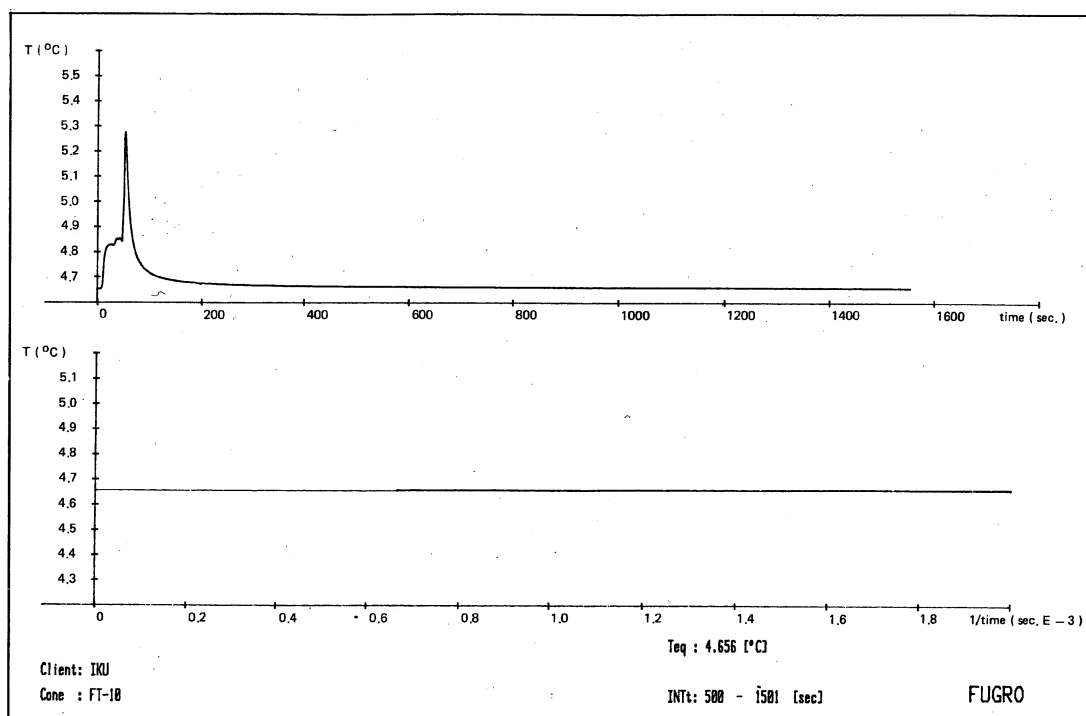


Figure 3.2 Example of a plot of temperature versus time (upper plot) and temperature versus 1/time with extrapolation towards 1/time = 0 (lower plot).

Table 3.2 Final equilibrium temperatures.

Site	Test	Probe assembly	Test depth (m)	Probe depth below drill (m)	Temperature (°C)	Time interval used for extrapolation (s)	Comments
7120/6-U-1B	WT2A	FT10	13.06	0.76	4.486	200-450	Cooling/warming
	WT2B	FT10	13.86	1.56	4.482	100-300	
	WT2C	FT10	14.51	2.21	4.495	200-1000	
	WHT3A	FHT6	18.19	0.89	4.601	100-270	
	WHT3B	FHT6	19.19	1.89	4.676	200-594	Cooling/warming (Cooling/warming?)
	WT4A	FT10	21.22	0.92	4.782	101-160	
	WT4B	FT10	22.07	1.77	4.812	200-350	
	WT4C	FT10	23.07	2.77	4.806	499-1018	
	WHT5	FHT3	26.53	1.23	4.778	501-1149	Unreliable See text
	WT6A	FT10	30.61	0.51	5.1?	1001-1119	
	WT6B	FT10	30.70	0.60	5.05?	1000-1218	

Table 3.3 Thermal conductivity from on board needle probe measurements.

Site	Depth (m)	Probe axis related to core axis	Laboratory temperature °C	Thermal conductivity		R-square
				W/m °C	mcu/ °C cm s	
7120/6-U-1B	10.30	PAR	22	1.80	4.30	.9998
		PERP	22	1.83	4.38	.9999
	10.40	PAR	22	2.00	4.77	.9999
		PERP	22	1.96	4.69	1.0000
	10.48	PAR	22	2.06	4.93	1.0000
		PERP	22	1.96	4.69	.9998
	12.39	PAR	22	1.90	4.53	.9999
		PERP	22	1.86	4.44	.9999
	12.45	PAR	22	1.90	4.55	1.0000
		PERP	22	1.93	4.60	.9998
	17.37	PAR	22	1.71	4.09	.9999
		PERP	22	1.88	4.49	.9997
	17.43	PAR	22	1.96	4.69	.9999
		PERP	22	1.99	4.76	.9999
	17.63	PAR	21	1.91	4.56	1.0000
		PERP	21	1.97	4.70	1.0000
	17.71	PAR	21	2.03	4.85	.9996
		PERP	21	1.96	4.69	1.0000
	20.45	PAR	21	1.78	4.25	.9998
		PERP	21	1.84	4.40	.9998
	20.52	PAR	21	1.77	4.22	.9997
		PERP	21	1.84	4.39	.9999
	20.75	PAR	21	1.77	4.22	.9999
		PERP	21	1.90	4.53	1.0000
	20.82	PAR	21	1.90	4.55	1.0000
		PERP	21	1.90	4.55	1.0000
	25.37	PAR	21	1.90	4.55	.9999
		PERP	21	1.94	4.63	1.0000
	25.42	PAR	21	1.94	4.63	.9999
		PERP	21	1.93	4.60	.9998

3.3.3 In situ thermal conductivity

The in situ thermal conductivity probe (Appendix I) is essentially a needle probe of the same size and strength as the down hole temperature probe and is mounted in an epoxy housing and deployed in a similar way.

As for the temperature probe, the conductivity probe is pushed into the undisturbed sediment and then allowed to equilibrate to in situ temperature. Simultaneous recording of temperature thereby provides a temperature/depth-datapoint. Then a constant energy is introduced to a

heating wire mounted inside the probe, and the increase of temperature as a function of time is recorded. From this function the thermal conductivity of the sediment is found. This is similar to the standard needle probe procedure (von Herzen and Maxwell 1959).

It should be noted that with this instrument the in situ horizontal component of the thermal conductivity is found.

Table 3.4 Thermal conductivity (horizontal component) measured in situ by a vertical 100 mm x 6 mm needle probe.

Site	Test	Probe assembly	Test depth (m)	Thermal conductivity		Standard deviation	
				W/m °C	mcal/°C cm s	W/m °C	mcal/°C cm s
7120/6-U-1B	WHT3A	FHT6	18.19	1.864	4.46	0.061	0.15
	WHT3B	FHT6	19.19	1.883	4.50	0.076	0.18
	WHT5	FHT3	26.53	1.847	4.41	0.041	0.10

3.4 Calculated heat flow value - field results

3.4.1 Temperature data assessment and selection of mean temperature gradient

The temperature data are generally of very high quality, and except from the occasions where particular problems occur, the given temperature values are calculated to have a resolution of 0.01°C and an accuracy of about 0.02°C .

The temperatures are plotted as a function of depth in Figure 3.3. The temperatures from the temperature probe and the combined probe are plotted together.

The data from site 7120/6-U-1 (Figure 3.3) shows some scatter in the temperature versus depth plot. This scatter is probably because some of the measurements may have been influenced by heat transfer along the steel rod from the Wison system or in some other way influenced from the borehole. This effect was discovered by a detailed investigation of the temperature versus $1/\text{time}$ plots performed by Omegalink and is found in four of the measurements (identified by brackets on the depth temperature plots).

Measurement WHT5 is clearly erroneous as it would imply a negative gradient. This data point is neglected.

Measurements WT6A and WT6B at 30.61 and 30.71 m are plotted as dots with the uncertainty interval showed with dashed lines. Both these measurements show anomalous behaviour as a function of time. This is clearly demonstrated by the plots in Figures 3.4 and 3.5. Under ideal conditions temperature as a function of $1/\text{time}$ would plot as a straight line. In these cases the plot starts to curve as $1/\text{time}$ approaches low values (time goes towards infinity). This is probably an effect of some drifting function superimposed on the theoretical function. The fact that the plot of temperature versus time seems to go asymptotically towards a sloping line supports this explanation.

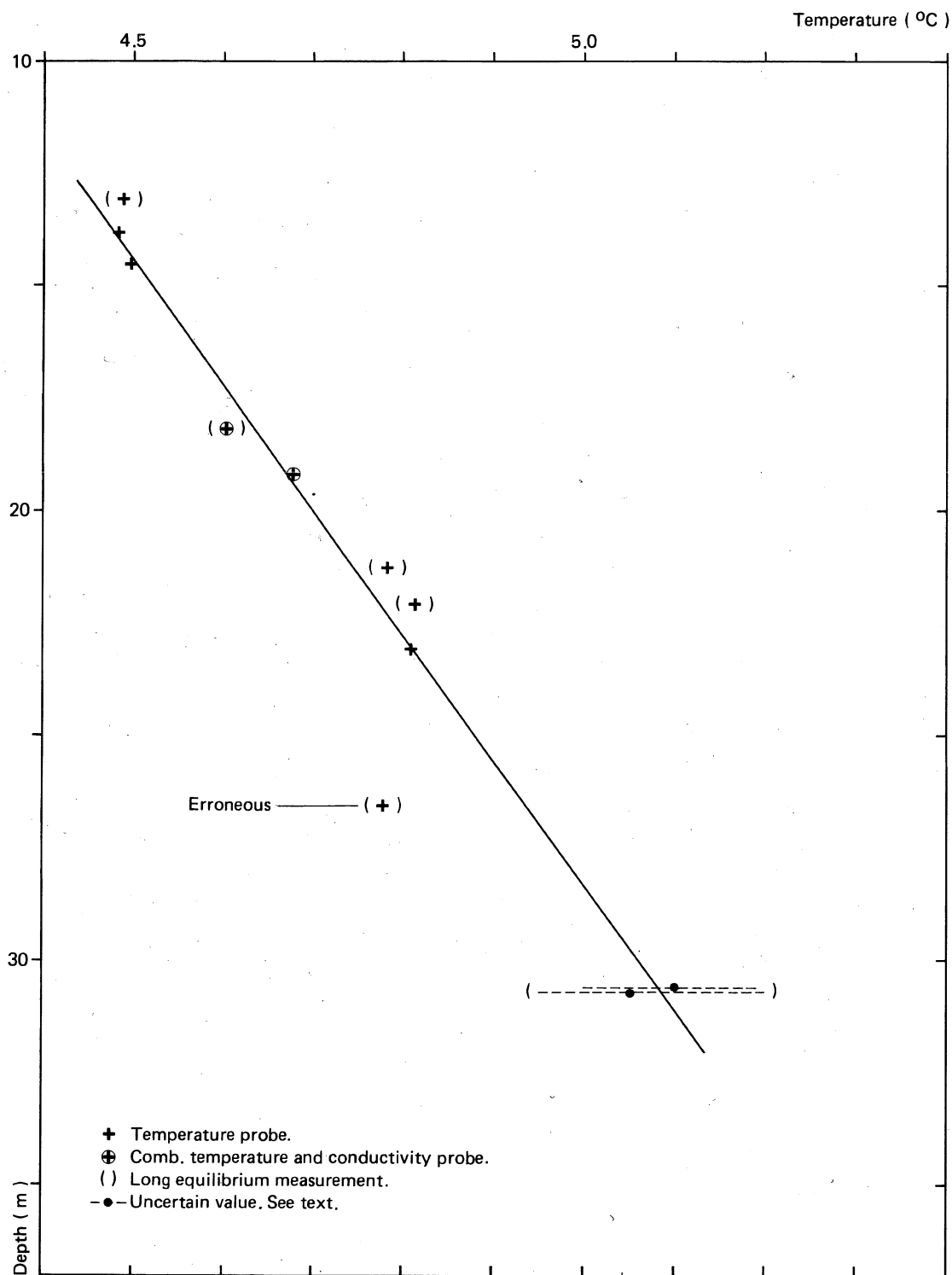


Figure 3.3 Temperature versus depth from site 7120/6-U-1. For the two lowermost plots the broken lines indicate the estimated uncertainty.

To obtain temperature points from Figures 3.4 and 3.5 we have chosen the following procedure:

- Within the $1/\text{time}$ interval corresponding to the mean $1/\text{time}$ interval used for all other measurements, we have chosen the segment that fits best to a straight line and extrapolated this line back to $1/\text{time} = 0$. This would be the most reliable temperature point.
- The maximum temperature is found from a subjective integrated evaluation of both the temperature versus time plot and the temperature versus $1/\text{time}$ plot.
- The minimum temperature is found by extrapolation from $1/\text{time} = \text{approx. } 0.8$ (time is about 20 min.), as heat transfer through the equipment would start to influence the measurements at this time.

As an overall assessment, we feel that the interpreted values of 5.05 and 5.1°C are close to reality. This is also supported by the regression line drawn through the reliable data points in Figure 3.3, which corresponds very well with the interpreted values. This regression line is based on WT2B, WT2C, WHT3B and WHT4C and gives a temperature gradient of 36.0°C/km with an R-square of 0.9993. A regression line through all datapoints except WHT5, gives a temperature gradient of 35.2°C/km (R-square 0.9928). Excluding also tests WT6A and WT6B gives a gradient of 36.7°C/km (R-square 0.9843). We therefore feel confident in recommending a gradient of 36°C/km at site 7120/6-U-1.

3.4.2 Thermal conductivity profile

The thermal conductivity based on the on board needle probe measurements and the in situ thermal conductivity probe is plotted in Figure 3.6 as a function of depth. The conductivity values obtained by the two methods show good correlation on the plots in Figure 3.6, and this indicates high confidence in the data.

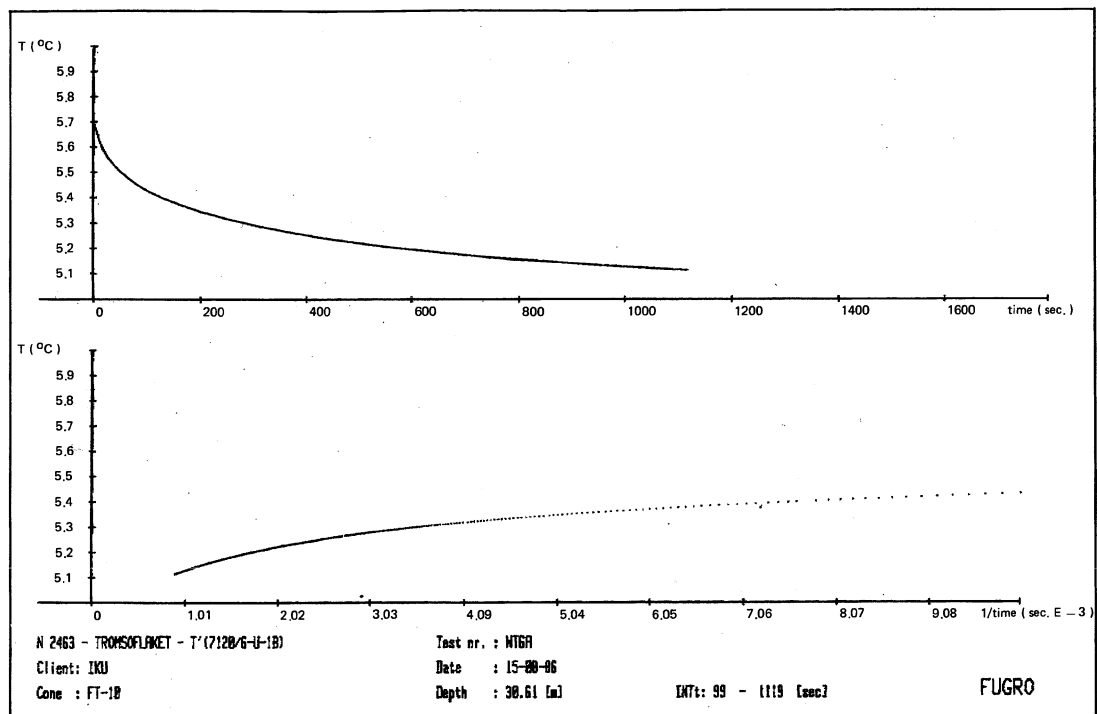


Figure 3.4 Temperature plots from tests WT6A at 30.61 m, site 7120/6-U-1.

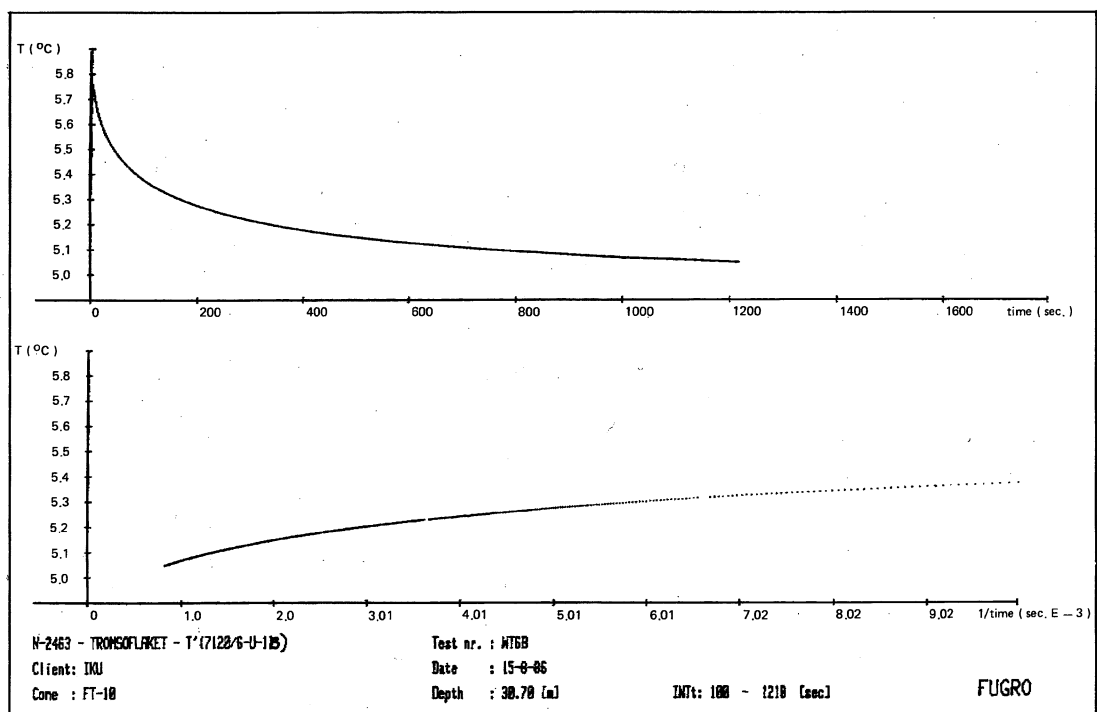


Figure 3.5 Temperature plots from test WT6B at 30.70 m, site 7120/6-U-1.

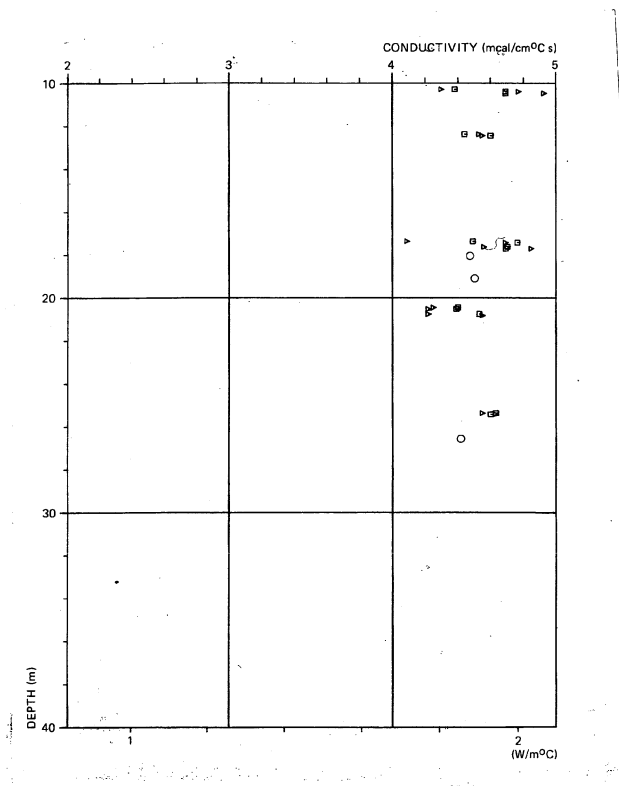


Figure 3.6 Thermal conductivity versus depth, site 7120/6-U-1. Triangles: needle probe parallel to core axis. Squares: needle probe perpendicular to core axis. Circles: in situ measurement of thermal conductivity.

The average thermal conductivity at site 7120/6-U-1 is 4.55 mcal/cm°Cs (standard deviation 0.13 mcal/cm°Cs).

3.4.3 Final field value of heat flow

The data reported in the preceeding chapters are summarized in Table 3.5 giving final field values of heat flow. These values will subsequently be subjected to corrections due to influence on the temperature gradient from earlier glaciations and due to anisotropy in the thermal conductivity of the sediments (Chapter 6).

Table 3.5 Summary of field value of heat flow. (For final value see Chapter 6).

Site	Temperature gradient ($^{\circ}\text{C}/\text{km}$)	Thermal conductivity		Heat flow	
		$\text{W}/\text{m } ^{\circ}\text{C}$	$(\text{mcal}/\text{cm } ^{\circ}\text{C s})$	mW/m^2	$(1\text{HFU} = \text{u cal}/\text{cm}^2 \text{ s})$
7120/6-U-1	36.0	1.90	4.55	68.4	1.64

4. THERMAL CONDUCTIVITY, LABORATORY ANALYSES

4.1 Summary

Analyses of physical properties of the Quaternary cores are described in Appendix II and summarized in Table 4.1. In addition to standard soil mechanical testing also mineral composition analysis (XRD) has been carried out on a representative selection of samples.

Results from the above tests are used as input for theoretical calculation of thermal conductivity based on known thermal conductivity of water and the various mineral compounds.

The need for correction due to differences in temperature and pressure from in situ to laboratory conditions has been investigated. The temperature is found to be insignificant because of the low water content of the samples.

Tests for comparison of thermal conductivity have been performed at the University of Aarhus (Figure 4.2).

Differences in vertical and horizontal thermal conductivity have also been investigated. Although no difference in vertical versus horizontal thermal conductivity could be expected from the field measurements, it seems evident from thorough laboratory analyses that such an effect is present in the samples from the entire depth interval below 11 m at site 7120/6-U-1. The factor of anisotropy (K_h/K_v) is found to be 1.1.

4.2 Analyses of physical properties

Several physical properties are analysed on selected Quaternary samples. A purpose of these analyses has been to enable correlations of these properties with thermal conductivity. In the literature such correlations are given both on a theoretical basis (conductivity of multi compound media) as well as on an empirical basis (e.g., Bullard & Day 1961; Lachenbruch & Marshall 1961; Johansen 1975; Matsuda & von Herzen 1985). Such correlations of the Barents Sea data will thus provide quality control and increase the confidence of the final thermal conductivity values.

A description of the Quaternary cores and a complete documentation of all the analyses performed on the Quaternary material is given in Appendix II. In Table 4.1 we have extracted the most relevant data for evaluation of thermal conductivity. These data comprise the following parameters:

- thermal conductivity ($\text{mcal}/^{\circ}\text{C cm s}$) by use of the needle probe method
 - 1) the needle oriented vertically in the sediment
 - 2) the needle oriented horizontally in the sediment
- water content in per cent of dry weight sample, $w(\%)$.
- wet density of the sample, γ (kN/m^3).
- in situ sample temperature ($^{\circ}\text{C}$)
- temperature during laboratory test ($^{\circ}\text{C}$)
- vertical sound velocity, V_{sv} (m/s)
- horizontal sound velocity, V_{sh} (m/s)
- quartz content in per cent of mineral fraction
- chlorite content in per cent of mineral fraction
- undrained shear strength obtained by the falling cone method, S_u (kN/m^2).

Site	Depth	Thermal conductivity (mcal/°C cm s) Horizontal Vertical and horizontal (see text)	Water content in per cent of dry weight (%)	Wet sample density (kg/m^3)	Sample temperature (°C) In situ Laboratory condition (°C)	Sound velocity Vertical Horizontal (m/s) (m/s)	Mineral fraction of weight dry sample Quartz Chlorite (%) (%)	Undrained shear strength (falling cone) S_u (kN/m^2)
7120/6-U-1B	10.30	4.30	16.9	21.7	4.4	1820.	35	74
	10.40	4.37	21.6	20.6	4.4	1820.	27	196
	10.50	4.53	21.0	20.7	4.4	1990.		
	11.00	4.53			4.4			
	11.25	4.53			4.4			
	11.45	4.53			4.4			
	11.70	4.53			4.4			
	11.75	4.53			4.4			
	11.85	4.53			4.4			
	12.00	4.53			4.4			
	12.15	4.53			4.4			
	12.30	4.53			4.4			
	12.45	4.53			4.4			
	12.60	4.53			4.4			
	12.75	4.53			4.4			

Table 4.1 Input data for theoretical calculation of thermal conductivity.

4.3 Theoretical calculation of thermal conductivity

4.3.1 Methods and input data

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 4.2.

When the measurements are made on board a ship, 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 factors 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 seem to cancel each other, and temperature deviations may therefore be neglected.

For 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:

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

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

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

- Void volume fraction (gas): $v = 1-(n_s + n_w)$ (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.:

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

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

- Volume fraction of water: $n'_w = 1 - \gamma'_d/\gamma_s$

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 4.2.

Table 4.2 Thermal conductivity of compounds in atmospheric pressure and 20°C.

Compound	Thermal conductivity	
	W/m °C	mcal/cm °C s
Water	(0.599)	(1.431)
Chlorite	3.5	8.36
Quartz	7.7	18.36
Mineral rest.	2.0	4.78

Input values to equations 1-5c about composition of each sample are taken from Table 4.1. All the values are correlated to on board thermal conductivity measurements at certain depths.

The mineral composition is based on XRD-analyses. Some calculations are based on "estimated mineralogy". In these cases the mineralogy is taken as an average composition of representative depth intervals at each site.

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 is therefore necessary to correct for the effect of these gas voids. The in situ thermal conductivity measurements gave values that fitted well with the values from the laboratory measurements. This indicated that no such pressure release effect was present in the data. 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).

4.3.2 Results

Thermal conductivity adjusted to in situ conditions

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. The temperature effect was found above to be negligible.

In order to ensure that the on board thermal conductivity measurements gave values representative for in situ conditions it is also necessary to check whether gas voids have formed in the samples due to the pressure release from in situ to laboratory conditions. This was checked according to the procedure above, and negligible gas void formation was found.

The plot of thermal conductivity versus water content also includes curves for this theoretical relation for different quartz contents (Figure 4.1).

The actual range in quartz content in the 1986 samples is 26-36 in per cent of the mineral fraction, and this gives a good correlation with the theoretical curves.

4.3.3 Comparative measurements of thermal conductivity

Measurements and results

A selection of Quaternary samples have been subjected to thermal conductivity measurements by the Geophysical Laboratory at the University of Aarhus, Denmark.

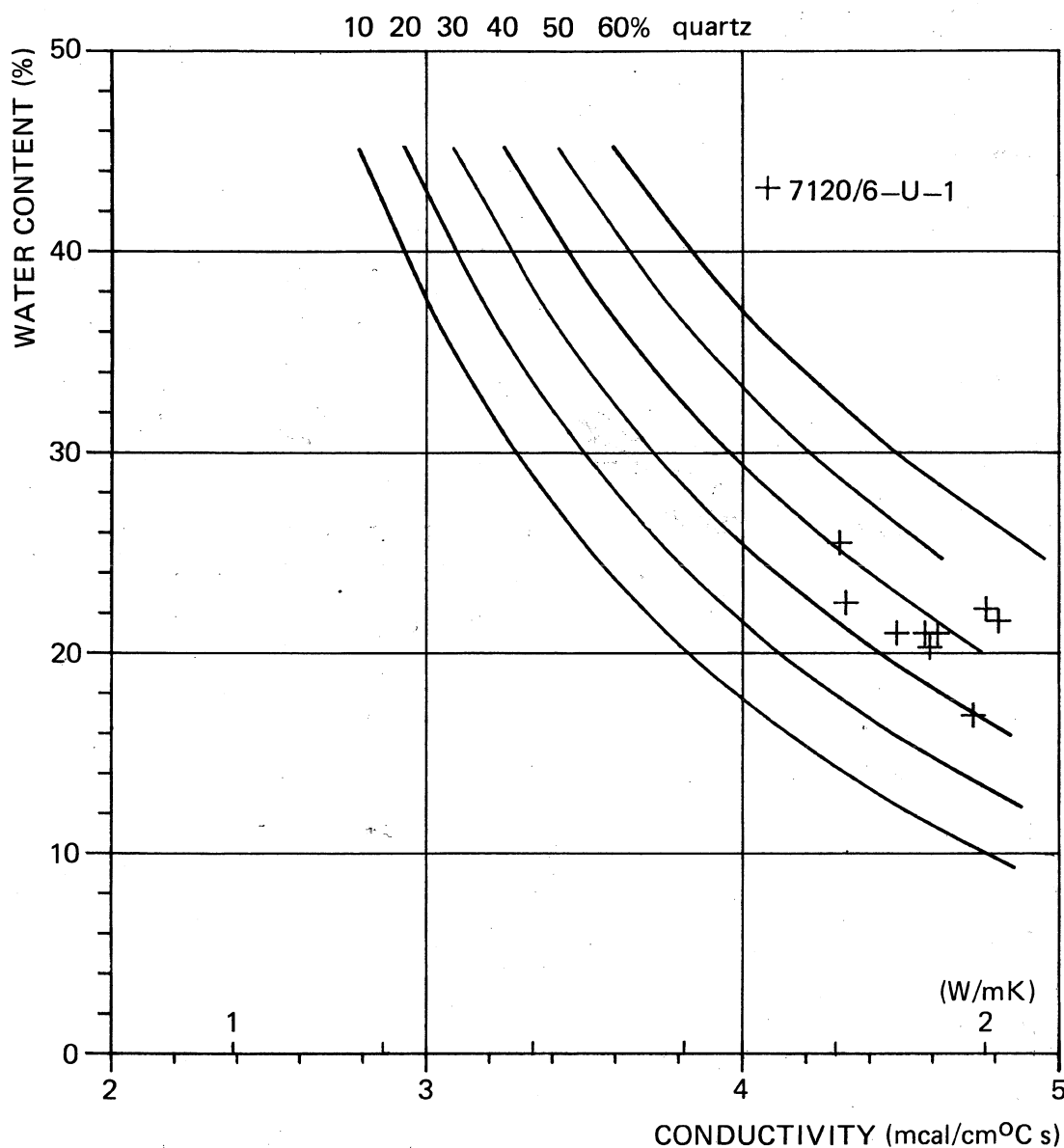


Figure 4.1 Thermal conductivity versus water content. The curves show the theoretical relation.

All the measurements were performed by use of a standard needle probe with the following specifications:

probe length: 50 mm and 80 mm
probe diameter: 1.5 mm

The results of these measurements are presented in Table 4.3.

The conductivity values are originally reported in $\text{mcal}/^{\circ}\text{C cm s}$, but are below also given as $\text{W/m } ^{\circ}\text{C}$ ($1 \text{ mcal}/^{\circ}\text{C cm s} = 0.4186 \text{ W/m } ^{\circ}\text{C}$).

The results are also included in the plots in Figure 4.2. From this figure it is seen that the measurements performed in Aarhus generally support the on board results if only the horizontal thermal conductivity values from Aarhus are considered. We therefore feel confident that the on board measurements are reliable. The significance of the difference between vertical and horizontal thermal conductivity is discussed below.

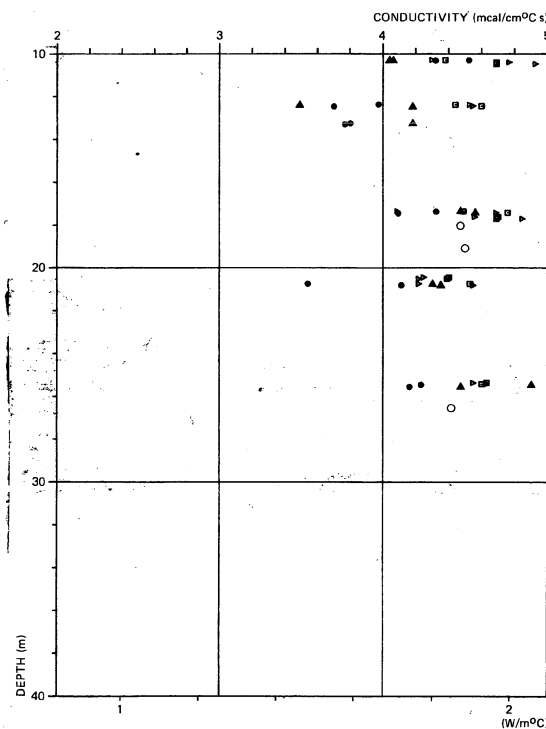


Figure 4.2 Thermal conductivity versus depth, site 7120/6-U-1.

On board measurements: Open triangle = horizontal thermal conductivity.
Open square = vertical thermal conductivity.
University of Aarhus: Filled triangle = horizontal thermal conductivity.
Filled circles = vertical thermal conductivity.
In situ measurements: Open circles

Table 4.3 Thermal conductivity measurements performed at the University of Aarhus, Denmark.

SITE	DEPTH (m)	W/m °C	K _h K _v			Anisotropy (K _h /K _v)
			mcal/°C cm s	W/m °C	mcal/°C cm s	
7120/6-U-1	13.21	1.75	4.18	1.59	3.80	1.10
	13.32	1.75	4.18	1.58	3.77	1.11
7120/6-U-1B	10.27	1.69	4.04	1.89	4.52	0.89
	10.34	1.70	4.06	1.81	4.32	0.94
	12.36	1.67	3.99	1.66	3.97	1.01
	12.52	1.75	4.18	1.55	3.70	1.13
	17.34	1.87	4.47	1.81	4.32	1.03
	17.46	1.91	4.56	1.71	4.09	1.12
	20.72	1.80	4.30	1.48	3.54	1.22
	20.85	1.82	4.35	1.72	4.11	1.06
	25.45	2.05	4.90	1.77	4.23	1.16
	25.60	1.87	4.47	1.74	4.16	1.07

4.4 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).

By the needle probe a weighed thermal conductivity in all directions perpendicular to the needle axis will be measured. Thus a weighed value of thermal conductivity in all horizontal directions will be measured when the needle is pushed vertically into the sample, and a combination of horizontal and vertical thermal conductivity will be measured when the needle is pushed horizontally into the sample.

The on board laboratory measurements were performed with the needle axis both horizontally and vertically.

When averaging the horizontal and vertical measurements (neglecting all data from less than 12 m below the sea bed) there was found a quite insignificant difference in thermal conductivity measured vertically

and horizontally. (A coefficient of 0.98 between the two measurements for site 7120/6-U-1).

The samples that were measured at the University of Aarhus were subjected to a thorough investigation with respect to anisotropy in thermal conductivity. The measurements done in this case were the same as done on board. However, several measurements were taken in both directions on each sample. The average values in the two measured directions were then used to calculate thermal conductivity in the vertical, K_v , and horizontal, K_h , direction.

The measurement and calculation procedures necessary to calculate K_v and the factor of anisotropy have been developed at the University of Aarhus (Balling et al. 1981, pp. 73 and 74). Their experience is that several measurements on each sample are required to obtain a sufficient basis for the calculation (Balling pers. commun. 1986).

The results of the Aarhus measurements are given in Table 4.3. A plot of the factor of anisotropy,

$$A \left(A = \frac{K_h}{K_v} \right)$$

found from these measurements versus depth is presented in Figure 4.3.

From Figure 4.3 it can be suggested that a slight anisotropy in thermal conductivity is present in the samples from site 7120/6-U-1. An average factor of anisotropy for this site (neglecting data points shallower than 11 m) is calculated to $A_{av} = 1.1$ (standard deviation 0.06).

The measured thermal conductivity seems to be too high by a factor of about 1.13, compared to the conductivity computed from sediment composition (Fig. 4.4). The theoretical calculation of thermal conductivity assumes that the sediments are isotropic. If this assumption fails, a difference in measured and calculated thermal conductivity would result.

It is not possible to correlate the factor of anisotropy (1.10) with the correction factor (1.13) directly. One reason is that the measurements are not based on a steady state method, a second reason is that it is unclear

which component that should correspond to the theoretical ("isotropic") value. It is, however, concluded that the measured anisotropy is realistic and it is recommended to apply this value in the calculation of final heat flow value.

A puzzling conclusion that can be drawn from these comparisons is that the theoretical model for thermal conductivity seems to break down for water contents of less than approx. 30% of dry sample. This is probably an effect of the high content of anisotropic mineral grains (clay minerals) in the samples.

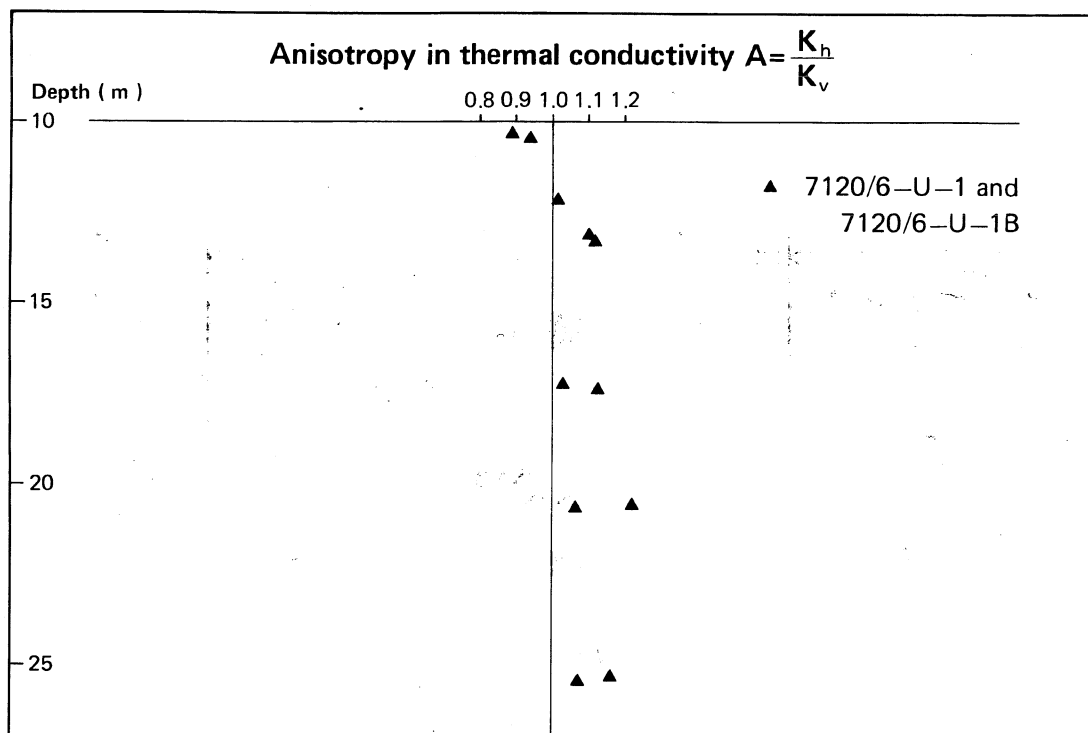


Figure 4.3 Anisotropy in thermal conductivity versus depth based on results given in Table 4.3 from the University of Aarhus (Balling, pers. commun. 1986).

4.5 Selection of mean thermal conductivity values

At site 7120/6-U-1 the thermal conductivity is constant with depth, and the mean value is representative for the whole interval. This value is 1.90 W/m °C (4.55 mcal/°C cm s). The standard deviation is 0.054 W/m °C (0.13 mcal/°C cm s). The factor of anisotropy is found to be 1.1 (Chapter 4.4). When

accounting for this, the mean vertical thermal conductivity for site 7120/6-U-1 is found to be $1.73 \text{ W/m } ^\circ\text{C}$ ($4.14 \text{ mcal/}^\circ\text{C cm s}$).

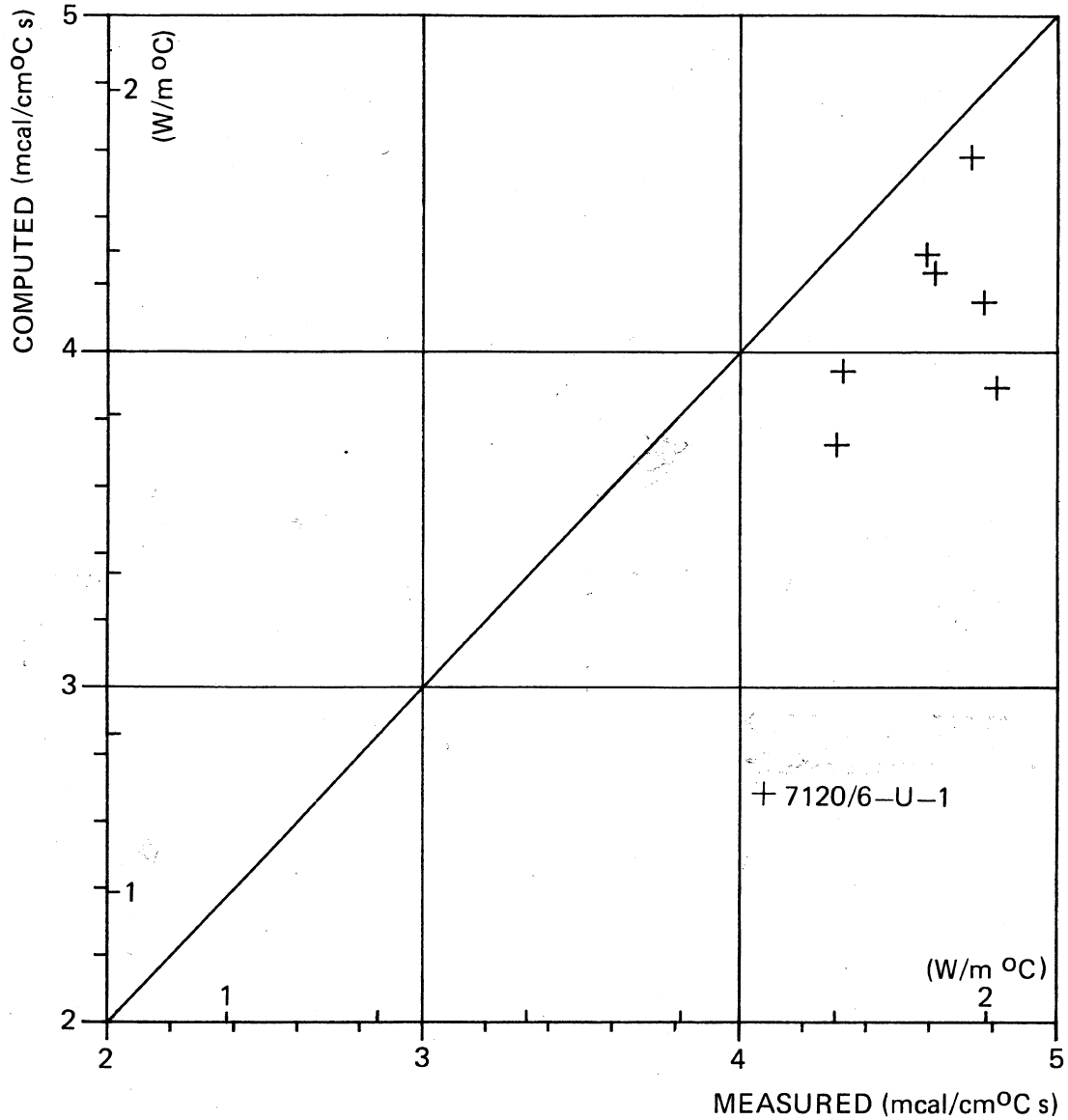


Figure 4.4 Computed versus measured thermal conductivity.

5. CORRECTION FOR PERTURBATIONS IN MEASURED TEMPERATURES DUE TO THE LATE QUATERNARY HISTORY

5.1 Summary

Possible perturbations in the measured data due to topographic relief and the glacial history are investigated.

The effects from topographic relief and lateral variations in Quaternary sediment thickness close to the heat flow sites are found to be negligible.

The climatic effect is treated individually for each site. Based on published information and data gathered within the Barents Sea Mapping Program we have deduced two alternative glacial history models causing minimum and maximum transient effects on the measured temperatures. These models are used as input to computer calculations of maximum and minimum perturbations.

The maximum and minimum transient effects on the measured gradients are summarized in Table 5.1.

Table 5.1 Summary of transient effects on the present temperature gradient based on two alternative glaciation models.

Site	Correction	(°C/km)
	Minimum glaciation model	Maximum glaciation model
7120/6-U-1	4.5	6.8

Although it is difficult to favour one of the two alternative temperature history models from scientific evidence (Appendix III), we feel that the minimum glaciation model probably is the most realistic. One reason for this is that the maximum model includes the presence of a large cold based ice sheet which we tend to believe must have been the exception rather than the rule during glaciations in the southern Barents Sea.

5.2 Objective and limitations

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 sea bed) with similar data from exploration wells (2000-4500 m below the sea bed) 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) relates a time span of 200 000 years to a depth range of 10 km. Nielsen & Balling (1985) show 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 (15-40 m) should be comparable to exploration well data if they are corrected for late Quaternary climatic changes according to the models below.

In our study we have chosen a time span of 245 000 years for the climatic correction models. This span is chosen because 245 000 y. BP is regarded as the best estimate of the onset of the warm Holsteinian interglacial before the Saalian glacial period (Balling pers. commun. 1986).

The effect from erosion and deposition within the same time span should also be considered in order to have a more complete reduction of shallow data for comparison with well data. However, such events are less established than the temperature history at our sites. Furthermore, as several episodes of erosion and deposition may have occurred, the summarised effect of these processes may largely be cancelled.

5.3 Temperature history models

The background for the chosen temperature history models is given in Appendix III based on a review of current opinions on the Quaternary history of the area. For convenience a figure from Appendix III, summarizing the temperature history models, is shown below (Figure 5.1).

5.4 Method and results

The calculation of the theoretical transient effect upon the measured temperatures is calculated by the Geophysical Laboratory, Department of Geology, at the University of Aarhus in Denmark. This work follows a scheme earlier published by this institution (Balling *et al.* 1981) and the mathematical part will not be further discussed here.

A stepped temperature versus time-function is applied. Input to this function is taken from the temperature history in Figure 5.1.

The present day surface temperature is chosen as reference level. This temperature is deduced from an extrapolation of the depth/temperature profile obtained in the boreholes.

The calculations are based on a theoretical half space with a constant thermal diffusivity. It should be noted that this assumption is valid only down to the base Quaternary boundary. However, to the extent reality deviates from this assumption, the real effect from the temperature history would be less than the calculated effect. The thermal diffusivity is proportional to the thermal conductivity and inversely proportional to the specific heat per volume. For the Barents Sea samples, the average value for thermal diffusivity will be about $0.4 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$ to $0.6 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$. Calculations are done using both these alternatives.

Table 5.2 summarizes the calculated disturbances of the temperature gradient. To arrive at maximum and minimum correction alternatives, temperature history model I is combined by a thermal diffusivity of $0.4 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$, whereas temperature history model II is combined with a thermal diffusivity of $0.6 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$. This table thus provides extreme boundaries resulting from the alternative input data.

These values are slightly uncorrect as the temperature 10 m below the sea bed was used as input for the mean annual temperature. A more correct temperature would be obtained by extrapolating the temperature to the sea bed. This implies that the calculated transient effects and the temperature gradients should be reduced by about 10% (0.1-0.5°C/km). Considering the overall confidence in the climatic models, this is an insignificant difference.

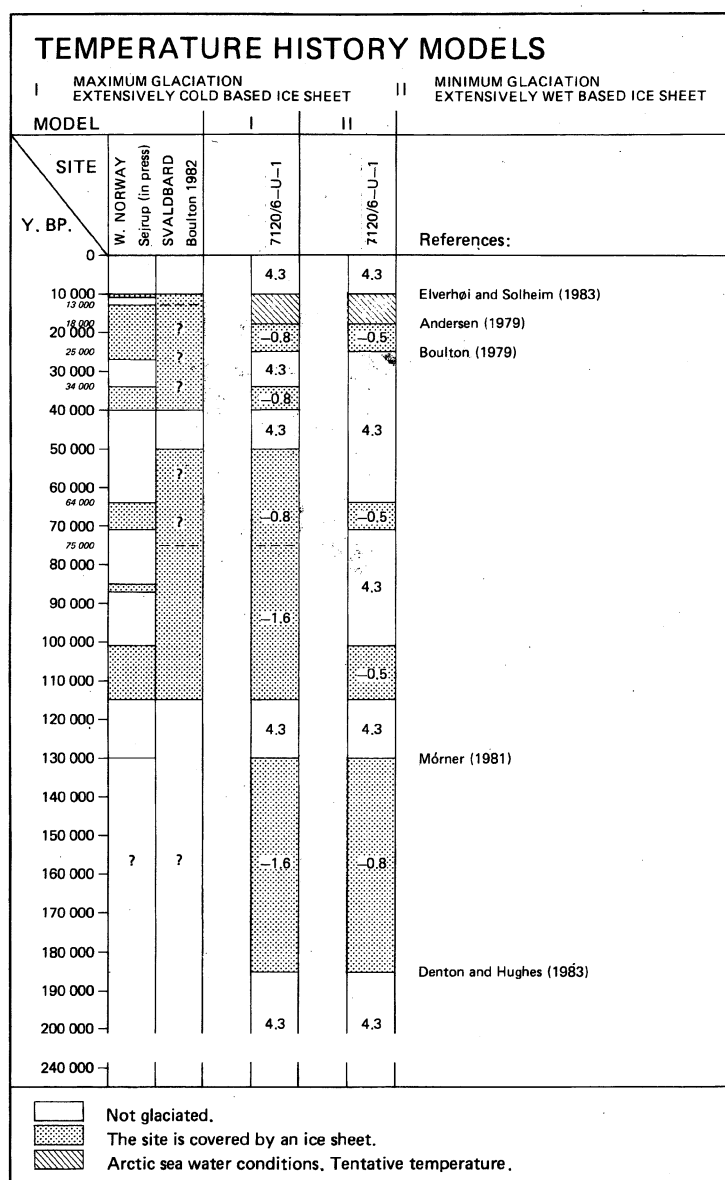


Figure 5.1 Temperature history models (Ref. Appendix III).

5.5 Topographic effects

Topographic corrections of the thermal gradient are necessary in areas with marked local variations in surface altitude. This is necessary when the surface towards which the heat flows (representing a boundary condition) is at different levels and has different temperatures in short enough distances away from the site to affect the downward temperature increase (i.e. the topography causes the heat flow to deviate from the vertical).

The topographic effect on temperature gradients can be estimated by an equation derived by Jeager (1965) (in Kappelmayer & Haene1 1974):

$$G = G_u - \frac{x \cdot T_o}{T_i (x^2 + z^2)}$$

where

- G is the apparent gradient influenced by topography
- G_u is corrected thermal gradient in the underground
- x is the distance away from the site to a change in annual surface temperature T_o
- z is the depth below the surface of the site.

On land the use of this equation is relatively simple as the mean annual temperature for a given region generally can be expressed as a linear function of altitude. In the sea water masses, however, there may exist different sheets of water with different temperatures. Mean annual temperature difference within a given water depth range at a specific geographical position is therefore influenced by 1) the depth to the boundary between different water masses, and 2) the mean annual temperatures within the actual water masses.

From the equation above it can easily be shown that with the actual sea bed relief at the two heat flow sites (smooth sea bed is found along the seismic profiles in both cases), no topographic effect on the temperature gradient should be present.

Similar effects from lateral variations in Quaternary thickness can also be neglected.

The topographic effect from relict plough marks from drifting icebergs (Lien 1983) is also found negligible. For this case the topographic conditions may be less favourable. T_0 , however, is quite insignificant, and this will imply a negligible correction.

Table 5.2 Maximum and minimum disturbance based on temperature history models A and B.

Site	Depth (m)	Disturbance			
		Temperature history model A. Thermal diffusivity $0.4 \times 10^{-6} \text{ m}^2/\text{s}$		Temperature history model B. Thermal diffusivity $0.6 \times 10^{-6} \text{ m}^2/\text{s}$	
		Temperature (°C)	Temperature gradient C/km	Temperature (°C)	Temperature gradient C/km
7120/6-U-1	0.0	0.000	-.0068	0.000	-.0045
	25.0	-.171	-.0068	-.113	-.0045
	50.0	-.341	-.0068	-.225	-.0045
	75.0	-.511	-.0068	-.337	-.0045
	100.0	-.679	-.0067	-.449	-.0044
	125.0	-.846	-.0066	-.559	-.0044
	150.0	-1.011	-.0065	-.669	-.0044
	175.0	-1.173	-.0064	-.777	-.0043
	200.0	-1.332	-.0063	-.885	-.0043
	225.0	-1.489	-.0062	-.990	-.0042
	250.0	-1.642	-.0061	-1.094	-.0041
	275.0	-1.791	-.0059	-1.196	-.0040
	300.0	-1.937	-.0057	-1.296	-.0040
	325.0	-2.078	-.0056	-1.394	-.0039
	350.0	-2.215	-.0054	-1.490	-.0038
	375.0	-2.348	-.0052	-1.584	-.0037
	400.0	-2.476	-.0050	-1.675	-.0036
	425.0	-2.599	-.0048	-1.763	-.0035
	450.0	-2.717	-.0046	-1.849	-.0034
	475.0	-2.830	-.0044	-1.933	-.0033
	500.0	-2.939	-.0042	-2.013	-.0032
	1000.0	-4.219	-.0013	-3.082	-.0013
	1500.0	-4.667	-.0007	-3.543	-.0008

6. FINAL HEAT FLOW VALUE

6.1 Mean thermal conductivity value

Thermal conductivity data for the same depth intervals as represented by the measured temperature gradients are given in Chapters 3.3 and 4.

Chapter 3.3 includes all measurements done on sediment samples on board and measurements done in situ by the Fugro thermal conductivity probe.

From previous experience it was known that certain effects could influence on the thermal conductivity measurements and cause systematic errors in the data. These effects are:

- gas voids forming in the samples due to different pressure in situ and in the laboratory
- change in the thermal properties of sediment compounds due to temperature differences in situ and in the laboratory
- anisotropy in thermal conductivity.

A detailed study of these possible effects is presented in Chapter 4, and we conclude that all the above effects except anisotropy are negligible. Anisotropy in thermal conductivity is found to exist in all the samples from below 11 m at site 7120/6-U-1. Accounting for this effect gives a mean thermal conductivity of $1.73 \text{ W/m } ^\circ\text{C}$ ($4.14 \text{ mcal/}^\circ\text{C cm s}$) for site 7120/6-U-1.

6.2 Mean temperature gradient

The measured temperature gradient is 36.0°C/km for site 7120/6-U-1.

In Chapter 5 it was found that the shallow temperature gradient is affected by transient effects from late Quaternary temperature variations and we suggest to apply a correction for this effect in order to arrive at steady state heat flow values for these two sites. The gradient should be increased by 4.5°C/km at site 7120/6-U-1. This correction is included in the temperature gradient value in Table 6.1.

6.3 Calculation of final heat flow value

The heat flow calculated directly from the field data is given in the first column of Table 6.1.

As summarized above in Chapters 6.1 and 6.2 certain corrections should be applied both to the thermal conductivity values and to the measured temperature gradients. The values given in Table 6.1 are corrected for this, and the final heat flow values are calculated as the product of the thermal conductivity and temperature gradients given there.

In Figure 6.1 we have plotted both the final heat flow value and the value resulting directly from the uncorrected field data. The figure also presents published heat flow values from other areas for comparison.

Table 6.1 Heat flow data from the IKU 1986 site in block 7120/6.

A: Heat flow resulting from uncorrected field results.

B: Final heat flow value, based on corrected thermal conductivity and temperature gradient.

Site	A: Field result		B: Final results			
	Heat flow		Temperature gradient (°C/km)	Thermal conductivity		Heat flow
	(mW/m ²)	(μgal/cm ² s)		(W/m °C)	(mcal/cm °C s)	
7120/6-U-1	68.4	1.64	40.5	1.73	4.14	70.1 1.68

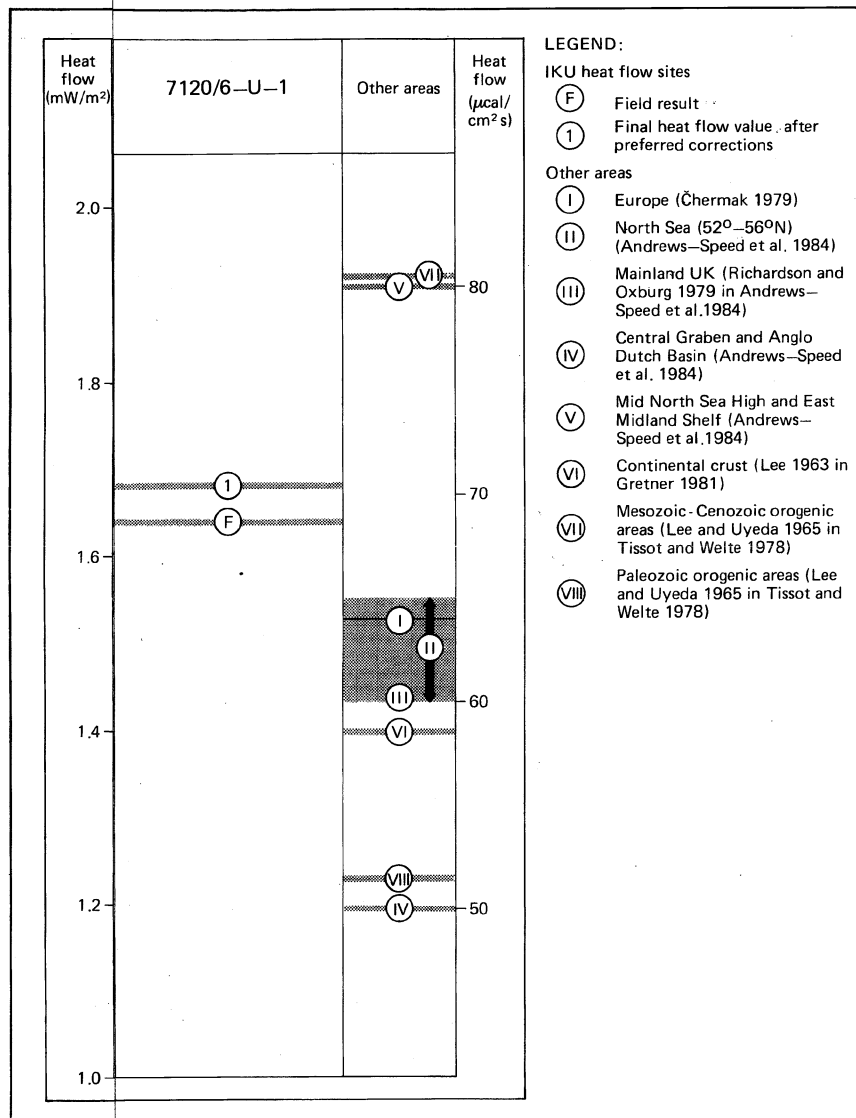


Figure 6.1 Heat flow at site 7120/6-U-1. Published heat flow values from other areas are shown for comparison.

7. HEAT FLOW MEASURED IN WELL 7120/6-1

7.1 Summary

Heat flow in well 7120/6-1 is computed from obtained temperature gradient and thermal conductivity between seabottom and 2447 m. The minimum possible temperature gradient is defined by the BHT-data, whereas the maximum is defined by DST-temperatures. Thermal conductivity is obtained from log data using published conductivity versus porosity curves for different lithologies. Assessed temperature gradients range from 31.3 to 37.9°C/km with a most likely value of 37.4°C/km. Corresponding thermal conductivities are 1.60 (minimum) 1.99 (maximum) and 1.70 mcal/cm°C s (most likely). Using triangular probability distributions and multiplying, heat flow is found to be in the range from 52.7 to 72.5 mW/m² (1.26 to 1.74 µcal/cm² s) with 95 % certainty and an expected value of 62.6 mW/m² (1.50 µcal/cm² s). A better constraint on range of possible heat flow should be based on measurements of thermal conductivities in the well.

7.2 Introduction

As is usually the case for deep oil exploration wells, no direct heat flow measurements are available in well 7120/6-1. As part of standard procedures, bottom hole temperatures (BHT) are measured and recorded in the header of most log runs. Temperatures are also recorded during testing of the well : drill stem test (DST) and run formation test (RFT).

As is also customary, thermal conductivity is not measured in this well, and thermal conductivity has to be derived from other sources such as electric logs.

Due to fairly large uncertainties in both the temperature and thermal conductivity assessments, it is important to assess the uncertainties in the heat flow values derived.

The heat flow analysis assumes steady-state conditions to be present in the well. Heat transfer by convection may modify the results, but is not treated due to lack of reliable information.

7.3 Temperature assessment

Bottom hole temperatures and run formation test temperatures were provided by Norsk Hydro. Drill stem test reports from which DST-temperatures were obtained, were also provided by Norsk Hydro.

The 18 BHT-temperatures at 5 depths were corrected to equilibrium temperatures (T_{eq}) by means of the Horner plot method (Table 7.1). Only the temperature measurement at 813 m could not be corrected by standard procedure because of lack of data. The uncorrected temperature is used in Table 7.1. The uncertainty involved in the correction of the BHT can be seen to decrease significantly below 2500 m.

Table 7.1 Temperature summary

TYPE	DEPTH (m KB)	MEASUREMENTS	T_{eq} (°C)	UNCERTAINTY	NOTE
	337		4	0	Inferred from shallow meas. Uncorrected temperature
BHT	813	1	24	+/- 12	
BHT	2034	3	51	+/- 6	Depth of gauge is used
DST	2447		83	+/- 1	
BHT	2580	5	76	+/- 1	
BHT	2727	3	82	+/- 2	
BHT	2810	6	89	+/- 2	

The obtained equilibrium (BHT) temperatures are lower than the true formation temperatures. This fact has been observed in many exploration wells. Oil companies use different procedures to compensate for the deficiency of the obtained temperatures (for instance adding a fixed or depth dependant temperature). The problem has also been investigated from a theoretical viewpoint, by considering the temperature difference to be caused by convection in the mud. The additional correction needed is strongly dependant on borehole diameter. No formulas are, however, available for accurately correction of the BHT and RFT temperatures. Also considering the accuracies given in Table 7.1, a decision is reached to use only the temperature difference between seabottom and the deeper recording for heat flow calculation. In Figure 7.1 a possible but speculative temperature-depth curve corrected for mud circulation effects is shown together with the

temperature-depth curve for the equilibrium BHTs. The appearance of the temperature-depth profile is moderately changed when a depth-dependant correction is introduced.

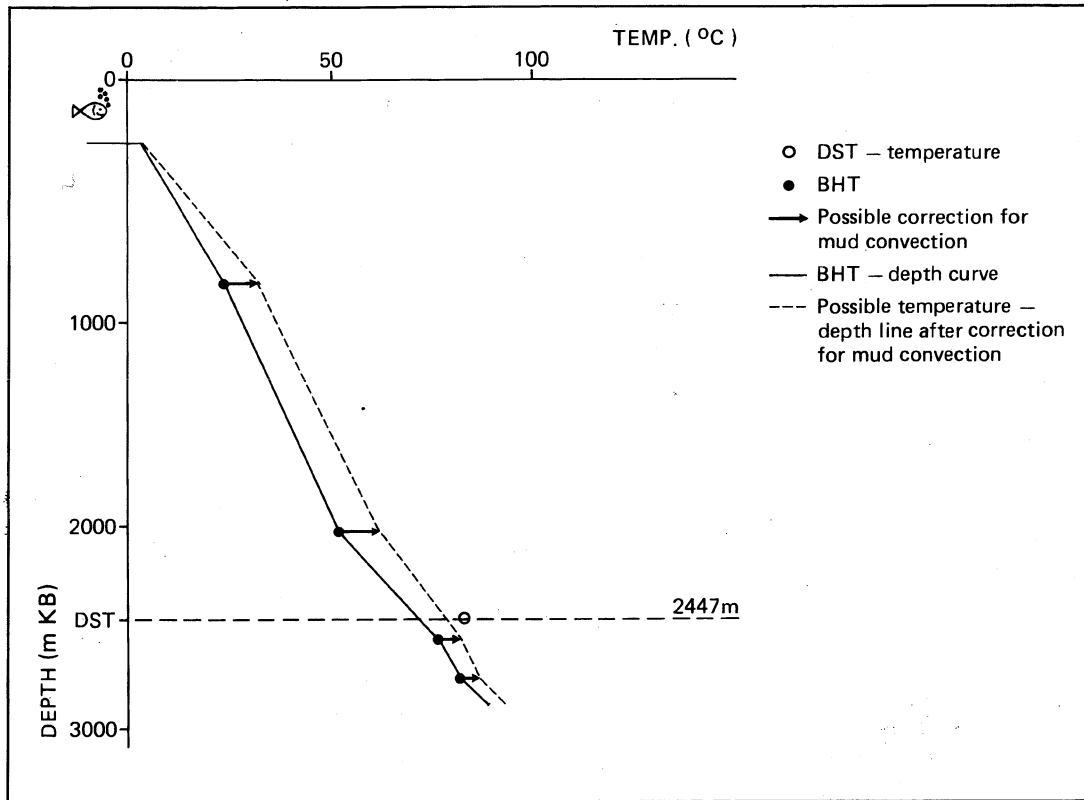


Figure 7.1 Temperature versus depth in well 7120/6-1.

Four drill stem tests were performed in the 7120/6-1 well at depths from 2380 m to 2460 m. The upper two tested gas, whereas the lower two tested fluids. Because of the heating of the formation during the testing of the gas zone, the temperatures recorded in the upper two tests can not be used in this study. From tests 1 and 2 an equilibrium temperature of 83°C is computed. The two tests are so close in depth that only a single depth-temperature data point can be achieved.

It is generally accepted that the DST-temperatures are the most accurate routine temperatures recorded in deep exploration boreholes. Whereas the BHT and RFT-temperature are too low, the DST-temperatures may be expected to be slightly on the high side because of energy released by friction between the flowing fluid and the rock it flows through. The DST temperature of 83°C

at 2447 m (depth of gauge) is, however, still considered to be the most likely temperature. Thus, for this depth, a temperature of 70°C inferred from Figure 7.1, is used as a minimum temperature value and 84°C (83 + uncertainty of DST-temp.) as maximum temperature. In summary, the temperature range at 2447 m is:

Minimum : 70°C
 Most likely : 83°C
 Maximum : 84°C

7.4 Thermal conductivity assessment

The COMPULOG software (IKU property, Griffiths 1984) was used for deriving thermal conductivity from the electrical logging data provided by Norsk Hydro. A survey of available literature gave a number of different methods for computing the conductivity. Some of them are :

- From sonic log (e.g., Goss et al. 1975)
- From sonic log and computed porosities "
- From lithology and computed porosities (Balling et al. 1981).

An important part of the COMPULOG software is the ability to distinguish between different lithologies based on M,N-crossplots (Burke et al. 1969). It was therefore decided to use the third (and possibly most reliable) method. Thermal conductivities for clay, claystone, sandstone and limestone were taken from Balling et al. (1981) (Figure 25, page 34 and Figure 26 page 35), see Figure 7.2. A power-law expression relating the conductivity to porosity for each of the three lithologies used was deduced and used in COMPULOG. Subsequently, a conductivity-log was plotted (Figure 7.3) based on neutron-porosity and quicklook porosity. A full suite of logs was only available for depths deeper than 800 m. Therefore the COMPULOG approach could only be applied for the deeper part, whereas the section shallower than 800 m had to be treated manually. No significant differences in conductivities arise from the use of the two porosity functions in Figure 7.3.

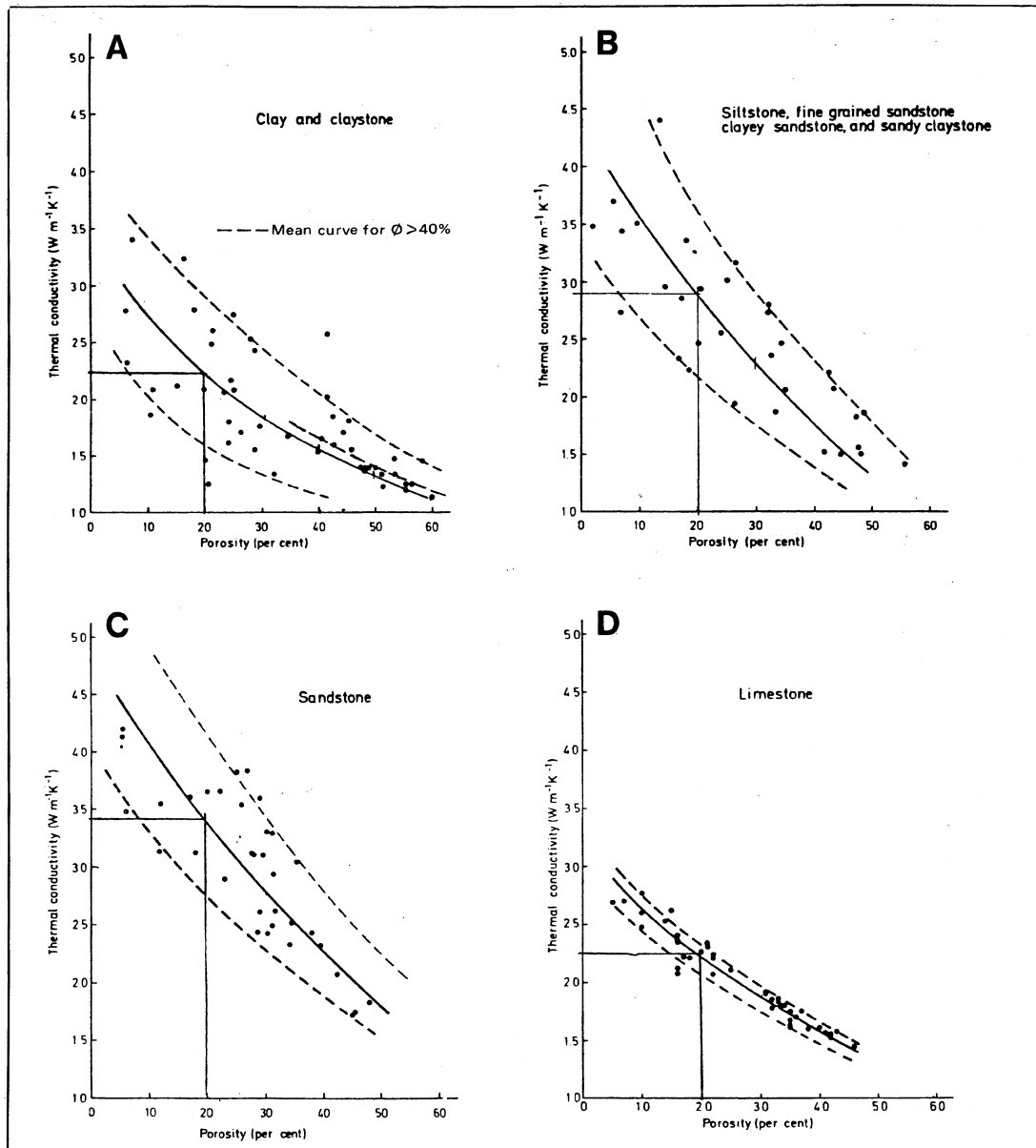


Figure 7.2 Thermal conductivity versus porosity for clay, claystone, shale, siltstone, sandstones and limestone. Modified from Balling *et al.* (1981).

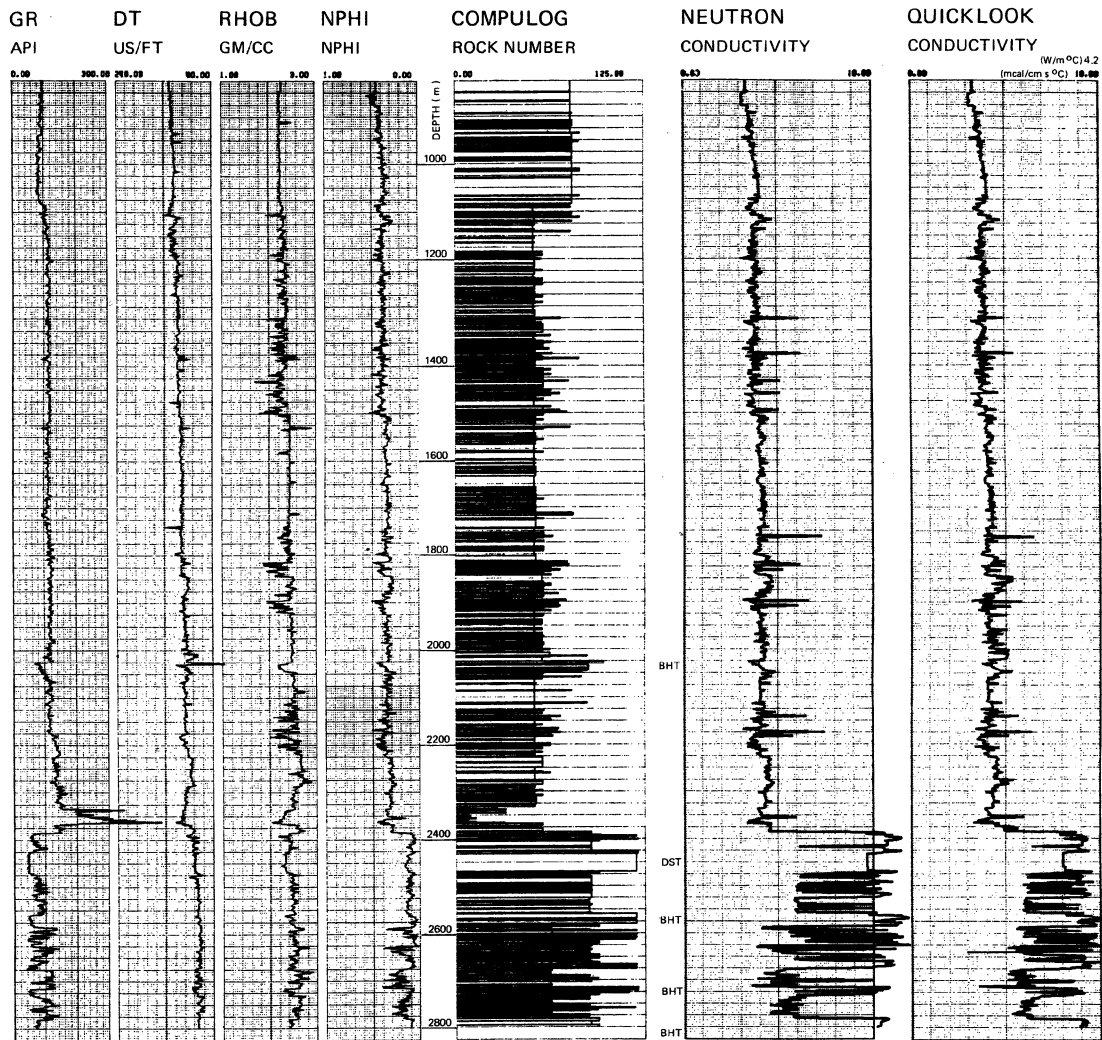


Figure 7.3 Sonic-, density-, neutron-logs, rock number and thermal conductivity logs for well 7120/6-1 between 800 and 2800 m.

The minimum and maximum conductivities of Figure 7.2 can be seen to be within $\pm 0.5 \text{ W/m } ^\circ\text{C}$ of the mean-curve. Most of the sediments above the DST temperature measurement consist of shale/clay. Only the lower part consists of sands of varying quality. Therefore, errors in bulk conductivities are most influenced by errors in the conductivities of the shale. Calculated shale porosities in the well (below 800 m) are in the range 30 to 40 %. In this porosity range almost all data points of Figure 7.2a are positioned between the mean and the maximum curve. This is also the case for porosities above 40 %, expected to be found shallower than 800 m. Therefore a new mean curve is constructed $0.1 \text{ W/m } ^\circ\text{C}$ above the mean of the hole clay data set.

The shale conductivities of Figure 7.3 (resulting from the old mean-curve of Figure 7.2a) are used as the minimum thermal conductivity in our calculations. The maximum curves of Figure 7.2 are used for the maximum conductivity computations.

For the section above 800 m, porosities are considered to change from 40 % at a depth of 800 m to 60 % at the water - sediment interface, resulting in an average thermal conductivity for this depth interval of 1.30 W/m °C (minimum case, Figure 7.2a). The corresponding most likely and maximum thermal conductivities are also taken from Figure 7.2a.

The calculated thermal conductivities for the well are summarized in Table 7.2.

Table 7.2 Average thermal conductivity for well 7120/6-1.

Depth (m KB)	Thermal conductivity (W/m °C)			Note:
	minimum	most likely	maximum	
337	1.30	1.40	1.62	From Figure 7.2
813				From Figures 7.2 and 7.3
2034				"
2447				
337	1.60	1.70	1.99	Computed from above
2447				

7.5 Heat flow assessment

Heat flow is calculated from the formula (steady state heat transfer by conduction) :

$$Q = K \cdot dT/dZ$$

where

Q = heat flow

K = thermal conductivity

dT/dZ = temperature gradient

Between seabottom and 2447m (DST-depth) heat flow is calculated from the temperature data of section 7.3 (minimum, most likely and maximum temperature) and the thermal conductivity data of Table 7.2. Results are shown in Figure 7.4 and Table 7.3.

Table 7.3 Temperature gradient, thermal conductivity and heat flow from seabottom to 2447 m (Heat flow from simple multiplication, no statistical treatment).

	minimum	most likely	maximum	
Temperature gradient:	31.3	37.4	37.9	$^{\circ}\text{C}/\text{km}$
Thermal conductivity:	1.60	1.70	1.99	$\text{W}/\text{m } ^{\circ}\text{C}$
Heat flow:	50.1	63.6	75.4	mW/m^2
	1.20	1.53	1.81	$\text{uCal}/\text{cm}^2 \text{ s}$ (HFU)

The temperature gradient and thermal conductivity variations may also be considered to form two triangular probability distributions. The minimum, most likely and maximums of Table 7.3 then represent the corresponding parameters of the probability distributions for the temperature gradient and thermal conductivity. The resulting heat flow probability distribution is

shown in Figure 7.4. Heat flow is between 52.7 and 72.5 mW/m^2 with a 95 % certainty. The most likely heat flow is now computed to be 61.5 mW/m^2 , which is slightly less than a direct multiplication of the most likely temperature gradient and thermal conductivity values of Table 7.3. The expected value of the heat flow probability distribution is 62.6 mW/m^2 .

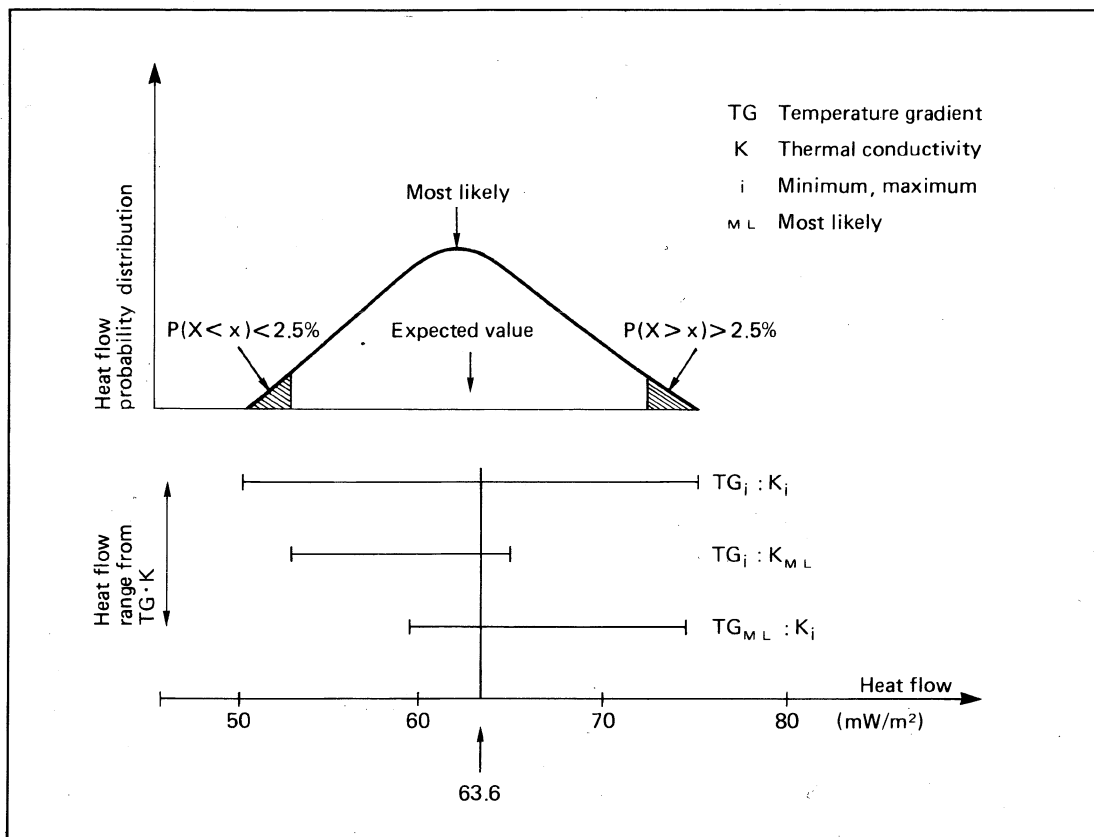


Figure 7.4 Heat flow ranges in well 7120/6-1.

7.6 Conclusion

The heat flow estimate may be improved by improving the temperature estimates or the thermal conductivity assessment. The temperature has been measured in the well. The thermal conductivity is only modelled from published data. Whereas the temperature is less constrained in the low value range, the thermal conductivities for the predominantly shaley sequence are less constrained on the high side (Figure 7.2a). Uncertainty in the average temperature gradient is 17 %. For the thermal conductivity, the corresponding figure is 22 %.

For these reasons, attention should be focused on the thermal conductivities in the well. The accuracy of the heat flow assessment could be significantly increased by a systematic study of the thermal conductivities in well 7120/6-1 based on measurements from available cores (scarce) and cuttings.

With the available data, however, the heat flow is estimated to lie between 52.7 and 72.5 mW/m^2 (1.26 and 1.74 $\mu\text{cal/cm}^2\text{s}$) with an expected value of 62.6 mW/m^2 (1.50 $\mu\text{cal/cm}^2\text{s}$).

8. DISCUSSION

Our final heat flow value are calculated in Chapter 6 (Table 6.1) to be 70.1 mW/m^2 ($1.68 \text{ } \mu\text{cal/cm}^2 \text{ s}$) for site 7120/6-U-1.

In Chapter 7 we calculated an expected heat flow value of 62.6 mW/m^2 ($1.50 \text{ } \mu\text{cal/cm}^2 \text{ s}$) for the deep well 7120/6-1. Lower and upper uncertainty values (95% confidence interval) were found to be 52.7 mW/m^2 ($1.26 \text{ } \mu\text{cal/cm}^2 \text{ s}$) and 72.5 mW/m^2 ($1.73 \text{ } \mu\text{cal/cm}^2 \text{ s}$). This corresponds to an uncertainty of $\pm 16\%$.

The shallow heat flow value, 70.1 mW/m^2 ($1.68 \text{ } \mu\text{cal/cm}^2 \text{ s}$) from site 7120/6-U-1 fits within this range, but is about 10% higher than the value obtained from the deep well.

The scatter in the shallow measurements is low. The standard deviation from averaging all the on board thermal conductivity measurements is 3% of the mean value. The uncertainty in the temperature gradient that is interpreted from the depth - temperature data is $\pm 2\%$. From this it may be inferred that the uncertainty in the heat flow value is about 3-4% for the measurements themselves. The main source of uncertainty may be the correction due to the late Quaternary climatic variations. This effect is negligible at 1 km depth but may in the upper 100 m below the sea bed introduce an uncertainty of the measured temperature gradient. Because the quantification of this influence is based on certain glaciation models (see Chapter 5) and not on measured values, it is not possible to give an exact estimate of the uncertainty introduced. The range of influence from extreme models is, however, so small, that we believe that the overall uncertainty introduced from previous glaciations is in the order of about 5%. Added with the uncertainty in the measurement of thermal conductivity and temperature gradient, it may be concluded that the difference between the shallow and deep heat flows at this site is within the uncertainty of the data.

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A P P E N D I X I

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AI FIELD OPERATIONS

AI 1. SUMMARY OF FIELD OPERATIONS

AI 1.1 General

The heat flow sites 7120/6-U-1 and 7227/7-U-1 were drilled as part of the field work of the IKU project "Nordkapp Basin shallow seismic, shallow drilling and heat flow measurements 1986". The total field work activity of this project comprised a shallow seismic survey in May -86 and a shallow drilling cruise in late July - early August -86.

The shallow seismic profiling was carried out by Nor Surveys A/S and comprised collection of data using analog sparker, digital airgun, deep tow boomer and side-scan sonar. Bentech A/S was sub-contracted for the positioning and A/S Geoteam processed the digital seismic data.

The drilling cruise was performed by the Norwegian drillship M/S Bucentaur which was contracted from von der Lippe (Ship Management) A/S.

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

Fugro B.V., Holland was sub-contracted to perform the down-hole sampling and thermal measurements. Omegalink International Ltd., USA provided heat flow expertise for quality control and data assessment and also performed the on board thermal conductivity measurements. The down-hole probes were designed and manufactured jointly by Fugro B.V. and Omegalink International Ltd.

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

On request from NPD, IKU on this cruise tested a procedure for cementing the boreholes. This work was performed by Halliburton overseas Ltd. (Norway).

The drilling cruise for the present project was carried out as a continuation of the IKU Dia-Structure shallow drilling 1986 and lasted from 29 July 1986 to 15 August 1986. The operations went technically well and only 5% of the total time was spent on repairs of equipment. In addition the ship had to go off hire for about three days and go to Honningsvåg for repair of the moonpool. The time spent on different activities is summarized in Figure AI 1.1 below.

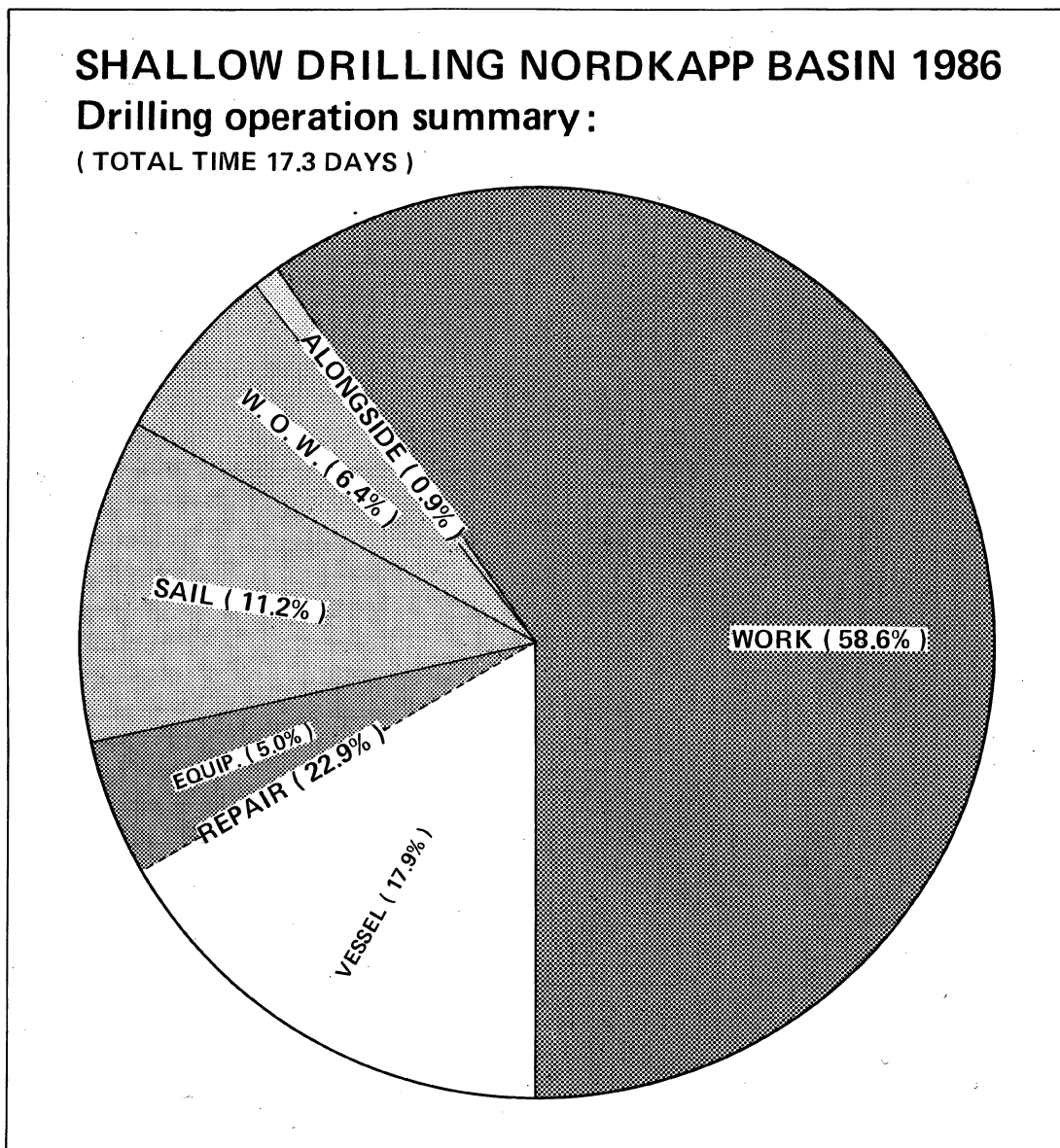


Figure AI 1.1 Time consumption summary of the shallow drilling cruise in the Nordkapp and Hammerfest Basins 1986 in per cent of total cruise time (total time 17.3 days).

An outline of the heat flow measurement procedure at a drilling site will be as follows (Figure AI 1.2).

- a) The drillship moved into position and lowered the sea bed guide frame.
- b) Drill pipes were run until the sea bed frame was entered and the bit touched the sea bed. Then an accurate reference depth measurement on the drill string was made.
- c) The drilling commenced and from about 10 m below the sea bed 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). 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.
- 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.

- 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.

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. The position of site 7120/6-U-1 is given in Table AI 2.1.

Both systems worked well during the cruise.

Table AI 1.1 Final position of heat flow site 7120/6-U-1.

Site	Seismic line	Fix pt.	Geographical co-ordinates	UTM co-ordinates
7120/6-U-1 and 7120/6-U-1B	NH84- 53-301	161	LATITUDE 71° 37' 12.117" LONGITUDE 20° 56' 30.079"	NORTHING 7 946 767.6 EASTING 497 947.7
UTM ref.: Geogr. co-ordinates:			CM 21° EAST ED 50	

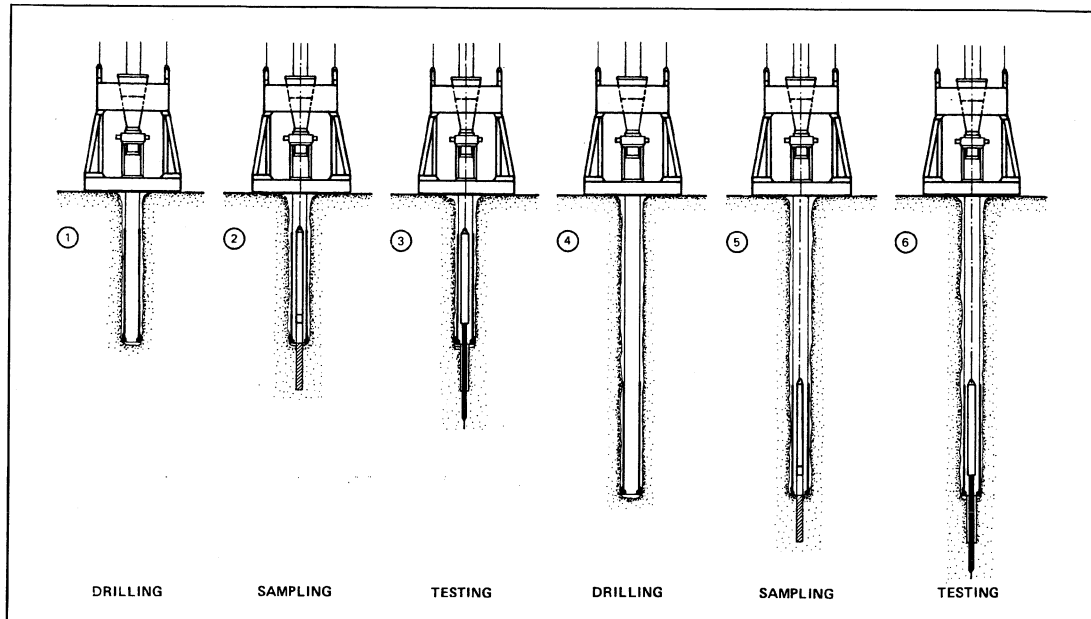


Figure AI 1.2 Summary of heat flow measurement procedure during shallow drilling (From Zielinski et al. 1986).

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 system

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 system

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.

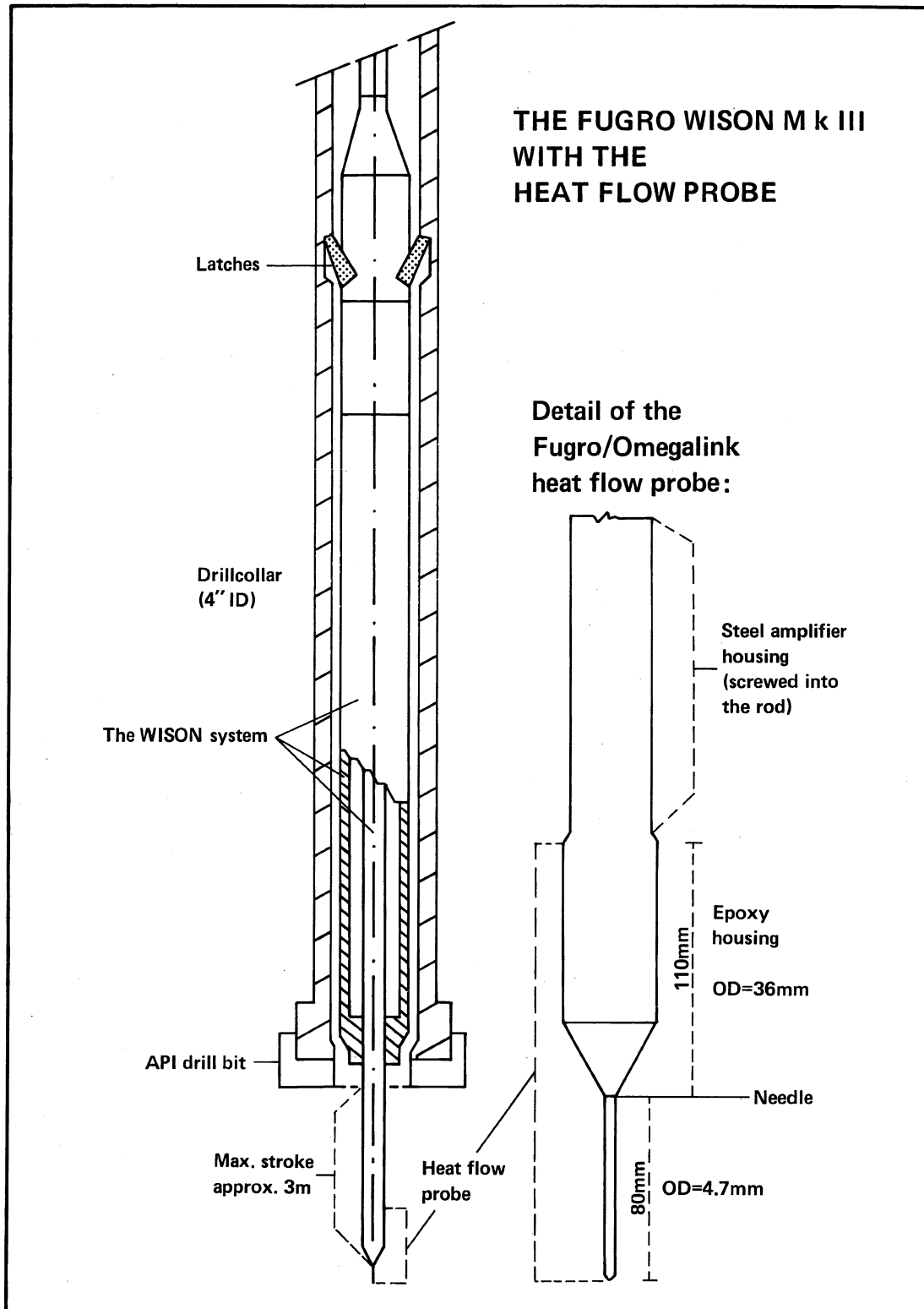


Figure AI 2.1 The combined temperature and thermal conductivity probe mounted in the Fugro WISON Mk III system.

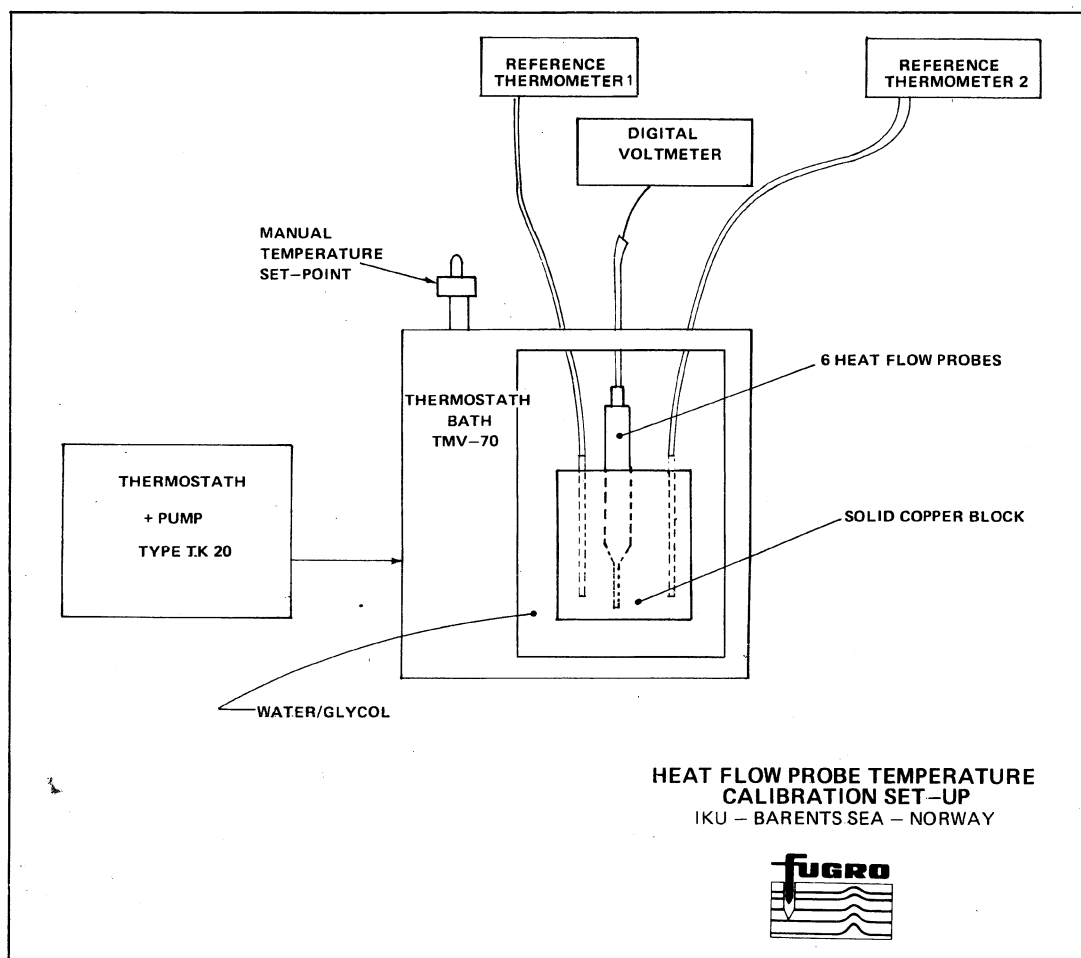


Figure AI 2.2 Temperature calibration set up.

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.

Unfortunately all the FT-probes and the FHT probe no 3 were damaged during the tests and therefore no comparison of pre- and post cruise calibration is possible in these cases. However, FHT probes 1, 2 and 6 and three FT probes similar to those used (and pre cruise calibrated at the same time), 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:

- Guildline Digital Platinum Resistance Thermometers 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 $+30^{\circ}\text{C}$.

Our conclusion from the calibration results is that the drifting of both the FT and FHT sensors is less than 0.02°C .

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 6 cm long "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.

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, a work that is partly funded by the present project. 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. The temperature recorded by the thermistor in the tip of the probe is used to quantify and thereby correct for the effect of this.

The reliability of the thermal conductivity values obtained by the in situ probe can be evaluated from the plot in Figure AI 2.3 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.

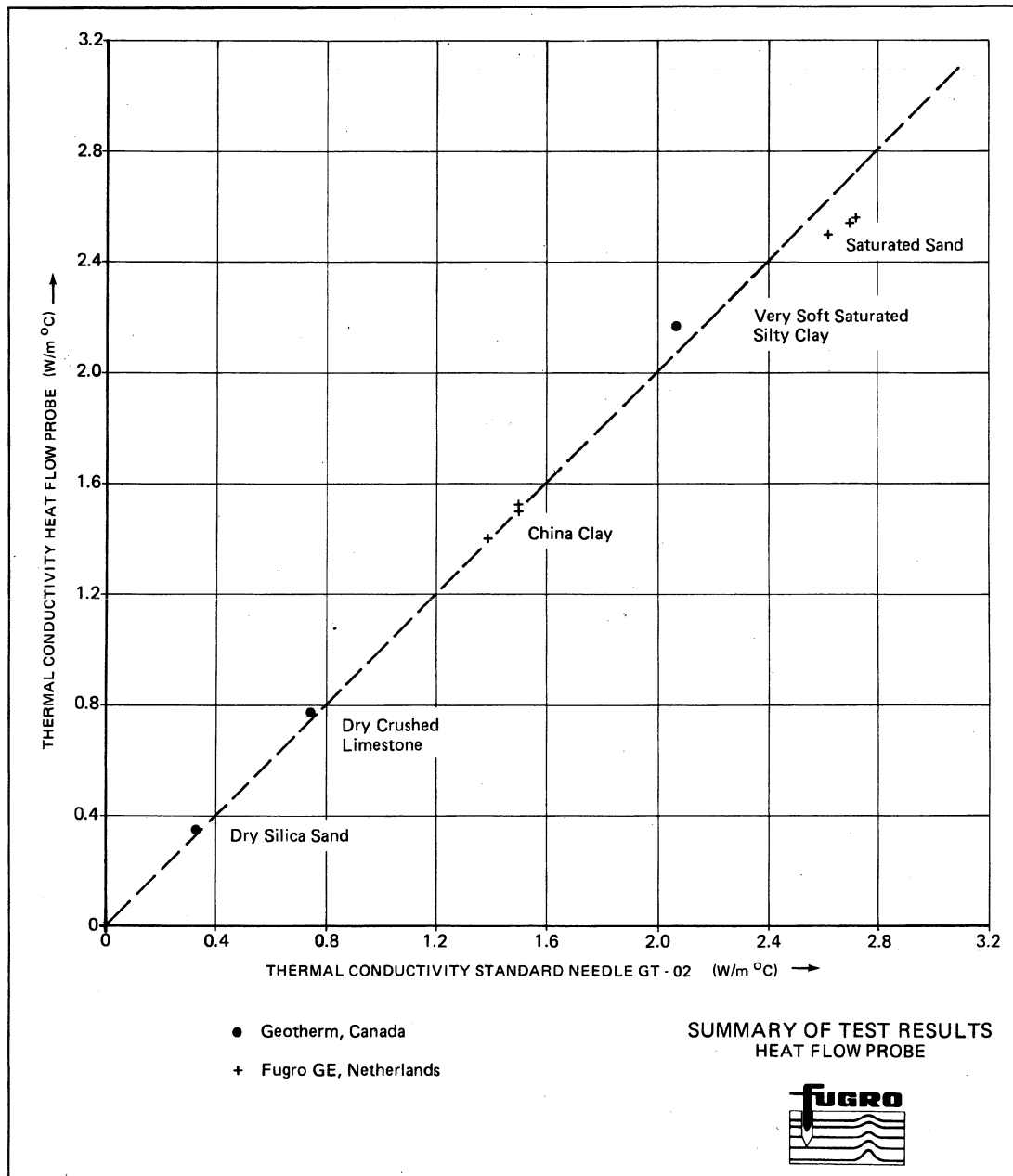


Figure AI 2.3 Comparison of thermal conductivity measured by the Fugro in situ probe and a standard probe from Geotherm, Canada. (The plot is shown by permission from Fugro G.E. B.V., The Netherlands, for restricted use and must not be reproduced without their written permission).

AI 3. REFERENCES

ZIELINSKI, G.W., GUNLEIKSRUD, T., SÆTTEM, J., ZUIDBERG, H.M. and GEISE, J.M., 1986: Deep Heatflow Measurements in Quaternary Sediments on the Norwegian Continental Shelf. Paper presented at the Offshore Technology Conference, Houston 1986. 6 pp.

VON HERZEN, R. and MAXWELL, A.E., 1959: The Measurement of Thermal Conductivity of Deep-Sea Sediments by a Needle-Probe Method. J. Geophys. Res., 64, pp. 1557-1563.

A P P E N D I X II

QUATERNARY SAMPLES

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AII 1. COLLECTED DATA

Totally 1.32 m cumulative length of Quaternary samples were collected. All the sampling was performed through the drill string and below the drill bit in undisturbed sediments. Samples of generally very good quality were obtained.

Two types of sampling equipment were used: The Fugro Wip sampler and a hammersampler. These two systems were combined with 3 inch and 2 inch steel sampling tubes, respectively.

The Wip system comprises a hydraulically operated jack that is lowered down inside the drill string and latched with the sampling tube cutter at drill bit level. The sampling tube is then pushed down into undisturbed sediments and cuts a cylindrical sample.

Table AII 1.1 Co-ordinates and other key data for the 1986 IKU shallow drilling site in block 7120/6.

Site	Total core length (m)	Coordinates				Water depth (m)	Quaternary sediment thickness (m)
		Lat.	Long	Northing	Easting		
7120/6-U-1	1.26	71°37'12.117"	20°56'30.079"	7946767.6	497947.7	315	50
7120/6-U-1B	2.69	71°37'12.117"	20°56'30.079"	7946767.6	497947.7	315	50
Geographical co-ordinates: ED 50 Grid projection : UTM - CM 21°EAST							

The hammersampler is mechanically operated from a winch on the main deck and comprises a load that can move freely a certain distance up and down along a shaft which on the lower end is connected to the tube. During sampling the load is pulled up and allowed to drop freely down about 10-30 times and by this the sampling tube is hammered into the sediment.

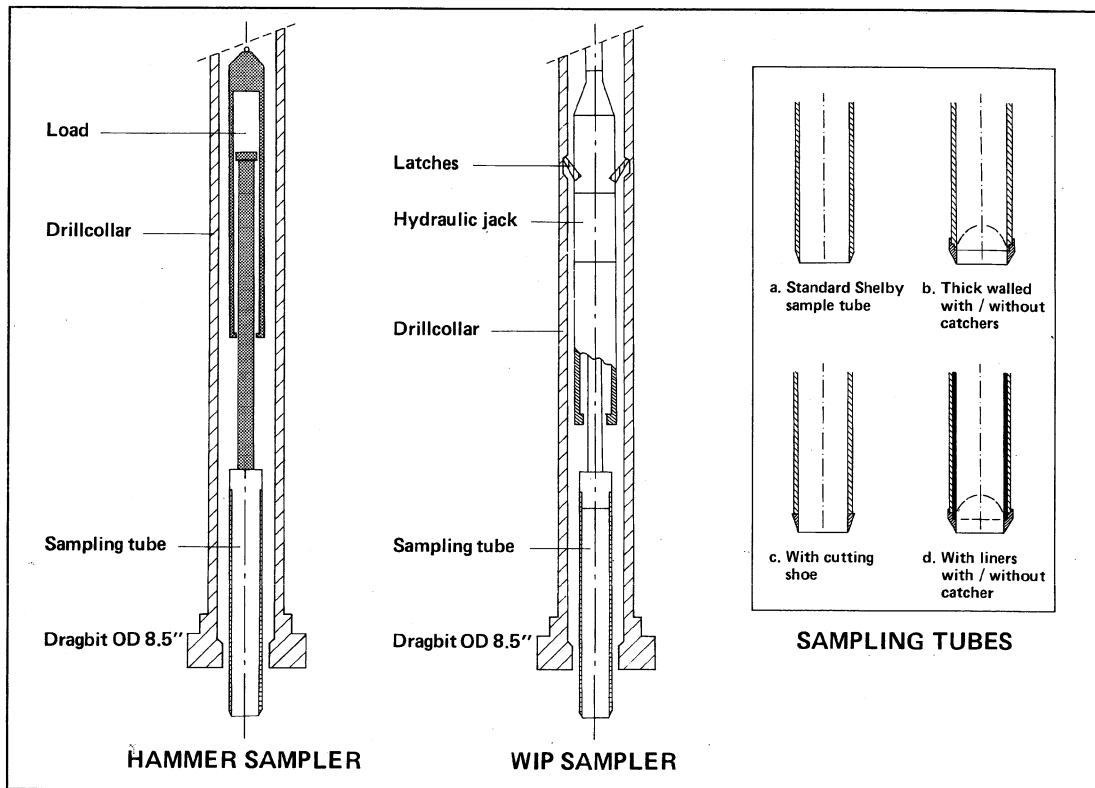


Figure AII 2.2 Hammer sampler and Wip sampler.

Table AII 1.2 Quaternary core material obtained at site 7120/6-U-1 in 1986.

SITE	SAMPLE	DEPTH (m)	SITE	SAMPLE	DEPTH (m)
7120/6-U-1	WIP 1	10.96		WIP 3,A	17.30-17.34
	WIP 2,A	13.00-13.21		WIP 3,B	17.34-17.46
	WIP 2,B	13.21-13.32		WIP 3,C	17.46-17.60
	WIP 2,C	13.32-13.41		WIP 3,D	17.60-17.74
	WIP 2,D	13.41-13.61		WIP 3,E	17.74-17.78
	WIP 2,E	13.61-13.65			
	WIP 3	14.90-15.47		WIP 4,A	20.30-20.42
7120/6-U-1B	WIP 1,A	10.20-10.27		WIP 4,B	20.42-20.55
	WIP 1,B	10.27-10.34		WIP 4,C	20.55-20.72
	WIP 1,C	10.34-10.37		WIP 4,D	20.72-20.85
	WIP 1,D	10.37-10.51		WIP 4,E	20.85-20.90
	WIP 1,E	10.51-10.66			
	WIP 2,A	12.30-12.36		WIP 5,A	25.30-25.34
	WIP 2,B	12.36-12.48		WIP 5,B	25.34-25.45
	WIP 2,C	12.48-12.60		WIP 5,C	25.45-25.60
	WIP 2,-	12.60-12.68		WIP 5,D	25.60-25.68
	WIP 2,E	12.68-12.72			
				WIP 6,A	30.10-30.23
				WIP 6,C+D	30.23-30.45

AII 2. LABORATORY ANALYSES

AII 2.1 Analysis program (for results reference is made to Chapter AII.4)

The main objective of the analysis program was to provide necessary data to document the thermal properties of the sediments. A second objective was to document the soil mechanical properties of the sediments, and these two objectives partly require the same type of analyses.

Other tests and studies of the samples aim to investigate physical and chemical composition and the history of the sediments. This work will be done in co-operation with universities and will for instance comprise thesis work by students.

The following tests are performed or planned:

- Thermal conductivity
- Visual description
- Falling cone test (undrained shear strength)
- Water content
- Bulk unit weight
- Sound velocity
- Mineralogy (XRD)
- Oedometer testing
- Triaxial testing
- Atterberg limits

- Grain size distribution
- Total carbon (TC)
- Total organic carbon (TOC)
- Composition of organic geochemical composition
- Micropalaeontology
- Sediment petrography

AII 2.2 Thermal conductivity

Thermal conductivity has been measured extensively by use of the needle probe method (i.e. von Herzen and Maxwell 1959). This was mainly done on board during the drilling cruise, but a number of selected samples have also been sent to the Geophysical Laboratory at University of Aarhus for such measurements.

AII 2.3 Radiographs

All samples were radiographed before they were split. This work was done at The Museum of the University of Trondheim. The radiographs were taken through the plastic foil or wax emballage in which they were stored, and with the samples resting in loose, dry fine-grained sand.

The radiographs were of variable but partly good quality and give valuable information about textures and structures (fragments of rocks or fossils).

AII 2.4 Visual description

Subsequent to measurement of thermal conductivity and radiographing the samples were unpacked, split and visually described in the IKU laboratory. This description also includes the following tests:

- Falling cone
- Water content
- Bulk unit weight
- Sound velocity

The colours were determined by comparison with the Munsell colour chart.

During the description all necessary subsamples for other tests were selected.

AII 2.5 Sound velocity measurements

Sound velocity was measured in both horizontal and vertical direction of the samples (radially and axially on the cores) using a "Pundit Portable Ultrasonic Digital Indicating Tester" with a 25 mm diameter, flat surface, receiver and 150 kHz transmitter. This apparatus measures sound travel time. Distance between transmitter and receiver was measured with a calliper.

AII 2.6 Soil mechanical tests

Advanced soil mechanical testing was done by the SINTEF Division of Geotechnical Engineering (Senneset 1986). These tests were performed at representative samples that were waxed and selected for this purpose on board.

The following parameters are recorded:

- w_p - plasticity limit (%)
- w_L - liquid limit (%)
- w - natural water content (%)
- γ - density (unit weight) (kN/m^3)
- S_u - undrained shear strength (kN/m^2)
- a - attraction kN/m^2
- $\tan\phi$ - ϕ angle of friction
- m - modulus number
- C_v - coefficient of consolidation (m^2/yr)
- p'_c - effective preconsolidation pressure (kN/m^2)
- p'_o - overburden pressure (calculated from column density) kN/m^2

The results are summarized in Table AII 2.1.

Table AII 2.1 Summary of results from soil mechanical analyses at the SINTEF Division of Geotechnical Engineering.

Boring No.	Sample depth m	Index properties					Overburden pressure $\sim p_0'$ kN/m ²	Oedometer tests			Triaxial tests			Remarks
		W %	W _L %	W _p %	Unit weight kN/m ³	S _u kN/m ²		Vertic./ Horiz.	$\sim p_c'$ kN/m ²	Modulus number	Attr. a kN/m ²	tan ϕ	Def. at failure ϵ_f %	
7120/6-U-1B	12.30	22.8	39.0	19.2	20.7	110	132	V	400	19.4	10	0.59	7.0	Clay
		20.1						H	450	26.0				Clay
	17.30	21.4	34.5	18.2	21.3	74	195	V	750	32.0	20	0.56	6.0	Silty, sandy layers
		20.7						V	1400	30.0	100	0.52	2.0	Hard, stiff
	30.10-30.28	15.7	39.7	18.2	21.8	345	365	H	900	40.0				

*) S_u from triaxial tests.

AII 2.7 Mineralogy analyses by X-ray diffraction (XRD)

The mineralogical composition of a sediment is necessary input for theoretical calculation of thermal conductivity. The mineral composition was analysed on selected samples by use of the semi-quantitative XRD technique.

The XRD analyses were performed on bulk samples crushed in a mortar, suspended in water and sucked onto a millipore filter. Qualitative and semi-quantitative mineralogy was then performed on a Phillips diffractometer with the setup described below:

Radiation: monochromatic CuK

Voltage: 40 kV

Current: 30 mA

Speed: 2°/minute, from 3°-35° (20)

The semi-quantitative results are based on an area calculation on XRD strip chart records (height x width, at half maximum height) multiplied by the weighed factors given below. The factors are experimentally determined by mixing minerals in different proportions.

Table AII 2.2 XRD weighed factors used by IKU

Mineral	Weighed factor	d-value (Å)
Quartz (Qtz)	1.00	4.26
Alkalifeldspar (K-spar)	0.50	ca. 3.24
Plagioclase (Plag)	0.50	ca. 3.18
Smectite (Smec)	0.35	ca. 14.7
Smectite mixed layer (10-14Å)	0.55	10-14
Illite (Ill)	1.40	10
Amphibole (Amp.)	0.80	8.45
Chlorite (Chl)	0.70	7 *
Kaolinite (Kaol)	0.70	7 *
Calcite (Calc)	0.25	3.04
Dolomite (Dol)	0.20	2.89
Siderite (Sid)	0.25	2.79
Pyrite (Py)	0.70	2.71

* The chlorite - kaolinite ratio is based on measurements of the intensity of the 001 reflex of chlorite and the 002 reflex of kaolinite.

Table AII 2.3 Mineral composition (wt%) based on X-ray diffraction analyses.

Site	Depth (m)	Semi-quantitative whole-rock analysis based on XRD technique.												
		QTZ	ALK	PLA	CAL	DOL	SID	M/I	CHL	KAO	MIX	SME	AMP	PY
7120/6-U-1	13.41-13.60	33	5	18	1	2	1	15	6	9	7	1	2	1
7120/6-U-1B	10.37-10.51	35	4	29	2	2	Tr	5	3	4	5	4	4	4
7120/6-U-1B	10.51-10.66	27	7	22	2	1	0	19	5	4	4	1	6	2
7120/6-U-1B	20.42-20.55	26	8	22	1	2	0	14	5	15	3	2	2	2
7120/6-U-1B	25.34-25.45	34	5	25	1	1	0	13	2	4	6	2	4	1

AII 2.8 Micropalaeontology

From previous work with Quaternary shallow drilling samples in the Barents Sea it is known that fossil fragments and microfossils are very sparse (Hald pers. commun. 1986). A thorough study of the present fossils will, however, be performed. This work will be done at the University of Tromsø, partly as thesis work.

AII 2.9 Other tests

All the samples comprise silty clay with variable amount of coarser fragments (diamictons). They are probably of glacial or glaciomarine origin. The depositional history is, however, far from understood. Study of sediment texture, structure and petrography of rock fragments may give important information in this context. This work will mainly be performed at the University of Tromsø.

Radiocarbon dating and amino acid analyses will be carried out on all samples with sufficient fossil fragments.

AII 3. REFERENCES

SENNESET, K., 1986: IKU shallow borings Barents Sea 1986. Geotechnical laboratory investigations. Report from the SINTEF Division of Geotechnical Engineering, 35 pp. Confidential.

VON HERZEN, R. and MAXWELL, A.E., 1959: The Measurement of Thermal Conductivity of Deep-Sea Sediments by a Needle-Probe Method. J. Geophys. Res., 64, pp. 1557-1563.

AII 4. DOCUMENTATION

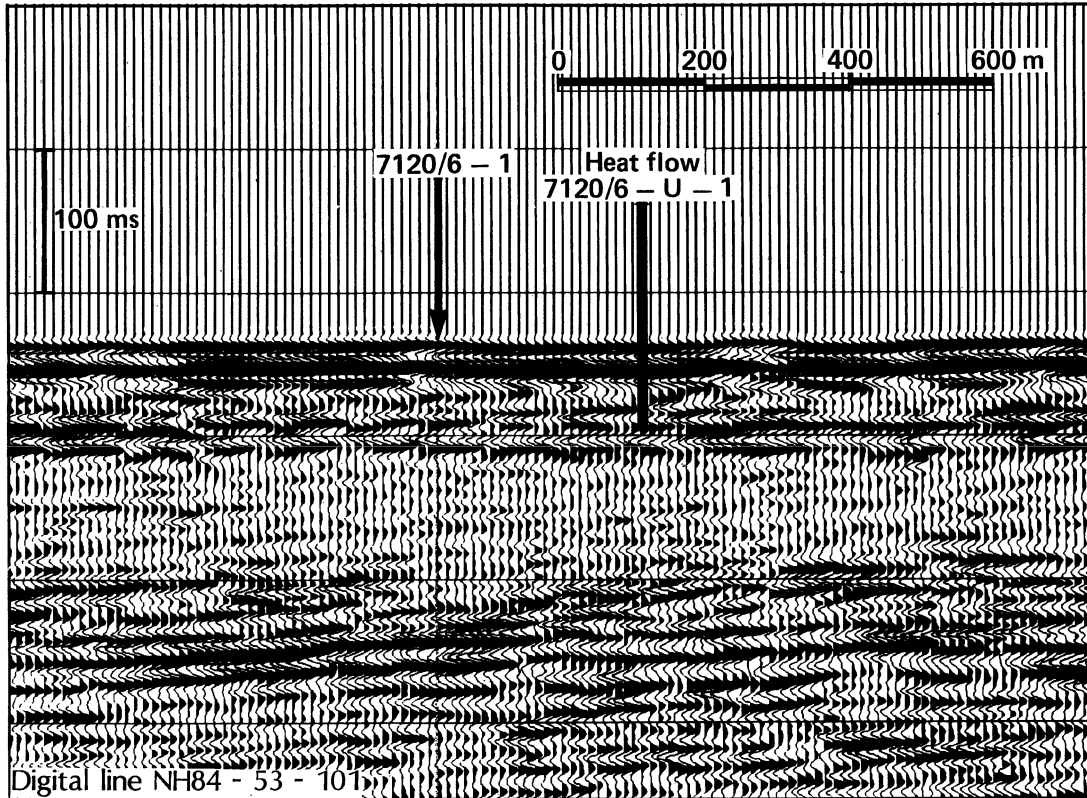
AII 4.1 General

Chapter AII 5 comprises documentation for each site. In addition to seismic records this includes sample recovery sheets, soil mechanical analysis summary, sediment description sheets and grain size distribution sheets.

The documentation represents a status of the analysis per January 1987. Some alterations/additions may occur in the future.

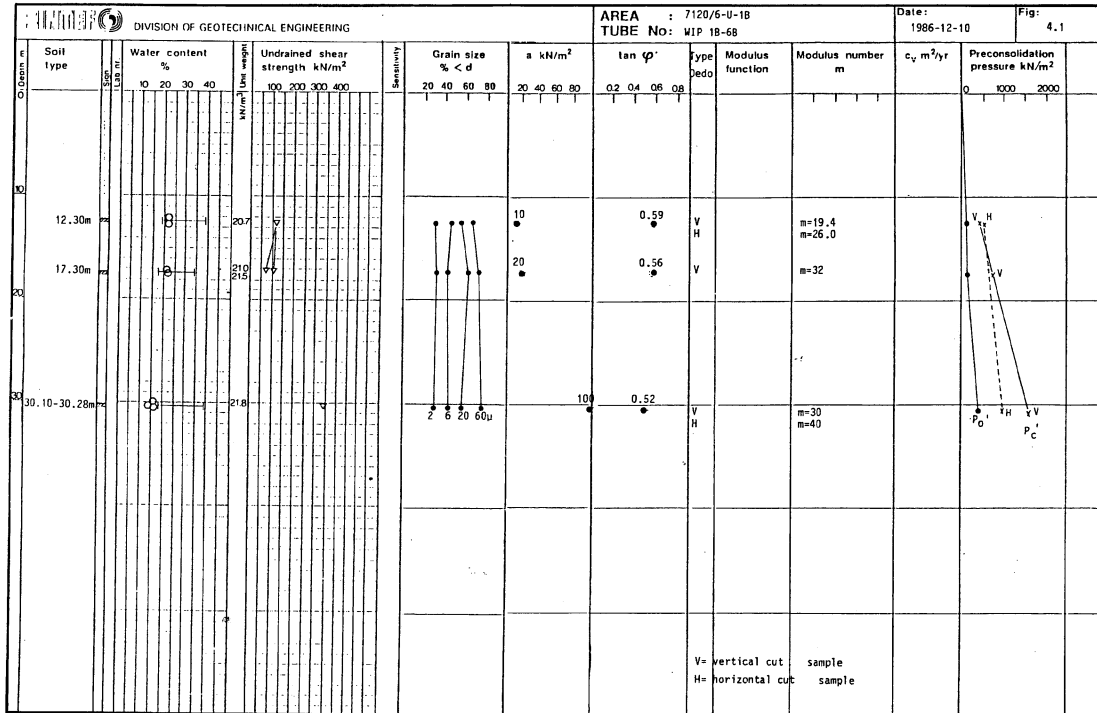
Analysis results of total carbon, total organic carbon and carbonate content are given on the last page of this appendix.

AII 4.2 Data sheets

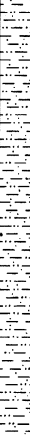


Depth below sea bed (m)	Undrained shear strength S_u (kN/m ²)	Vertical sound velocity V_p (m/s)	Water content w (%)	7120/6-U-1 and 7120/6-U-1B Brief sediment description
11 10.20 - 10.66 10.96	74 - 198	1820	17 - 22	CLAY silty, sandy. Fragments (sand and gravel) size of claystone, siltstone and sandstone.
12 12.30 - 12.72	110			
13 13.00 - 13.65	> 245	1850	22	Small shell fragments.
14 14.90 - 15.47				
15 17.30 - 17.78	74	1870	22	
16 20.30 - 20.90	200	1700	23 - 26	
17 25.30 - 25.98	115	1860	21	
18 30.10 - 30.45	365			
19				
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40				

Data sheets



Project 21.3419.00 1986		Level 13.00 - 13.65 m		Equipment WIP 3"		 IKU SINTER-GRUPPEN	
Age Quaternary	Water depth 316.5 m	Latitude 71°37'12.117"	Longitude 20°56'30.079"	Location 7120/6 - U - 1		WIP 2	
Analytical results	Anal.	m	Lith.	Core description		S _u	Class
V _{SH} = 1760 m/s	k _T 						

Project 21.3419.00 1986		Level 14.90 - 15.47 m		Equipment WIP 3"							
Age Quaternary		Water depth 316.5 m		Latitude 71°37'12.117"		Longitude 20°56'30.079"		Location 7120/6 - U - 1		WIP 3	
Analytical results		Anal.		m		Lith.		Core description		Su Class	
				14.90				CLAY, silty, sandy Col. 5Y 3/1 very dark gray			
				15.47							
Comments: The sample is disturbed and stored in bags. Intervals for m.pal. and sed.petr.: 14.90 - 15.57.				Symbols: K _f = grain size distribution k _T = thermal conductivity m = mineralogy (XRD) w = water content (% water of dry sample) γ = unit weight of soil (kN/m ³) V _{SH} = horizontal sound velocity (m/s) V _{SV} = vertical sound velocity (m/s) O _e = oedometer test T = triaxial test TOC = total organic carbon TC = total carbon S _u = undrained shear strength from falling cone test (kN/m ²)							

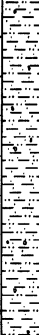
Data sheets

Project 21.3419.00 1986		Level 10.20 - 10.66 m		Equipment WIP 3"					
Age Quaternary	Water depth 316.6 m	Latitude 71°37'12.117"	Longitude 20°56'30.079"	Location 7120/6 - U - 1B		WIP 1			
Analytical results	Anal.	m	Lith.	Core description		S _u	Class		
V _{SH} = 2040 m/s w = 16.9 % γ = 21.66 kN/m ³ V _{SH} = 1990 m/s V _{SV} = 1820 m/s w = 21.6 % γ = 20.7 kN/m ³ V _{SH} = 1780 m/s V _{SS} = 1820 m/s	Org. Geoch.	10.20		CLAY, silty, sandy. Sand and gravel fragments of claystone, siltstone and sandstone Col. 5Y 3/1 very dark gray		74			
		k _T m							
		k _T m				196			
		k _T m							
		k _T m							
		k _T m							
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		k _T m							
		k _T m							
Comments: Intervals (m) for m.pal. and sed.petr.: 10.37 - 10.51.		Symbols: K _f = grain size distribution T = triaxial test k _T = thermal conductivity TOC = total organic carbon m = mineralogy (XRD) TC = total carbon w = water content (% water of dry sample) S _u = undrained shear strength from falling cone test (kN/m ²) γ = unit weight of soil (kN/m ³) V _{SH} = horizontal sound velocity (m/s) V _{SV} = vertical sound velocity (m/s) O _e = oedometer test							

Project 21.3419.00 1986		Level 12.30 - 12.72		Equipment WIP 3"					
Age Quaternary	Water depth 316.6 m	Latitude 71°37'12.117"	Longitude 20°56'30.079"	Location 7120/6 - U - 1B		WIP 2			
Analytical results	Anal.	m	Lith.	Core description		S _u	Class		
	Oe/T	12.30		CLAY, silty, sandy One rock fragment (undifferentiated) 3 cm. Col. 5Y 3/1 very dark gray					
									
	Org. Geoch.								
									
		12.72							
									
									
									
									
									
									
									
									
									
									
									
									
									
Comments: Intervals (m) for m.pal. and sed.petr.: 12.30 - 12.36.			Symbols: K _f = grain size distribution T = triaxial test k _T = thermal conductivity TOC = total organic carbon m = mineralogy (XRD) TC = total carbon w = water content (% water of dry sample) S _u = undrained shear strength from falling cone test (kN/m ²) γ = unit weight of soil (kN/m ³) V _{SH} = horizontal sound velocity (m/s) V _{SV} = vertical sound velocity (m/s) O _e = oedometer test						

Data sheets

Project 21.3419.00 1986		Level 17.30 - 17.78 m		Equipment WIP 3"			
Age Quaternary	Water depth 316.6 m	Latitude 71°37'12.117"	Longitude 20°56'30.079"	Location 7120/6 - U - 1B		WIP 3	
Analytical results	Anal.	m	Lith.	Core description		S _u	Class
V _{SH} = 1780 m/s V _{SV} = 1670 m/s w = 22.2 % γ = 21.4 kN/m ³	Oe/T	17.30		CLAY, silty, sandy. Stone, 5 cm, undiff.			
		17.78		CLAY, silty Col. 5Y 3/1 very dark gray			
Comments: Intervals (m) for m.pal. and sed.petr.: 17.30 - 17.34, 17.74 - 17.78.				Symbols: K _f = grain size distribution k _T = thermal conductivity m = mineralogy (XRD) w = water content (% water of dry sample) γ = unit weight of soil (kN/m ³) V _{SH} = horizontal sound velocity (m/s) V _{SV} = vertical sound velocity (m/s) O _e = oedometer test T = triaxial test TOC = total organic carbon TC = total carbon S _u = undrained shear strength from falling cone test (kN/m ²)			

Project 21.3419.00 1986		Level 20.30 - 20.90 m		Equipment WIP 3"				
Age Quaternary	Water depth 316.6 m	Latitude 71°37'12.117"	Longitude 20°56'30.079"	Location 7120/6 - U - 1B		WIP 4		
Analytical results		Anal.	m	Lith.	Core description		S _u	Class
V _{SH} = 1660 m/s V _{SV} = 1690 m/s w = 22.5 % γ = 21.2 kN/m ³ V _{SH} = 1700 m/s V _{SV} = 1700 m/s w = 25.5 % γ = 20.5 kN/m ³ V _{SH} = 1680 m/s V _{SV} = 1700 m/s		k _T m	20.30		CLAY, silty, sandy Coarse sand and gravel fragments of sandstone, siltstone and claystone. Col. 5Y 3/2 dark olive gray		200	
		k _T m					200	
		k _T m						
		k _T Org. Geoch.	20.90					
Comments:		Symbols:						
Intervals (m) for m.pal. and sed.petr.: 20.30 - 20.72.		K _f = grain size distribution k _T = thermal conductivity m = mineralogy (XRD) w = water content (% water of dry sample) γ = unit weight of soil (kN/m ³) V _{SH} = horizontal sound velocity (m/s) V _{SV} = vertical sound velocity (m/s) O _e = oedometer test						
		T = triaxial test TOC = total organic carbon TC = total carbon S _u = undrained shear strength from falling cone test (kN/m ²)						

Data Sheets

[illegible]

Q U A T E R N A R Y S A M P L E S
Total Carbon, Total Organic Carbon,
and Carbonate Content)

SAMPLE NUMBER	DEPTH m	TC %	TOC %	CaCO3 %
7120/6-U-1				
C-5905	13.65	.90	.51	3.25
7120/6-U-1B				
C-5906	10.51	.77	.37	3.34
C-5907	12.72	.85	.45	3.34
C-5908	20.85	.88	.45	3.59
C-5909	25.68	.87	.55	2.67
C-5804	35.20	.98	.79	1.58

) Carbonate content calculated from difference
TC - TOC; all carbonate assumed being CaCO3.

A P P E N D I X I I I

STATUS OF KNOWLEDGE ABOUT THE GLACIAL HISTORY OF THE AREA

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AIII 1. INTRODUCTION

This chapter provides a discussion of the status regarding knowledge about the glacial history of the Barents Sea. Based on this we have suggested two alternative temperature history models from the area implying a maximum (model I) and a minimum (model II) effect on heat flow measured in shallow boreholes.

The Quaternary is characterised by large changes in climate with glaciations and interglaciations.

Investigations in the north Atlantic (Shackleton et al. 1982) indicate that the first extensive ice sheets in the northern hemisphere occurred about 2.4 mill y BP. From then on there have been alterations between glacial and interglacial periods. The exact time for the first glaciation may, however, be disputed.

AIII 2. PUBLISHED KNOWLEDGE

The knowledge of how the last ice age (the Weichselian) developed and receded in the Barents Sea is scarce compared with the western and southern part of Europe. This relation is even more pronounced going back in time to the last interglacial (the Eemian) and the preceeding glacial (the Saalian) and interglacial (the Holsteinian).

For the present purpose the need for a detailed glacial history decreases with increasing age, and we have done the following simplifications:

For the interstadials Holsteinian and Eemian we have assumed that the climate was as today (Holsteinian in Europe was actually slightly cooler and Eemian slightly warmer). The duration of Eemian is in this context fixed between 115 000-130 000 B.P. (Sejrup in press) and we assume that the Holsteinian interglacial terminated around 185 000 BP (Denton & Hughes 1983).

The second last glacial period in our model, the Saalian had a more extensive ice cover than the Weichselian (Nilson 1983) and there are no stratigraphical work done in Scandinavia which are of any help in reconstructing the conditions in the Barents Sea. We have therefore assumed that the Barents Sea was covered by an ice sheet in large parts of this period. As a crude simplification we have not taken into account any interstadials in this period.

Our tentative relation between period nomenclature and age for the present purpose can thus be summarized as follows:

Weichselian ice age	10 000 - 115 000 BP
Eemian interglacial	115 000 - 130 000 BP
Saalian ice age	130 000 - 185 000 BP
Holsteinian interglacial	185 000 - 245 000 BP

Complicating factors for the glacial history of the area may be:

- The ice cover on Svalbard and adjacent areas was possibly not in phase with the southern and western margin of the European ice sheet (Boulton 1979; Boulton et al. 1982; Landvik pers. commun. 1986).
- The ice sheet in the Barents Sea was depending on ice feeding from as much as three possible different glacier domes. (Denton et al. 1981):
 - A) The ice sheet draining northwards through Finnmark (sev. authors).
 - B) Southerly drainage from a postulated ice dome east of Svalbard (Salvigsen 1981; Salvigsen & Nydal 1981; Häggbom 1982; Boulton et al. 1982, Elverhøi & Solheim 1983; Solheim & Kristoffersen 1984).
 - C) Feeding from a postulated culmination to the east (the Kara ice dome) (Schytt et al. 1968; Grosswald 1980; Denton & Hughes 1981).

The present published knowledge of the glacial history of the Barents Sea, which is based mainly on recent marine geological data and shore line investigations from the Svalbard archipelago, can briefly be summarized as done by Vorren & Kristoffersen (1986):

1. Grounded glaciers reached the shelf edge in front of Bjørnøyrenna at least four times during the late Cenozoic (Solheim & Kristoffersen 1984).
2. The northern Barents Sea was covered by an ice sheet in Late Weichselian (Salvigsen 1981; Salvigsen & Nydal 1981).
3. Spitsbergenbanken was covered by an ice sheet, possibly as late as the Late Weichselian (Elverhøi & Solheim 1983; Solheim & Kristoffersen 1984).

Vorren & Kristoffersen (1986) described undated ridges in the southwestern Barents Sea which they argue to represent the maximum of a Weichselian ice sheet.

In other words there does not exist an unambiguous model of glaciation for the last 200 000 years BP in the study area. To bypass this problem we are largely bound to use models of glaciations from other places. However, in the present work we pay more specific attention to results from Svalbard and the Norwegian mainland.

Western Norway. In this area there are many papers summing up the Weichselian stratigraphy (a.o. Mangerud 1981; Andersen et al. 1981). For the coastal areas Sejrup (in press) has summarized and correlated the existing works. His juxtaposition is the northernmost well-funded model of Weichselian stratigraphy and we use this model as a support in the Barents Sea. His model consists of four interstadials and five stadials in the timespan between Eem and Allerød. He regards this as a minimum number of interstadials.

The duration of the interstadials is in principle uncertain and in our models we use Sejrup's inferred time estimate of the different events (Figures 6.4.2 and 6.4.3).

Troms. In the coastal area the ice sheet has transgressed sorted sediments dated to 27 000 BP (Andreassen et al. 1984). Vorren et al. (1983) have shown that the ice sheet occupied the outer part of the continental shelf after about 36 000 BP, and Rokoengen et al. (1979)

indicated that the ice sheet may have reached the shelf edge as late as about 13 300 BP.

Finnmark. In the southwestern part of Finnmarksvidda several ice free periods are recognised, but none of them are dated (Olsen & Hamborg 1983, 1984).

Svalbard. The investigations by Salvigsen (1981) and Salvigsen & Nydal (1981) show that Svalbard was completely covered by an ice-sheet at least once, probably in Early Weichselian. The Late Weichselian glaciation was limited and local in the western part, while the eastern part of the archipelago was covered by an ice sheet.

In the scope of this presentation Boulton et al. (1982) are largely in agreement with Salvigsen & Nydal (1981). Boulton et al. (1982) is modified and presented in Figures 6.4.2 and 6.4.3.

Barents Sea. Solheim & Kristoffersen (1984) regarded the pre-Late Weichselian glacial chronology as completely open due to lack of stratigraphical tie points. However, presenting arguments for a maximum age of a few hundred thousand years for a moraine ridge complex in the western part of Bjørnøyarennå, they suggest that the last ice sheet that extended westwards into the deeper parts of Bjørnøyarennå was of Saalian or Early Weichselian age.

This is in agreement with Salvigsen & Nydal (1981) and Landvik (pers. commun.) who find that the most extensive ice cover on Svalbard occurred in early Weichselian, while Troitsky et al. (1979) and Miller (1982) suggested a Saalian age. For the Late Weichselian Elverhøi & Solheim (1983) found it most probable that the ice sheet was limited to the bank areas (present water depth 300-400 m) and thus formed a calving bay in Bjørnøyarennå.

Still they were open for the possibility that also a Late Weichselian ice sheet extended westwards to form parts of the ridge complex in the western part of Bjørnøyarennå.

Sparker data collected within the IKU Barents Sea Mapping Program shows evidences of a wedge shaped (in NW-SE cross section) deposit in the Nordkappbanken area. The northwestern limitation of this deposit subparallels the present 300 m water depth contour on the map in Figure AIII 2.1 and could tentatively be correlated with Elverhøi & Solheim's (1983) ice margin at 300-400 m water depth on the northern flank of Bjørnøyareenna, thus supporting the Bjørnøyareenna calving bay theory.

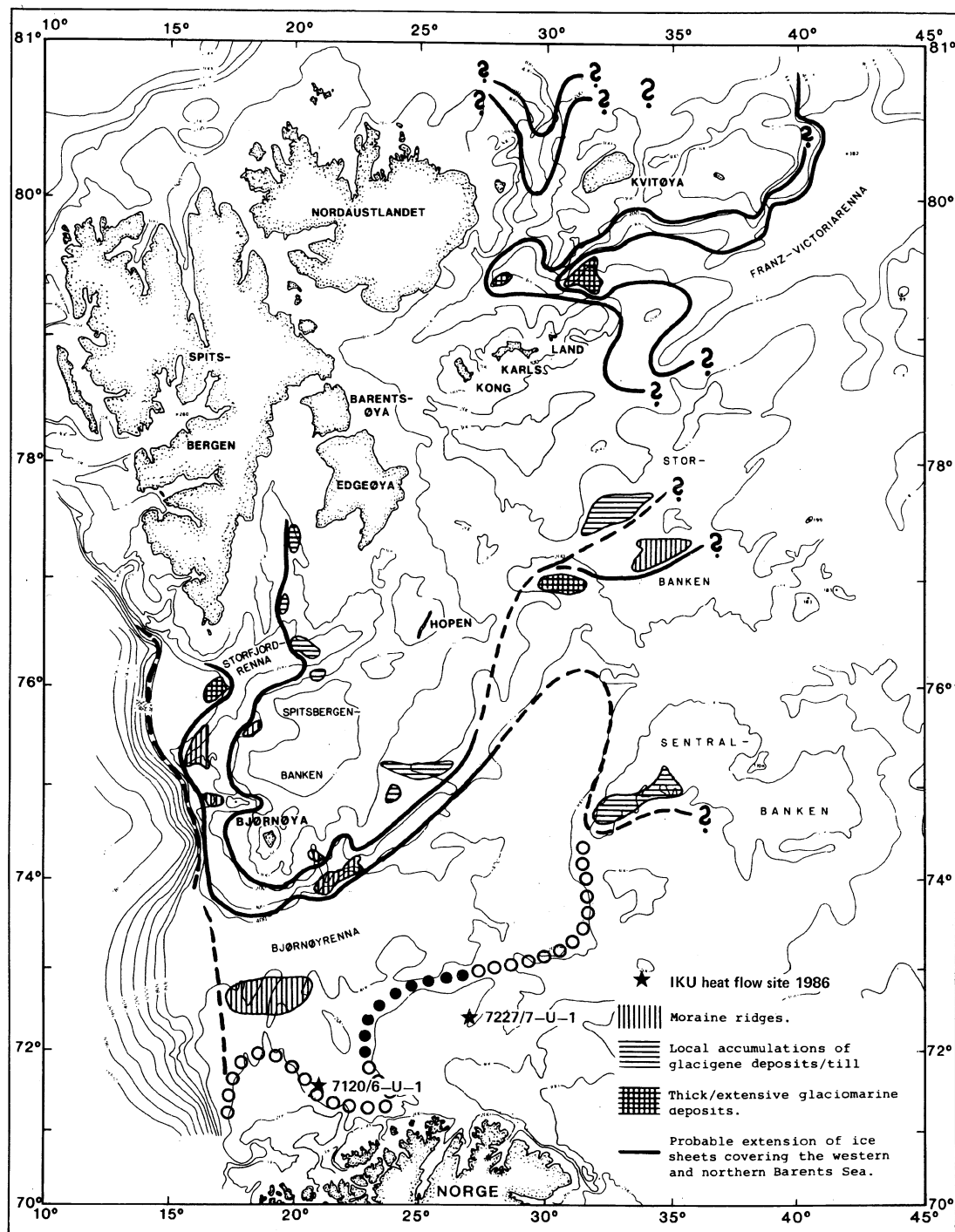


Figure AIII 2.1

Bathymetric map showing features related to former ice margins in the Barents Sea. Modified after Elverhøi and Solheim (1983). The heavy, dotted line shows the approximate western termination of a wedge shaped sediment thickening interpreted from IKU sparker data. Open circles indicate a tentative ice sheet margin related to this feature.

AIII 3. CONSTRUCTION OF TEMPERATURE HISTORY

AIII 3.1 Glaciation models

As can be seen from the previous discussion the geological data makes several models of glaciation possible.

In this work we are interested in the "coldest" and "warmest" probable temperature history.

We have therefore reconstructed what we regard as the probable maximum and minimum glacial influence in the area. These reconstructions are combined with the respective ice thicknesses which give the "warmest" and "coldest" condition at the base of the glacier.

These models are based on the following strong simplifications for the positions of the ice margin:

- 1) The ice-sheet was non existent or had retreated to the mainland.
- 2) The ice-margin was situated at 300-400 m present water depth forming a calving bay in Bjørnøyarena.
- 3) The ice-sheet was calving at the continental margin.

Maximum glaciation

Glaciers extending to the shelf edge occurred during Saale and Early Weichselian. In addition there were two periods when ice sheets grounded on the shallow banks in the Middle and Late Weichselian.

Minimum glaciation

Saalian glaciation with an ice-sheet extending to the shelf edge. Early, Middle and Late Weichselian ice sheets grounded on the shallow banks and did not extend to the shelf edge.

AIII 3.2 Temperatures underneath the Barents Sea ice sheets

There are several opinions regarding gradients and thicknesses of a Barents Sea ice sheet. In large there are two main temperature conditions to be considered, namely frozen (T_c) and wet-based (T_m) glaciers (cold and temperate glaciers).

For wet based glaciers there are grossly two main alternative approaches when calculating surface profiles of an ice sheet: A low profile ice sheet is a consequence of the model by Boulton & Jones (1979) which assumes that 90% of the movement of a glacier is due to deformation in the underlying sediments. The profile of an ice sheet will thus mainly depend on the shear strength of the underlying confined mixture of water and sediments.

The other model for temperate glaciers is based in internal flow of the ice (Paterson 1981) and ice sheet profiles given by Hughes (1981, Figure 5.8). The same profiles are used in the reconstruction by Hughes et al. (1981) of a Late Weichselian ice sheet in the northern hemisphere.

Our model II, representing a "warm" ice, is based on a low profile, wet-based ice sheet. We have assumed a shear strength of 20 kN/m^2 (0.2 bar) in the sediments just underneath the ice sheet (Boulton & Jones 1979, Figure 5).

In cold based ice sheets the deformation in the sole of the glacier is supposed to decrease strongly. Most of the movement will take part within the ice body. This is expected to give steeper gradients of the ice sheet surface and a greater maximum ice sheet thickness. According to the reconstruction of the maximum Late Weichselian ice sheet by Hughes et al. (1981), the temperature below the maximum Barents Sea glacier would be below the pressure melting point, T_m , for both the 1986 heat flow sites. Though Orheim (pers. commun. 1985) tends to assume that most of the large Barents Sea ice sheet (sheets) had temperatures equal to T_m .

In our model I, for a "cold" ice we have chosen the steepest probable ice profile by Hughes (1981, line 1 in Figure 5.8). We have furthermore chosen $T_c = T_m$ as an average temperature condition for the lifetime of a cold based ice sheet.

In a closed system underneath an ice sheet the pressure melting point temperature, T_m , will follow the phase equilibrium function for ice and fresh water. As a function of pressure this equilibrium temperature decreases with about $7 \cdot 10^{-3} \text{ } ^\circ\text{C/atm}$ or approximately 0.7°C/1000 m ice thickness (Sugden & John 1976).

From our alternative assumptions about ice margin positions and ice sheet profiles we have arrived at alternative ice sheet thicknesses. The corresponding temperatures are presented in Tables AIII 3.1 and AIII 3.2.

Table AIII 3.1 Temperature ($T_c = T_m$), underneath an ice sheet at site 7120/6-U-1 assuming the "cold" glaciation model.

- 1) The ice sheet terminated at the continental margin.
- 2) The ice sheet was restricted to the shallow banks.

Site	Average temperature under a cold based ice	
	1) ($^\circ\text{C}$)	2) ($^\circ\text{C}$)
7120/6-U-1	-1.6	-0.8

Table AIII 3.2 Pressure melting point temperature, T_m , underneath an ice sheet at site 7120/6-U-1 assuming the warm glaciation model.

- 1) The ice-sheet terminated at the continental edge.
- 2) The ice-sheet was restricted to the shallow banks.

Site	Pressure melting point temperature	
	1) (°C)	2) (°C)
7120/6-U-1	-0.8	-0.5

AIII 3.3 Sea water temperatures

For a simplified temperature model it may be assumed that the annual mean sea bottom temperature was as today during the whole Holocene period and in all periods between the glaciations. This temperature has been obtained by extrapolation of temperature gradients from the boreholes. The effect of variations in thermal conductivity with depth is accounted for.

The shelf area in front of a marine ice sheet will normally have abundant icebergs or be covered by an ice sheet or drifting ice. Under such conditions it can be assumed that the sea water even down to 400 m depth was between the freezing point for sea water (about -2.1°C) and the freezing point for fresh water (about 0°C). The actual temperature would vary with the salinity of the water and with depth.

Hald (pers. commun. 1985) tends to believe that most likely the sea water temperatures for a setting as described above would be between 0°C and -1°C . The exceptions would be if salt brines were developed as a result of increased salinity due to freezing of ice in the upper part of the water column - a process that could result in temperatures near -2.1°C close to the sea bed. A temperature of -0.5°C may probably be chosen as an average value under such conditions.

AIII 3.4 Temperature history models

Based on the discussions in Chapter 6.4.3 we have arrived at two temperature history models which we believe give realistic boundaries for maximum (Model I) and minimum (Model II) perturbation on heat flow data measured in the upper 10-100 m below the sea bed.

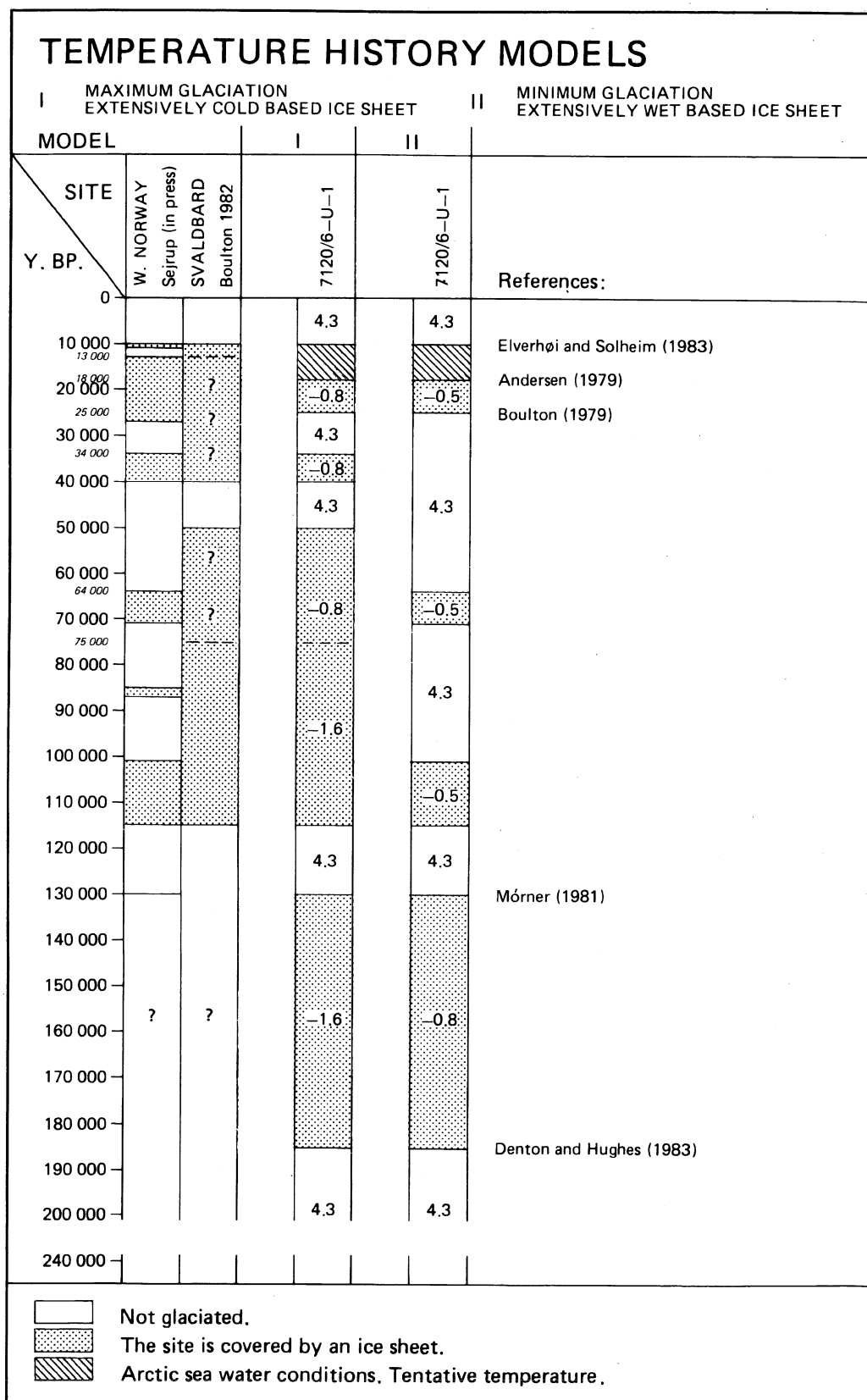


Figure AIII 3.1 Temperature history models.

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