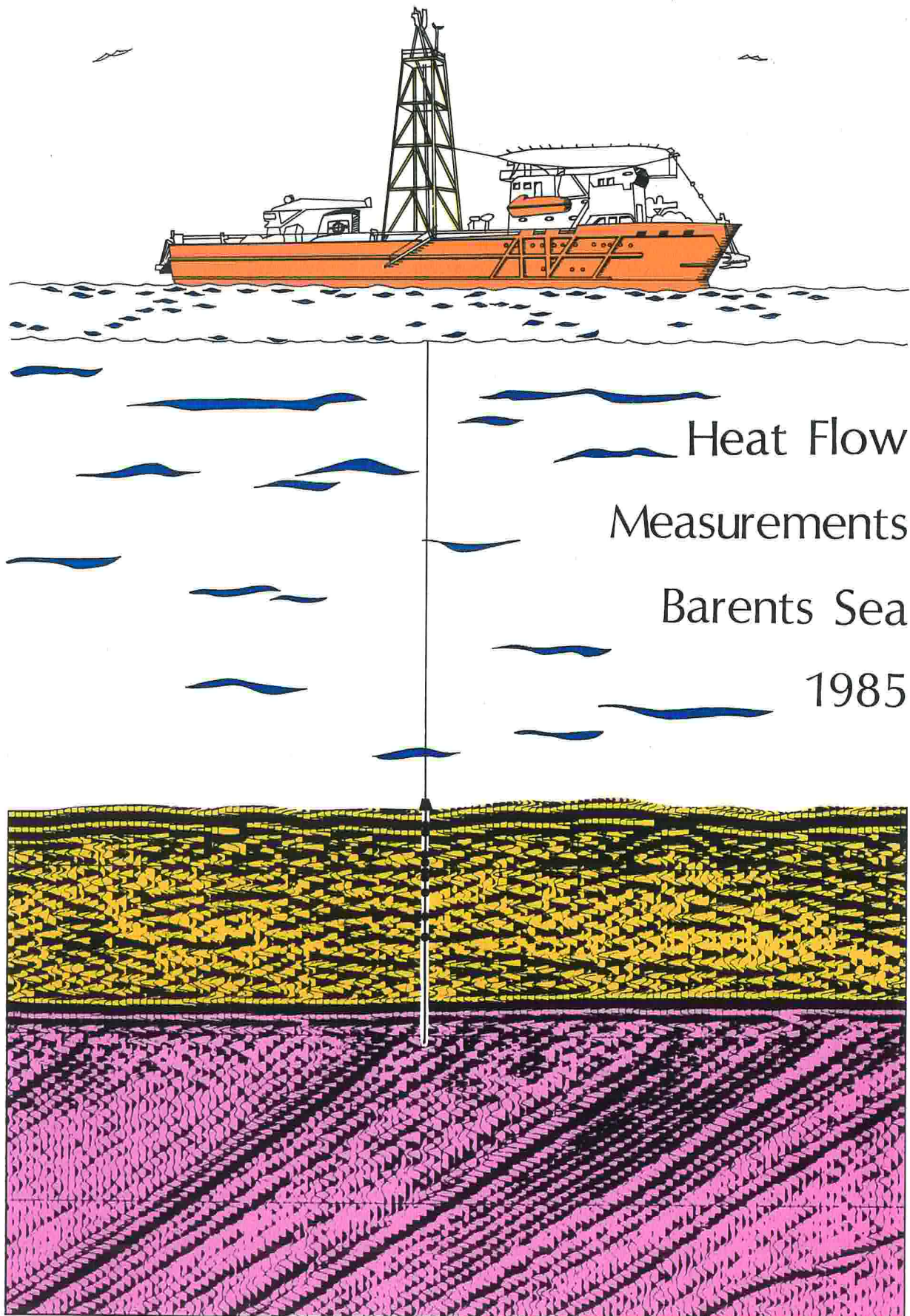






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SUMMARY/ SAMMENDRAG

As a part of the IKU Barents Sea Mapping Program, shallow drilling and heat flow measurements were carried out on 7 respectively 9 sites in the southwestern Barents Sea during July - August 1985. Heat flow values are presented for six of the sites, and values from another three sites (of which two are duplicates) will be reported later.

The present report is mainly a field data report and gives the results of 44 temperature tests in boreholes down to 65 m below sea bed and 27 surface (gravity spear) temperature tests. A qualitative of possible influences from the late Quaternary glacial history is also included. Thermal conductivity was measured both on Quaternary samples and bedrock cores.

The downhole temperature measurements are regarded to be of very good quality with a resolution and a absolute accuracy of 0.008 and 0.02 degC respectively. The presented results thus give valuable input for a first order mapping of the thermal regime in the study area.

KEY WORDS

Barents Sea

Heat flow

Thermal conductivity

Temperature measurements

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21.3405.00/01/85: "Shallow Drilling Barents Sea 1985"

21.3405.00/02/85: "Heat Flow Measurements Barents Sea 1985"

21.3405.00/03/86: "Shallow drilling and heat flow measurements Barents Sea 1985. Data report 3."

21.3405.00/04/86: "Barents Sea mapping program 1984/85. Comparisons and correlations."

21.3405.00/05/86: "Shallow drilling Barents Sea 1985 Macrofossil dating of core D85-K."

ADDENDUM

The coreholes drilled in the Barents Sea in 1985 were given preliminary names by IKU, and these were used in all reports. The table shows these names along with the later assigned official NPD names and the final coordinates and water depths.

IKU name	NPD name	Latitude	Longitude	Water depth (m)
C85-A	7126/06-U-01	71° 38' 49.795" N	26° 52' 43.295" E	369
D85-H	7220/02-U-01	72° 45' 3.095" N	20° 34' 45.644" E	429
C85-E	7222/09-U-01	72° 24' 19.739" N	22° 47' 39.787" E	322.5
D85-V	7317/02-U-01	73° 49' 10.924" N	17° 22' 4.526" E	296
D85-I	7317/02-U-02	73° 47' 8.062" N	17° 23' 35.505" E	324
D85-J	7320/03-U-01	73° 51' 15.18" N	20° 55' 0.802" E	419
D85-K	7323/07-U-10	73° 16' 51.539" N	23° 1' 25.834" E	420
D85-W	7323/10-U-01	73° 13' 15.87" N	23° 18' 42.716" E	380
D85-N	7425/09-U-01	74° 29' 25.296" N	25° 46' 19.261" E	334
D85-O	7524/12-U-01	75° 12' 20.536" N	24° 43' 21.607" E	108

The coreholes drilled in the Barents Sea in 1984 will get official NPD names in 2008.

PREFACE

This project is supported by the following companies:

BP Petroleum Development Ltd. Norway
Conoco Norway Inc.
Den norske stats oljeselskap a.s. (Statoil)
Esso Norge a.s., Exploration and Production
Fina Exploration Norway A/S
Norsk Agip A/S
A/S Norske Shell

Their participation is gratefully acknowledged.

The planning of field work was mainly based on shallow seismic data collected within the IKU Barents Sea Mapping program. However, also discussions with the Norwegian Petroleum Directorate (NPD) and data made available by the Norwegian Polar Research Institute (NP) gave valuable input to the site selection. This help is gratefully acknowledged. We also would like to thank Anders Solheim at NP who provided references and preprints for the study of glacial history.

The field work was coordinated by Torgeir Gunleiksrud. The drilling operation was carried out by the Norwegian drillship M/S "Bucentaur", and Fugro B.V. The Netherlands with Omegalink International Ltd., USA, as a subcontractor performed the temperature measurements. The latter also carried out the post cruise data reduction, and dr. Gary Zielinski, Omegalink, has contributed to parts of this report. The very good results obtained are very much due to the people involved from these companies and to the crew on board M/S "Bucentaur".

Niels Balling at the University of Aarhus, Denmark, has been responsible for the thermal conductivity measurements on bedrock samples and has also contributed in the evaluation of palaeoclimatic effects.

Tom Bugge has improved the report by constructive criticism of the manuscript.

The following staff at IKU has contributed to the project:

Program responsible:	Tom Bugge
Project responsible:	Joar Sættem
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1. SUMMARY AND CONCLUSIONS

Heat flow data from nine sites in the southwestern Barents Sea has been obtained by measuring temperature and thermal conductivity in Quaternary sediments down to 50 m or more below the sea bed. The survey was carried out from the Norwegian drillship M/S "Bucentaur". Downhole temperature measurements were performed by use of a high precision temperature probe developed by Fugro/Omegalink. The probe was mounted on a penetrometer device inside the API drill string and pushed into undisturbed Quaternary sediments. In addition to these measurements a 3 m long spear with thermistors mounted in fixed positions was used in order to obtain temperatures at the sea bed.

At levels corresponding to each temperature measurement, Quaternary sediment samples were collected and subjected to thermal conductivity measurement by use of a needle probe.

Based on this information mean heat flow values have been calculated at six of the investigated sites. For the remaining three sites the data are more uncertain and need a more thorough elaboration before reliable heat flow values can be deducted. Two of these sites are, however, located only a few km from other sites and may be regarded as duplicates. (Site D85-I, close to site D85-V and site D85-W, close to site D85-K).

The measured heat flow values summarized in Fig. 1.1 are believed to be the result of very high quality measurements. Linear regression of temperature plots versus depth for each site, all gave a standard coefficient of determination better than 0.99 and we may conclude that the used method has proven highly successful.

Our data seems to indicate that no significant effects from pore fluid flow in the Quaternary sediments are present in the measured heat flow values.

The measured heat flow values range from 0.73 HFU at site C84-E to 0.97 HFU at site C85-A (one Heat Flow Unit (HFU) = 1×10^{-6} cal/cm²s). 

The measured values may in the future be subjected to corrections for the effects caused by previous glaciations in the area. A preliminary study of this effect indicates that the measured HFU values may be

slightly too low, depending on the extent, temperature and timing of the glaciations. It further shows that the different sites should be treated individually with respect to this correction. This subject will be addressed in more detail in a subsequent project report.

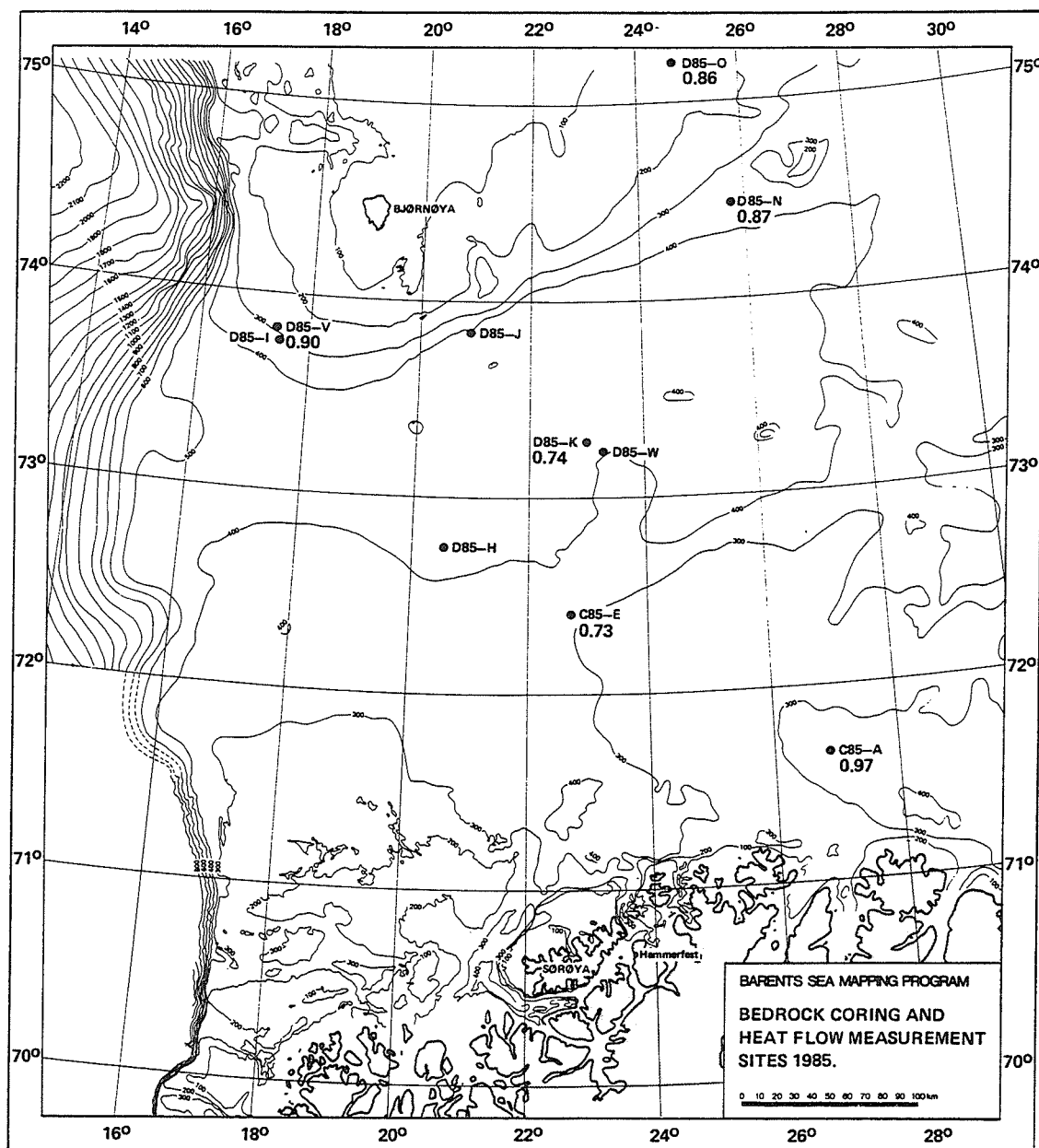


Fig. 1.1 Summary of measured heat flow values (HFU) in the Barents Sea during the IKU cruise in July-August 1985 ($1 \text{ HFU} = 10^{-6} \text{ cal/cm}^2\text{s}$).

2. INTRODUCTION

2.1 Geological setting

The generalized aeromagnetic map compiled by Am (1975) indicates a thick sedimentary succession above the mapped basement (Fig. 2.1.1). The basement in this context is by Am (1975) suggested to be the top of a Precambrian shield, and in the overlying succession also late Precambrian and Eocambrian sediments are included. Although more recent data show an even thicker sedimentary sequence in some areas the map gives an indication of the distribution of sediments.

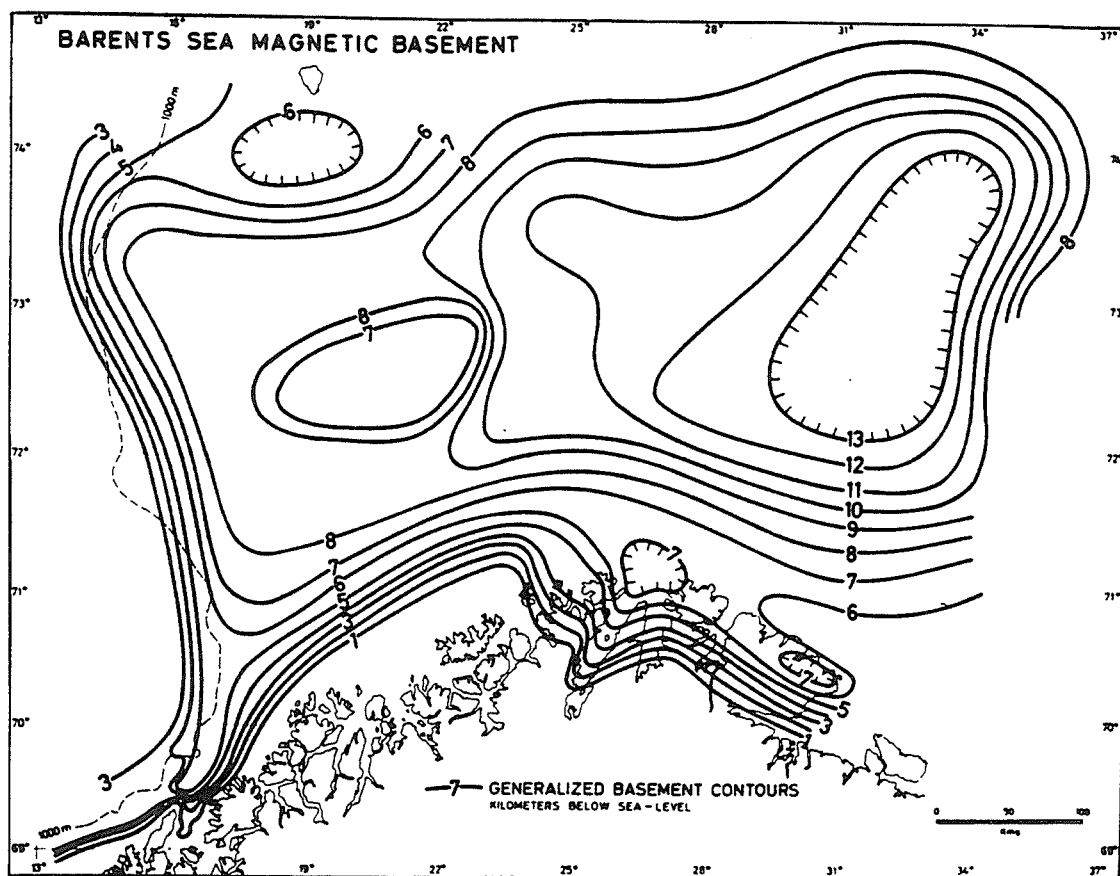


Fig. 2.1.1 Generalized contours of the magnetic basement surface (after Am, 1975).

Beskov et al. (1980) and later Rønnevik and Jakobsen (1984) have mapped the subcrop of main sequence boundaries in the Barents Sea with a span in age from Middle Carboniferous to base Pliocene.

They demonstrated that large areas in the western Barents Sea have had no net sedimentation since Upper Jurassic - Middle Cretaceous time (Fig. 2.1.2). However, several of the structural basins in the study area are believed to have experienced net sedimentation during the period between late Palaeozoic time and the late Tertiary. Since then there have been several events of regional erosion.

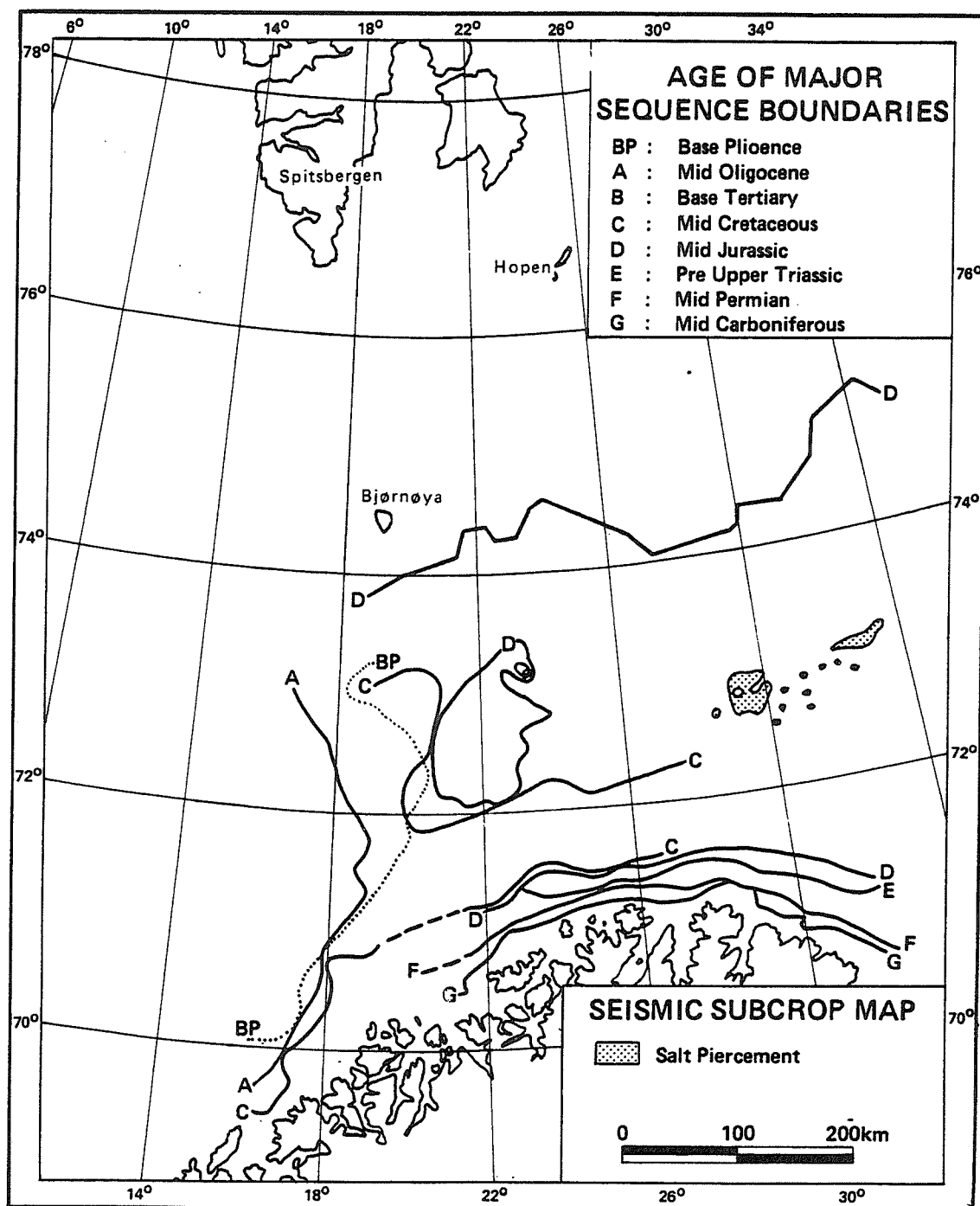


Fig. 2.1.2 Subcrop of main sequence boundaries in the southwestern Barents Sea after Beskov *et al.* (1980). The northernmost subcrop of the D reflector is named D' and tentatively dated to mid Jurassic by Rønnevik and Jacobsen (1984).

2.2 The use of heat flow data

Estimation of temperature conditions as a function of depth and time is a crucial factor in source rock maturation evaluation. In the southwestern Barents Sea possible source rocks occur at different stratigraphical levels, in various structural positions and in a wide range of present day burial depth. The maturation of the different source rocks may consequently vary widely, and a mapping of the thermal conditions is therefore an important part of the evaluation of the hydrocarbon potential of the area.

The temperature as a function of depth is basically dependent upon the heat flow through the earth's crust and the thermal conductivity properties of different layers in the underground. Assuming no fluid flow in the underground and that no thermal energy is absorbed by rise of temperature in any layer or created by cooling (as would be the case in non steady state heat flux-situations) or radioactive processes in any layer, the heat flux will be constant as a function of depth. Thus, by measuring the heat flow on the earth's surface in an area and thermal conductivities at different stratigraphic levels of the succession in the underground, one has established a tool for modelling of temperature as a function of depth. The present study is a first step towards obtaining such a tool for the Barents Sea region.

2.3 Location of the investigated sites

Fig. 2.3.1 shows the geographical distribution of the sites visited during the IKU shallow drilling and heat flow investigation cruise in 1985.

Table 2.3.1 gives the corresponding exact coordinates for these sites.

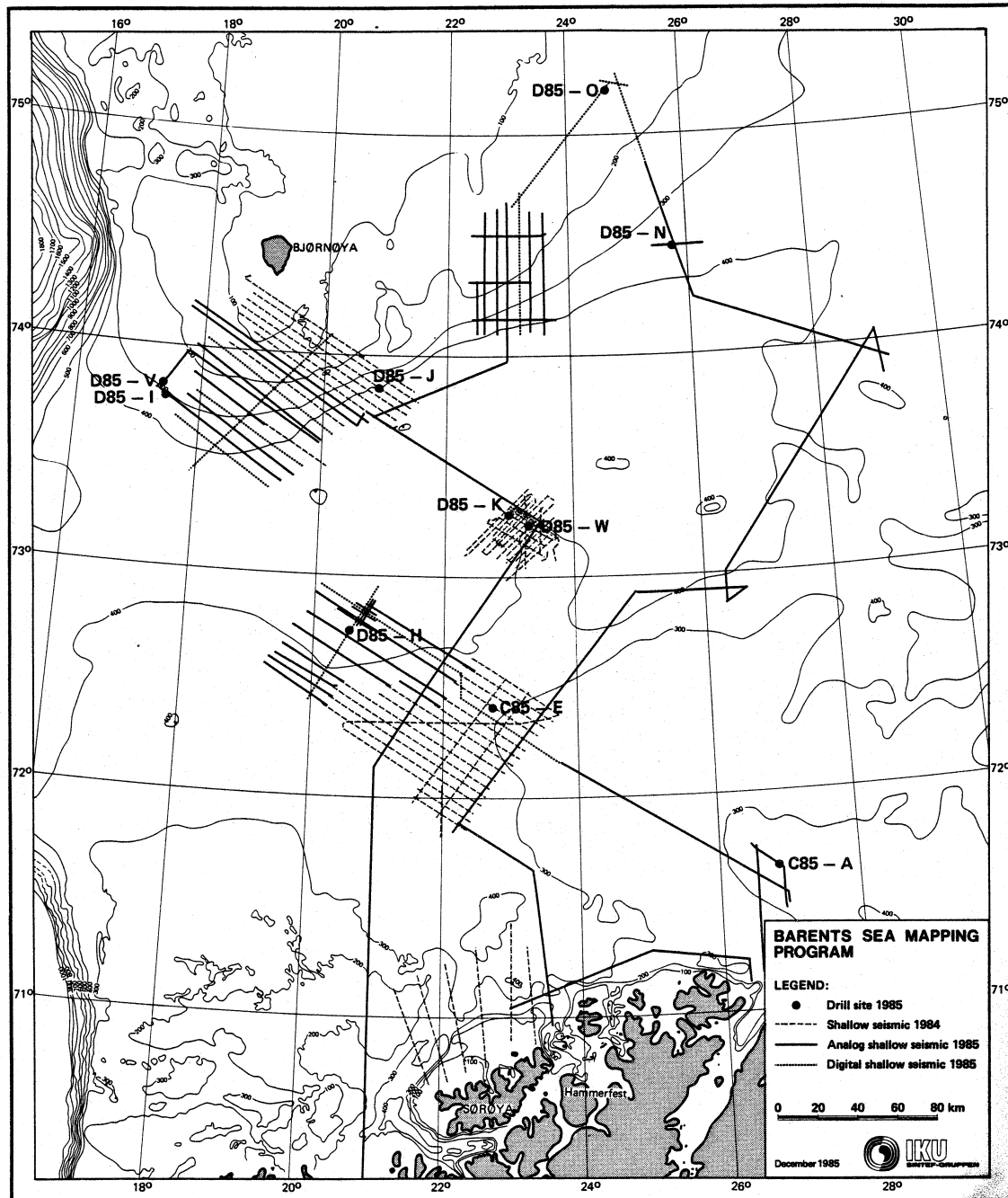


Fig. 2.3.1 IKU shallow drilling sites 1985.

The heat flow measurements are a part of the IKU project "Shallow seismic, shallow drilling and heat flow - Barents Sea 1985". The field work was combined with the bedrock drilling operation. Due partly to this two-fold objective, the site selection within the study area was a compromise between the following aims:

- ≥ 50 m Quaternary overburden required for temperature measurements in unconsolidated sediments
- Geographical distribution
- Stratigraphical distribution
- Variation in structural position
- Avoid features indicating shallow gas

In order to obtain a data base for the abovementioned site selection and to document the conditions at the selected sites, a shallow seismic survey (side scan sonar, deep towed boomer and analog sparker or digital airgun) was carried out in May-June 1985. All the sites were then selected along the profiles run during this cruise or along profiles gathered during a similar cruise carried out in 1984 within the IKU Barents Sea Mapping Program.

Table 2.3.1 Coordinates for the IKU shallow drilling sites 1985.

SITE	LATITUDE	LONGITUDE	NORTHING	EASTING
C85-A	71°38'49.795"	26°52'43.295"	7 959 849.47 m	706 315.15 m
C85-E	72°24'19.739"	22°47'39.787"	8 035 285.13 m	560 535.51 m
D85-H	72°45'03.095"	20°34'45.644"	8 072 958.02 m	486 076.87 m
D85-I	73°47'08.062"	17°23'35.505"	8 191 740.77 m	387 640.01 m
D85-V	73°49'10.924"	17°22'04.526"	8 195 589.69 m	387 085.33 m
D85-J	73°51'15.180"	20°55'00.802"	8 196 003.72 m	497 420.15 m
D85-O	75°12'20.536"	24°43'21.607"	8 350 126.02 m	606 049.12 m
D85-N	74°29'25.296"	25°46'19.261"	8 272 691.10 m	642 300.97 m
D85-K	73°16'51.539"	23°01'25.834"	8 133 148.60 m	564 978.00 m
D85-W	73°13'15.870"	23°18'42.716"	8 126 804.83 m	574 479.61 m
Geographical coordinates: ED 50				
Grid projection: UTM - CM 21 deg. east.				

The positioning of the cruises in 1985 was based on a Hyperfix chain with stations in the coastal areas of Troms and Finnmark and one station at Bjørnøya. The chain and the on board units of this system were operated by Bentech A/S.

2.4 Drill site description

The drilled sites were widely distributed in the south western Barents Sea and water depths ranging from less than 110 m to more than 430 m were encountered (Table 2.4.1).

The Quaternary sediments at the different sites were, however, strikingly uniform, and may generalized for all sites be described as a silty clay, occasionally with some sand, and with coarser fragments of sedimentary rock pieces.

The colour of the sediment normally varies between dark grey and very dark grey according to the Munsell Colour Chart. An exception is a few cm to a few dm thick soft layer of olive grey, silty, sandy clay or silty sand containing some gravel, that occurs on top of the gravity cores from several of the sites.

The dark grey to very dark grey clayey sediments show a very rapid increase in undrained shear strength and a corresponding reduction in water content towards depth. A large part of the cores tested by falling cone have an undrained shear strength of more than 250 kPa ($=\text{kN/m}^2$) (which is the highest value that can be recorded by the falling cone method). This is also in accordance with results from the threeaxial testing carried out on some of the samples, which shows generally high values for the undrained shear strength. Occasionally the values exceed 450 kPa.

Table 2.4.1 Water depth and Quaternary sediment thickness for the IKU shallow drilling and Heat Flow sites 1985.

1) Top bedrock was not penetrated.

Site	Water depth (m)	Quaternary thickness (m)
C85-A	369.0 m	37.80 m
C85-E	322.5 m	102.00 m ¹⁾
D85-H	429.0 m	app.68.00 m ¹⁾
D85-I	324.0 m	app.50.00 m ¹⁾
D85-K	434.0 m	97.05 m
D85-N	335.5 m	49.89 m
D85-O	107.5 m	55.70 m
D85-V	297.0 m	45.69 m
D85-W	368.0 m	8.20 m

3. FIELD WORK

3.1 Field operations

The present project is based on data collected during shallow seismic cruises and shallow drilling cruises carried out during the summer periods in 1984 and 1985. Only the field work carried out during the shallow drilling and heat flow measurement cruise in late July and August 1985 will be described here.

The Norwegian drillship M/S "Bucentaur" was contracted from von der Lippe Ship Management for the job. As subcontractors for von der Lippe, Diamond Boart performed the piggy-back bedrock coring and Fugro B.V., Holland, carried out the downhole sampling and temperature measurements. The downhole temperature measurements were done by use of a heat flow probe designed by Fugro B.V., and Omegalink International Ltd. Omegalink provided experts for the temperature measurement, the thermal conductivity measurements and data reduction afterwards.

The drilling cruise commenced with a test drilling off Kristiansund on July 22nd. The drilling in the Barents Sea started at site C85-A on 30th of July and the last site, D85-W was terminated on August 27th. Total drilled length was 510 m, and 44 downhole temperature tests and 9 surface temperature tests were carried out.

An outline of a typical heat flow measurement procedure at a drilling site will be as follows:

1. The drillship moved into position and lowered the jack. A piston corer was lowered from the stern of the ship to collect a sea bed surface sample (max 3.5 m long).
2. A gravity spear with thermistors was lowered from the stern of the ship and measured the temperature in the upper approximately 3 m of the sea bed.
3. The drilling commenced and was stopped every 5 m to 10 m for temperature measurement.
4. 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

- temperature probe, a temperature measurement was carried out.
5. 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.
 6. After the completion of a measurement, the equipment was retrieved and the drilling proceeded another 5-10 m.
 7. Thermal conductivity was measured on the obtained core material as soon as equilibrium with the on board temperature was obtained.

Maximum effort was put into bringing the temperature probe into undisturbed sediments, and by first taking the sediment sample the sediments that could have been thermally and mechanically influenced by the drill bit were removed. Normally the temperature probe was pushed another 0.5-1.0 m into the sediments. With support in the monitoring during the field operation and the obtained data we feel confident that the presented heat flow values are based on in situ temperature conditions.

The accuracy of the depth determination for each temperature measurement is crucial for establishing the temperature gradient. At location C85-A, C85-E, D85-H and D85-I this was done by measuring the penetration of the drill string relative to the drill floor. A correction to this depth was applied from a tidal curve obtained from the ships echosounder. The relative accuracy of this method is estimated to ± 0.25 m.

On the remaining locations the penetration of the drill string was measured relative to the lifting wires of the sea floor jack which are kept tight with a constant tension during drilling. The jack is resting on the sea floor during drilling, and thus the depth measurements were linked directly to the sea floor and decoupled from the tidal variations. The accuracy of this method is estimated to be within 10 cm. The penetration of the probe below the drill bit was recorded by Fugros WISON system within ± 1 cm.

3.2 Instruments, design and operation

3.2.1 General

This chapter gives a brief description of the design and operation of the main instruments that were used on board, and which are believed to

be most directly linked to the obtained heat flow data. These instruments are:

- The WISON system
- The WIP system
- The downhole temperature probe
- The temperature gravity spear
- The needle probe

3.2.2 The WISON system

The WISON system is a hydraulically operated system normally used for geotechnical testing (cone penetration tests). The system was lowered down in the API drill string and latched in with its lower end at drill bit level (see Fig. 3.2.4.1). 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.

3.2.3 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.

3.2.4 The downhole temperature probe

The downhole temperature probe was operated by the WISON system as shown in Fig. 3.2.4.1. The controlled push-in-operation made possible by use of the WISON system kept the frictional heat to a minimum and is thus

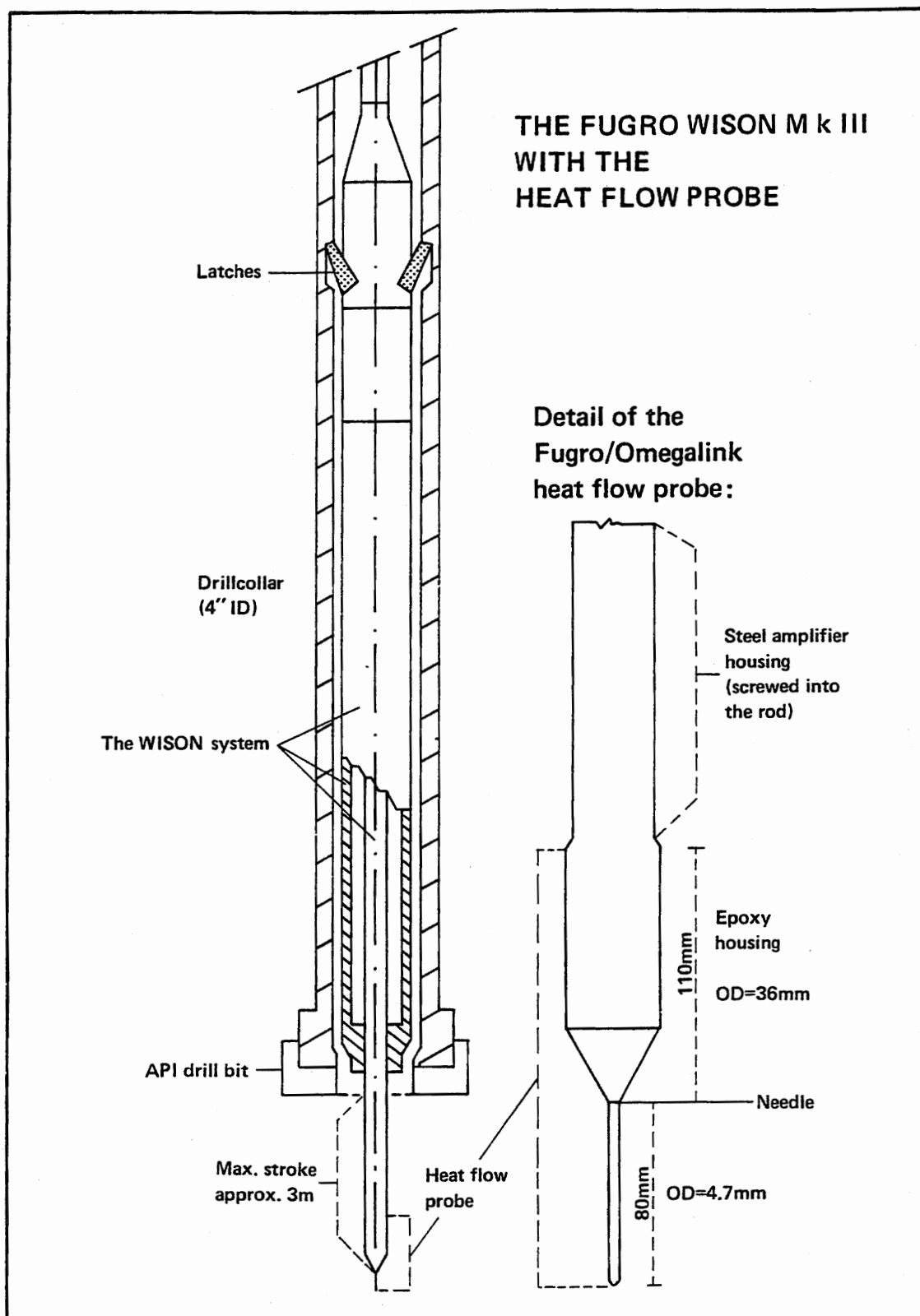


Fig. 3.2.4.1 The downhole temperature probe mounted in the Fugro WISON Mk III system.

one of the reasons for the good results obtained in the downhole measurements.

In order to transmit the thermistor output up to the surface vessel without loss of accuracy and resolution, a temperature stable two-stage 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 deg C with negligible influence of the umbilical or slip-ring connectors on the primary signal.

3.2.5 The shallow probe

The shallow probe instrument consisted of a steel spear with three thermistor "outrigger" assemblies and a lead weight mounted on top. The internal sensor of these assemblies are identical to those used for the downhole measurements, and the same calibration procedure was applied.

The purpose of the outrigger mounting is to fix the thermistor probes sufficiently far from the spear to avoid that heat from the spear can propagate to the thermistor. Output from the thermistors was digitized and recorded in situ on magnetic tape. A back-up tandem electronic memory was also present in the event of operational difficulties with the tape/ transport system. The digitizing/recording package was mounted in a pressure vessel attached to the spear/weight assembly. A tilt sensor inside the instrument continuously recorded if the angle of the probe was greater or less than 30 degrees from vertical.

The standard procedure was to perform sea bed core sampling and shallow probe measurements just prior to the drilling operation. Normally the probe was allowed to remain in the sediment for 20 minutes at a 15-second sampling rate for each thermistor.

3.2.6 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 ship-board conditions, a 6 cm long "hypodermic-like" probe was inserted into sediment samples. Only visibly undisturbed samples were 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.

4. RESULTS

4.1 Thermal conductivity measurements

The thermal conductivity values obtained from the Quaternary samples are presented in Table 4.1.1. These values were measured by use of the needle probe method as described in Chapter 3.2.6. For a short discussion of the obtained values, reference is made to Chapter 4.2.5.

Thermal conductivity was measured on 11 selected bedrock samples by use of the same technique, at the Geophysics Laboratory, University of Aarhus in Denmark. These samples are collected within the IKU Barents Sea Mapping Program and represent a variety of rock types and stratigraphic levels. The results from these analyses are presented in Table 4.1.2.

Table 4.1.1 Thermal conductivity data for Quaternary sediment cores collected during the IKU 1985 drilling cruise.

SITE	DEPTH (m)	K (mcal/degC cm sec)
C85 - A	0.03	1.64
	0.36	1.51
	0.87	1.43
	0.94	1.42
	1.20	1.37
	1.60	1.34
	1.85	1.36
	2.20	1.48
	2.55	1.46
	2.95	1.38
	5.90	1.76
	10.68-10.83	2.13
		2.13
		2.22
		2.38
	15.32-15.47	2.34
		2.43

Table 4.1.1 cont.

SITE	DEPTH (m)	K (mcal/degC cm sec)
C85 - A (cont.)	20.25-20.40	2.05
		2.31
	25.61-25.40	2.35
		2.32
	35.42	2.51
	35.25	2.27
	35.03	2.23
	35.19	2.34
C85 - E	0.04	2.01
	0.35	2.13
	0.70	1.71
	1.00	2.05
	1.03	2.02
	1.40	1.68
	1.80	1.67
	2.10	1.79
	10.53	2.18
	10.60	2.32
	10.64	2.17
	21.28	2.29
	21.34	2.36
	21.40	2.17
	21.47	2.19
	21.55	1.70
	31.03	2.26
	31.08	2.36
	31.13	2.49
	40.13	2.19
	40.21	2.15
	40.30	2.24
	40.37	2.06
	50.22	2.16
	50.15	2.20
	50.12	2.24

Table 4.1.1 cont.

SITE	DEPTH (m)	K (mcal/degC cm sec)
D85 - H	0.03	1.56
	0.24	1.55
	0.44	2.12
	0.50	1.98
	0.72	1.67
	0.97	1.61
	1.22	1.76
	1.44	1.90
	11.25	2.60
	13.56	2.57
D85 - I	0.03	2.05
	0.22	1.61
	0.47	1.88
	0.72	1.98
	0.97	2.49
	5.44	2.13
	5.54	2.42
D85 - K	0.03	1.51
	0.33	1.61
	0.71	1.63
	1.09	1.75
	1.17	1.68
	1.56	1.67
	1.86	1.69
	2.33	1.82
	9.97	1.93
	10.00	1.98
	10.08	2.06
	10.71	1.99
	14.64	2.00
	14.71	1.81
	14.77	2.01
	14.83	1.98

Table 4.1.1 cont.

SITE	DEPTH (m)	K (mcal/degC cm sec)
D85 - K (cont.)	14.83	1.98
	14.92	2.01
	19.63	2.26
	19.71	2.01
	19.78	2.27
	22.37	2.02
	22.46	2.07
	22.53	2.35
	25.52	2.19
	25.59	2.12
	25.63	2.24
	30.21	2.07
	30.27	2.14
	30.31	2.27
	34.51	2.24
	34.57	2.28
	34.63	2.45
	43.98	2.29
	44.03	2.35
	44.07	2.43
	54.66	2.17
	54.72	2.07
	54.79	2.23
	64.74	2.16
	64.79	2.18
	84.27	2.22
	94.92	1.96
	94.87	2.16
D85 - N	0.03	1.69
	0.23	1.89
	0.43	1.90
	0.62	2.09
	12.16	2.34
	12.08	2.10

SITE	DEPTH (m)	K (mcal/deg C cm sec)
D85 - N (cont.)	21.83	2.17
	21.89	2.13
	27.26	2.22
	27.31	1.95
	30.23	2.50
	30.26	2.66
	36.11	2.50
	36.14	2.51
	39.66	2.23
	39.70	2.44
	39.78	2.24
	41.55	2.32
	41.75	2.36
	42.07	2.02
D85 - 0	0.03	1.28
	0.30	1.28
	0.60	1.34
	0.90	1.36
	1.25	2.44
	5.28	2.19
	5.34	2.32
	5.38	2.41
	9.85	2.80
	9.94	3.00
	22.80	2.15
	22.14	2.22
	25.41	1.77
	25.48	1.82
	30.23	2.64
	30.28	2.84
	35.16	2.65
	35.23	2.84
	42.11	2.83
D85 - V	0.03	1.94
	0.03	2.01

SITE	DEPTH (m)	K (mcal/degC cm sec)
D85 - V (cont.)	0.14	2.34
	0.24	2.01
	0.27	2.33
	0.42	2.89
	14.67	2.26
	14.77	2.13
	20.20	2.38
	20.10	2.40
	24.58	2.24
	24.48	2.19
	25.12	2.08
	24.97	2.16
	24.84	1.91
	25.46	2.40
	25.34	2.04
	29.76	2.83
	29.63	2.55
	40.19	2.45
	40.12	2.52
	44.59	2.71
	44.50	2.57
	45.94	2.50
	45.82	2.73
D85 - W	0.03	1.59
	0.30	1.72
	0.60	1.66
	0.87	1.96
	0.93	1.86
	1.15	1.67
	1.40	1.69
	1.65	1.67
	1.87	1.85

Table 4.1.2 Thermal conductivity of selected bedrock samples from the Barents Sea collected within the IKU Barents Sea Mapping Program. k_h = horizontal thermal conductivity, k_v = vertical thermal conductivity. The values in brackets are results of a second test sequence carried out on some of the samples. The results may be slightly less than in situ rock property due to stress release. For location of the sites, see Tables 2.3.1 and 4.1.3. 1): See reservations in text below.

Site	Lithology	Depth in borehole (m)	Thermal cond. (mcal/degC cm sec)	
			k_h	k_v
D85-J	Claystone	14.6 - 14.23	5.57	3.11 (2.70)
	Limestone	30.7 - 30.87	6.57	6.14
	Claystone	34.26 - 34.32	7.07	2.80 (5.09)
D85 - K	Claystone	121.78-121.86	4.99	1.96 (2.27)
D85 - N	Claystone	52.88 - 52.94	5.09	4.66
	Claystone	62.23 - 62.35	4.97	2.44
D85 - O	Sandstone	57.32 - 57.48	7.91	7.57
D85 - V	Sandstone	50.52 - 50.72	4.97	4.32
D84 - 2	Siltstone	90.57 - 90.72	5.92	5.09 (4.66)
D84 - 11	Limestone	12.94 - 13.11	10.92 ¹⁾ (10.44) ¹⁾	11.44 ¹⁾ (11.97) ¹⁾
D84 - 31	Biogenic siltstone silicified	25.27 - 25.40	6.40	5.97

Table 4.1.3 Coordinates for IKU shallow drilling sites 1984
 represented by results in Table 4.1.2.

Site	LATITUDE	LONGTITUDE	NORTHING	EASTING
D84-2	73°16' 45.65"	23°09' 29.57"	8133 117.1 m	569 297.0 m
D84-11	73°15' 41.33"	23°16' 07.01"	8131 256.1 m	572 916.0 m
D84-31	73°13' 59.67"	23°26' 59.32"	8128 337.8 m	578 865.9 m
Datum: ED 50				
Grid projection: UTM Cm 21°				

The thermal conductivity values found in the sample from 12.94-13.11 m at site D84-11 may be anomalous for the lithological unit represented by this sample. The core is described as a limestone. However, the measured thermal conductivity rather resembles a sandstone or a quartzsite. This may indicate that the test has been carried out at a silicified part of the sample.

An important observation from Table 4.1.2 is the marked anisotropy in the thermal conductivity properties found in the claystone samples. In several of our tests the thermal conductivity is found to be about twice as high parallel to than perpendicular to the bedding plane.

The latter values may be the most appropriate for modelling of temperature towards depth if a horizontal or sub-horizontal stratification is assumed.

4.2 Temperature measurements

4.2.1 Downhole data reduction

Two amplifier outputs were recorded on strip charts to show voltage output from the downhole measurements in two different scales. Output V1 was intended to provide a quick indication of the overall performance of the system during measurement and output V2 was used to provide the

necessary resolution for heat flow purposes (Fig. 4.2.1.1). Voltages were converted to resistances (R) via the expression:

$$1/R = C0 - C1(V_{off} + (V2/VF)),$$

where V_{off} is an offset value and $C0$, $C1$ and VF are constants obtained from the calibration of each amplifier (Table 4.2.2.1). The amplifier numbers (AMP no.) designating which amplifier was used in each test are given in Table 4.2.4.1.

Resistance, R (Ohms) is converted to temperature, T (deg C) via the expression:

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

where A and B are constants obtained from the calibration of each thermistor. The values of A and B for each thermistor number are given in Table 4.2.2.2.

The data reduction procedure described above is in the present work carried out by digitizing points along the strip chart records corresponding to the $V2$ output. On the average, except in cases where large sections of the records were avoided due to noise problems, more than 50 points were digitized per test. Regardless of how well equilibrated (and constant) each record appeared, an extrapolation to equilibrium based on a mathematical analysis of the cooling of cylindrical probes (Jaeger, 1956) was applied to each test. This extrapolation is quite similar to the procedure routinely applied to shallow-probe data. The validity of that procedure is evidenced by the excellent agreement of the survey data to the theory, with coefficients of determination (R -square) generally greater than 0.99 (values near 1 indicating good agreement and near zero indicating poor agreement).

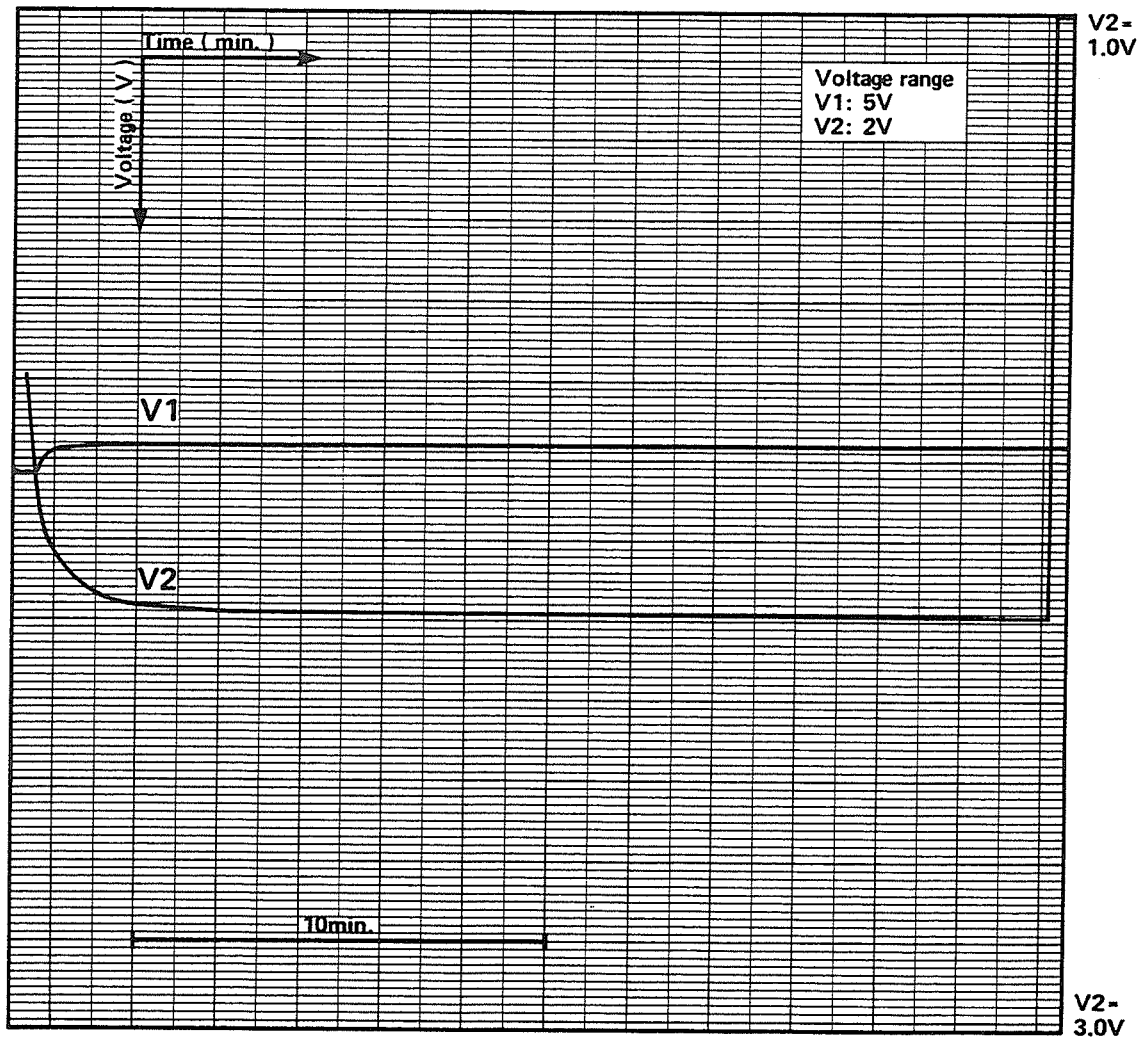


Fig. 4.2.1.1 Equilibration of the downhole probe to in situ temperature. (Redrawn strip chart record from a measurement at site D85-K.)

Equilibration of the downhole thermistor probe in most cases occurred within 10 to 15 minutes after the probe had been pushed the sediments. However, it was noted early in the survey that for a small portion of the tests, equilibration did not occur even after long periods of time, after which the output of the heat flow probe was still changing significantly. Two mechanisms could account for these observations. The first is that the measurements were being made in anomalous material that had presumably come from some other part of the hole and was itself in the process of equilibrating to the formation temperature.

A second factor capable of contributing to the long equilibrations is conduction of heat along the probe assembly. Despite efforts to thermally isolate the thermistor tip from the rest of the assembly and the WISON, it is possible that excessively large temperature gradients in the probe prior to the push into the sediments could propagate along the probe. The large thermal mass of the WISON and the low thermal conductivity of the sediments would require a long time for the heat to dissipate. It was observed that some instances of long equilibration could be halted by suspending the probe and WISON in the borehole prior to push, to allow the entire assembly to come to equilibrium, thus minimizing longitudinal thermal gradients before continuing the test.

Careful examination of the survey data has revealed that the "long equilibration" tests fall into two categories, both exhibiting temperatures significantly different from adjacent normal equilibration tests. The first are the tests that are equilibrating towards reasonable values for temperature and in the second category the trend is toward greater departure from formation temperature. For the latter category it was further noticed that a valid extrapolation of the data could be performed for the initial part of the test corresponding to the probe response time. This would result in a temperature in good agreement with adjacent normal tests. We believe that during these tests the probe initially came to near-equilibrium, after which a transient disturbance forced temperatures away from the equilibrium formation temperatures. Such a disturbance could be caused by longitudinal heat transfer from the WISON, described above. It was unlikely that temperature disturbances associated with drilling could contribute to this effect in view of the distances and times involved. Conductive heat transfer predicts that such disturbances require nearly an hour to propagate only 8 cm through the type of sediments encountered. Only through the formation of cracks during penetration, allowing heat transfer by forced convection, might this argument be contradicted. Still, the important point is that the disturbance, regardless of cause, is easily recognized and in cases where the quality of the initial part of the record is good, the measurement is recoverable.

An important operational conclusion can be drawn from the observations described above. During a test, if near equilibration is not reached in the first 10 to 15 minutes, the test should be terminated. If the test happens to fall into the second long equilibration category, the measurement should be successful.

4.2.2. Calibration

All downhole thermistor probes mobilized to the survey vessel underwent multiple calibrations with respect to both a quartz thermometer and an NBS traceable ultrastable reference thermistor. Calibrations, performed on all thermistors simultaneously, spanned a temperature range from -5 to 27 deg C with a concentration of points between -5 and 10 deg C. The corresponding outputs of the thermistors were measured with respect to NBS traceable reference resistors (0.0015% accuracy). By curve-fitting the resulting calibration data to a standard logarithmic function the mean residuals for the thermistors employed were found to be nominally 0.001 deg C.

An instrument calibration, analogous to the amplifier calibration, was performed on the shallow probe electronics prior to the survey. This consisted of inputting NBS traceable resistances while recording instrument output over the anticipated operating range. The estimated accuracy and resolution of the instrument plus thermistor probe as configured are 0.01 deg C and 0.005 deg C respectively.

Basic accuracy and resolution after calibration for the shallow probe and downhole probe are 0.01 deg C and 0.001 deg C respectively. It should also be noted that for both the shallow probe and downhole thermistors, test currents were held sufficiently low so as to render self-heating effects negligible.

Table 4.2.2.1 Amplifier calibration coefficients

AMP	C0	C1	VF
9	1.254484783E-5	3.931943460E-7	4.0850
10	1.260890946E-5	3.945296640E-7	4.0480
11	1.253415557E-5	3.955675220E-7	4.0370
14	1.255997388E-5	3.920706700E-7	4.0395

Table 4.2.2.2 Thermistor calibration coefficients. R-SQUARE is the standard coefficient of determination for regression. Values near 1.0 indicate good fit; values near zero indicate poor fit. MEAN RESID is the mean residual for at least 6 temperature calibration points (computed minus actual temperature).

THERM	A	B	R-SQUARE	MEAN RESID
9	5.687238883E-4	2.698329716E-4	1.0000	0.7 mdegC
10	5.664521120E-4	2.701259250E-4	1.0000	0.9 mdegC
12	5.835109188E-4	2.685091426E-4	1.0000	0.8 mdegC
13	5.675104267E-4	2.699350911E-4	1.0000	1.0 mdegC
22	5.764351133E-4	2.690198226E-4	1.0000	1.0 mdegC

4.2.3 Post cruise calibration/performance assessment

Routine post-cruise calibration checks were performed on both the shallow-probe heat flow instrument and the thermal conductivity apparatus.

It consists of checking temperature calibration of thermistors at appropriate test temperatures in a 1 mdegC stable temperature bath against an NBS traceable reference thermistor and cross-checking voltage, resistance and current measurement components of the instruments against fixed reference values for the operating range(s) encountered during the survey. As a result, both the shallow-probe and thermal conductivity instruments were found to conform to intended operating specifications of .02 degC accuracy for the shallow-probe and to the 3% accuracy normally attributed to needle-probe thermal conductivity measurements (Von Herzen and Maxwell, 1959).

Unlike the above, the downhole heat flow probe was used for the first time this past season, hence significantly more discussion of the evidence for overall measurement accuracy and reproduceability for this instrument is warranted. The initial part of this work focused on verifying the linearity of the voltage output of the amplifier with respect to the reciprocal of resistance (resistance being the primary output of the temperature sensor). It is essential that this linearity over the operating range was sufficient to assure resolution at the millidegree C level along with that order of interchangeability among all of the amplifiers employed. This was accomplished by cross-checking the calibration data. There was found a variation of less than 3 mdegC in temperature for amplifiers 9, 10, 11 and 14.

The thermistor calibration data used to generate the coefficients given in Table 4.2.2.2 was cross-checked against a second set of (pre-cruise) calibration data by inputting the values from the second calibration run into the resistance/temperature equation with coefficients derived from the first calibration. The corresponding residuals (computed temperature minus actual temperature) were in all but one case found to be less than 4 mdegC. It should be noted that this probably exaggerates the true error since it weights the individual test data (second calibration) heavily; whereas, the curve-fitting to the first calibration data makes use of multiple calibration points to remove emphasis on an occasional bad point. Hence, the value of 4 mdegC includes any error associated with the test data points as well. Based on the combined effects of amplifier and thermistor error we estimate the final system resolution and accuracy to be well within 0.008 and 0.02 degC respectively.

In addition to the above, the two probe assemblies consisting of amplifier no. 9/ thermistor no. 9 (9/9) and amplifier no. 11/ thermistor no. 12 (11/12) were placed in a calibration bath at ice point (0 degC). The 8 cm x 0.5 cm diameter tip of each probe was inserted into an aluminum block inside the ice bath to improve stability and minimize thermal gradients. The output of each assembly was recorded while monitoring the actual ice-point temperature with a reference thermistor. The resulting residual (reference temperature minus probe temperature) for probe assembly 9/9 was -0.008 degC and -0.0035 degC for assembly 11/22. Since the vast majority of the temperatures encountered by the probes during the survey was less than 5 degC, additional tests would appear to be unnecessary. Due to operational difficulties in fitting the rather large probe assemblies into the calibration bath, assembly 10/13 was omitted from this procedure. In view of the fact that assembly 10/13 was used in only two tests, both of which were of poor quality, this is not viewed to be a serious omission. Furthermore, during the survey thermistor 10 was broken off assembly 14/10 so that it was also not possible to run tests on that probe assembly. The broken thermistor, however, was recovered and the wire leads again exposed by cutting back the stainless steel sheath. This was also placed in the ice-point bath, yielding a residual of -0.011 degC. This somewhat larger residual could be the result of stress during breakage. Unfortunately, amplifier no. 14 was damaged during removal from the assembly prior to final testing. (If, after repair, testing of amplifier no. 14 is possible, any serious discrepancies will be reported.) It should, however, be emphasized that based on the final survey data results and the consistency of the assembly 14/10 data with respect to the other assemblies, no significant discrepancy is to be anticipated.

Our general conclusion from the above tests is that the performance of the downhole probe was well within acceptable limits for state-of-the-art heat flow measurements over the measured depth intervals.

4.2.4 Downhole results

The results of all reliable determinations of equilibrium temperatures obtained from reduction of the downhole thermal data are given in Table 4.2.4.1. Particularly noisy data are noted "n" and normally resulted from swell causing movement of the thermistor sensor during the test or were the result of cable problems. Both long equilibration categories (1e1 and 1e2) (ref. Chapter 4.2.1) are also noted. We have omitted final values in all tests where the level of uncertainty was likely to adversely affect the final heat flow determinations. All temperature values listed in Table 4.2.4.1 are believed to represent true equilibrium formation temperatures.

Site D85-K, with the most data over the largest depth interval, affords the best opportunity for assessing the measurement results.

A linear least-squares regression was performed on site D85-K using all temperature depth points resulting in a geothermal gradient determination of 34.4 mdegC/metre (Fig. 4.2.4.6). Despite the high coefficient of determination (0.9976) for the fit of a single straight line it was noted that better agreement to the data was obtained by performing two regressions, one to data above 25 metres depth, the other to data below 25 metres (Fig. 4.2.4.1). Points above 25 metres result in a gradient of 36.1 mdegC/metre while the points below 25 metres result in a gradient of 33.2 mdegC/metre. The (harmonic) mean thermal conductivities for each interval are 2.06 and 2.21 mcal/degC cm sec respectively, which yield corresponding heat flows (the product of conductivity and gradient) of 0.74 HFU and 0.73 HFU (1 HFU = 1 microcalorie per square centimetre per second).

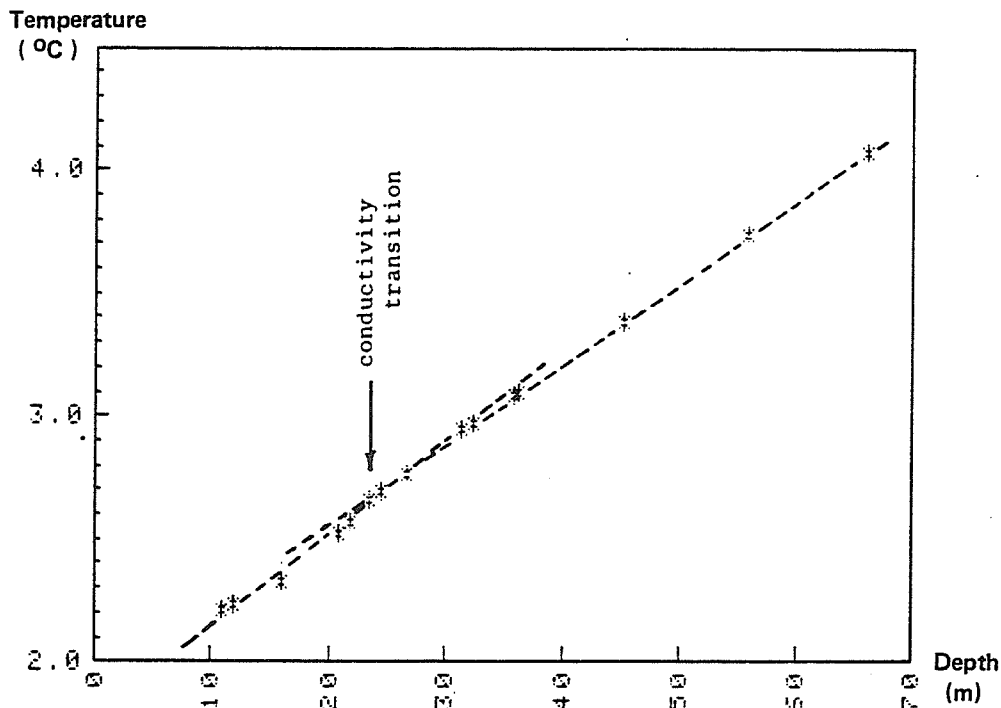


Fig. 4.2.4.1 Plots of temperature versus depth for site D85-K obtained by using two linear regressions of temperature versus depth. (See also Fig. 4.2.4.6).

The corresponding heat flow using all temperature-depth points is 0.74 HFU. This excellent agreement of the data to conductive heat flow theory for uniform heat flow through the sediment column effectively rules out the presence of significant pore-water advection or convection within the Quaternary sediments at site D85-K. Furthermore, the data for site D85-K were obtained at the same location but during three separate drilling starts, the first resulting in test 1a, the second tests 1-5.1 and the third tests 6-10. Still all data can be treated as obtained from one drilling start, with high degree of correspondence.

The final, calculated temperature values are given in Table 4.2.4.1 and the final values for temperature gradient and heat flow in Table 4.2.4.2. Sites D85-H, D85-I and D85-W are not included in this table as the results from these sites are not sufficient for a decision of mean values in the same way as for the other sites. It is, however,

Table 4.2.4.1. Final equilibrium temperatures and amplifier (AMP)/thermistor (THERM) assemblies used on the 1985 shallow drilling/heat flow sites.

SITE/TEST	DEPTH (m)	AMP no.	THERM no.	Temp. (°C)
C85-A/2	3.85	10	13	- n
3	9.58	11	12	- n
4	15.47	11	12	- le 1
5	18.66	11	12	4.591
6	23.36	11	12	4.776
7	34.32	11	12	5.247
C85-E/1	11.50	11	12	4.070
2	22.75	14	10	4.363
3	41.10	14	10	5.039
D85-H/1	13.85	11	12	- le ?
D85-I/1	6.19	11	12	2.085
D85-K/1A	11.63	9	9	2.197 n
1	10.62	9	9	2.181
2	15.59	9	9	2.292
3	20.39	9	9	2.488
3.1	21.35	9	9	2.528
4	26.25	9	9	2.733
5	30.91	9	9	2.911
5.1	31.92	9	9	2.939
6	23.12	9	9	2.626
6.1	24.16	9	9	2.663
7	35.33	9	9	3.050
7.1	35.82	9	9	3.060
8	44.69	9	9	3.353
9	55.34	9	9	3.709
10	65.60	9	9	4.032
D85-N/1	12.33	11	22	1.867
2	21.98	11	22	- le 1
3	30.30	11	22	2.540
4A	35.27	11	22	- le 1
4	35.94	11	22	- n
5	42.02	11	22	3.002
D85-O/1	10.43	14	10	- le 1
2	25.62	10	13	- le 1
3	30.61	9	9	0.470
4	35.39	9	9	0.611
5	42.42	9	9	0.835
D85-V/1	15.31	11	12	2.358 le 2
2	20.27	14	10	2.542
3	24.46	14	10	- le 1
4	25.64	14	10	2.710
5	29.81	14	10	2.940
6	41.92	14	10	- nle 2
7	44.65	14	10	3.428

possible that future elaboration on the data from these three sites by a method described by Zielinski and Bruchhausen (1983), may provide reasonable data also from these sites.

Site D85-I is located only a few km from site D85-V and a similar thermal condition may be assumed for these two sites.

Table 4.2.4.2 Final measured gradients and heat flow values. R-SQUARE is the standard coefficient of determination for regression (least square fit for all temperature-depth points). Values near 1.0 indicate good fit; values near zero indicate poor fit. 1 HFU=one microcalorie per square centimetre per second.

SITE	GRAD(mdegC/m)	N	R-SQUARE	Kav(mcal/degC cm s)	MHF(HFU)
C85-A	41.2	3	0.9996	2.31	0.97
C85-E	33.1	3	0.9925	2.19	0.73
D85-K	34.4	16	0.9976	2.15	0.74
D85-N	38.2	3	0.9998	2.28	0.87
D85-O	31.0	3	0.9996	2.76	0.86
D85-V	36.8	5	0.9953	2.45	0.90

Temperature profiles for each site are shown in Figs. 4.2.4.2-4.2.4.10. Shallow probe temperature data is plotted together with the downhole data with a dashed curves showing the interpreted correspondence between the two. The shallow probe data (Table 4.2.4.3) exhibits the effects of seasonal bottom-water temperature fluctuation. This fluctuation propagates with depth approximately as an exponentially damped sinusoid as is illustrated in the temperature profiles. Assuming that the seasonal temperature maximum in Barents Shelf bottom water occurs in September, conductive heat flow theory (e.g., Carslaw and Jaeger, 1959) predicts that the seasonal minimum in temperature should be at a depth of about 2 metres, which is in general agreement with the shallow probe data. It further predicts that by 10 metres depth the effect should be totally damped and the gradients should become essentially linear with depth below 10 metres, which is also in agreement with most of the interpreted temperature gradient curves shown in Figs. 4.2.4.2 - 4.2.4.10.

Table 4.2.4.3. Shallow probe data. Tilt = 0 implies that tilt of probe was less than 30° at all tests.

SITE	PROBE #	TEMP (degC)	TILT (deg)	DEPTH (meters)
C85-A	15	3.231	0	1.02
	14	3.297	0	1.95
	13	3.425	0	2.89
C85-E	15	3.209	0	0.90
	14	3.178	0	1.83
	13	3.289	0	2.77
D85-H	15	1.830	0	0.97
	14	1.759	0	1.90
	13	1.742	0	2.84
D85-I	15	1.727	0	0.05
	14	1.715	0	0.98
	13	1.716	0	1.92
D85-K	15	2.281	0	1.40
	14	1.514	0	2.33
	13	1.507	0	3.27
D85-N	15	1.249	0	0.90
	14	0.852	0	1.83
	13	0.952	0	2.77
D85-O	15	-1.261	0	0.67
	14	-0.999	0	1.60
	13	-0.798	0	2.54
D85-V	15	1.791	0	0.90
	14	1.770	0	1.83
	13	1.792	0	2.77
D85-W	15	2.964	0	0.90
	14	1.822	0	1.83
	13	1.889	0	2.77

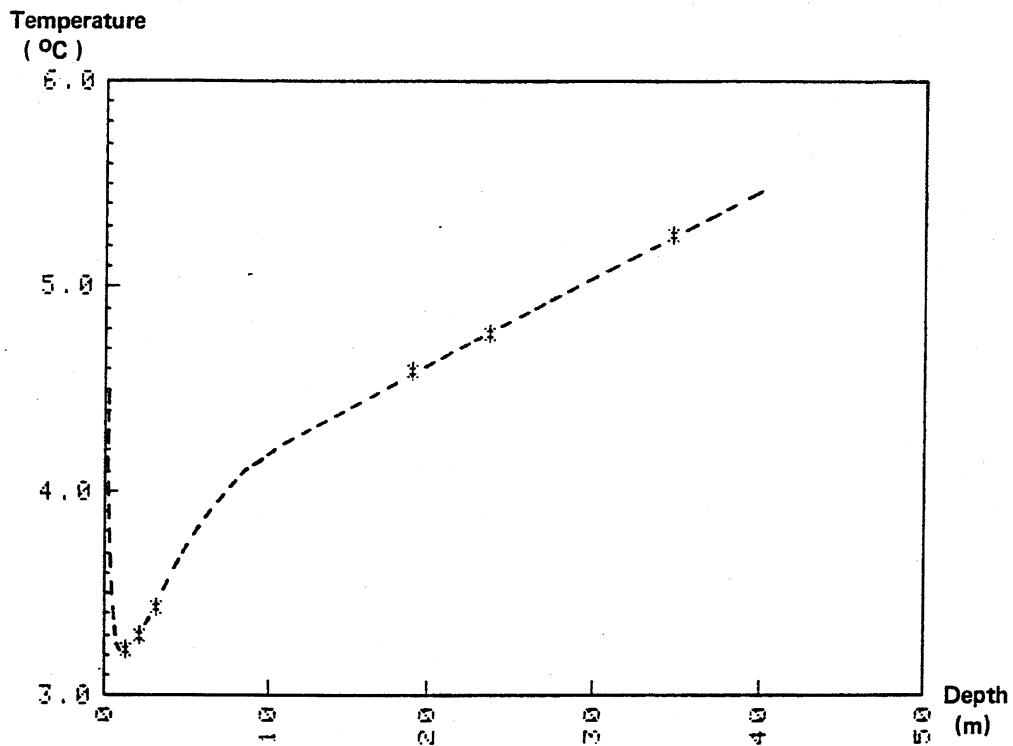


Fig. 4.2.4.2. Plot of temperature versus depth and interpolation curve for site C85-A.

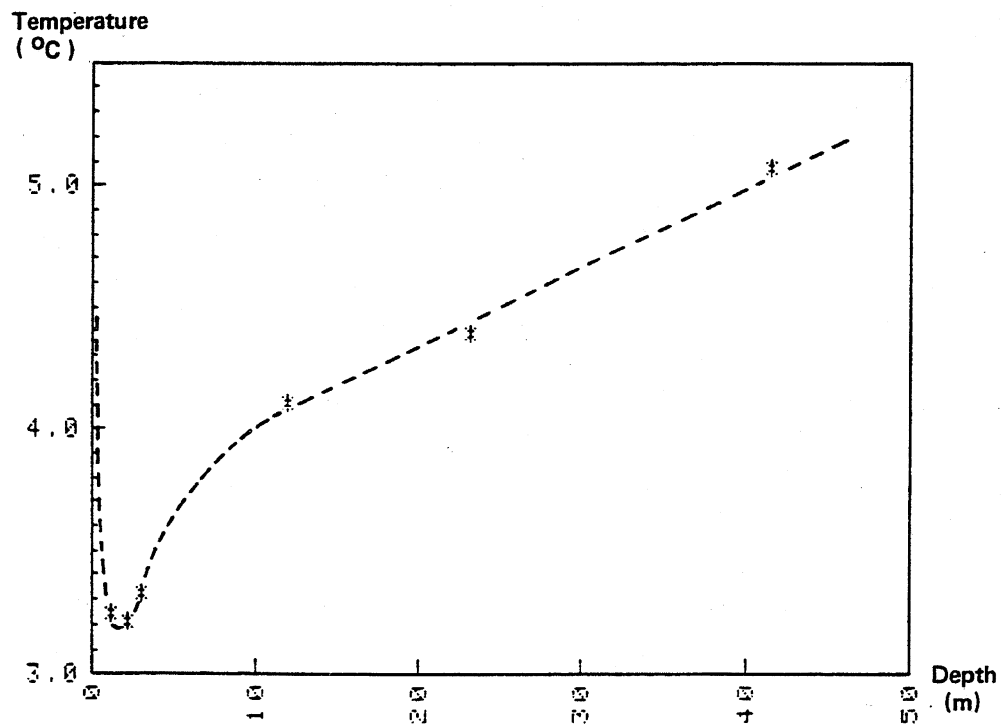


Fig. 4.2.4.3. Plot of temperature versus depth and interpolation curve for site C85-E.

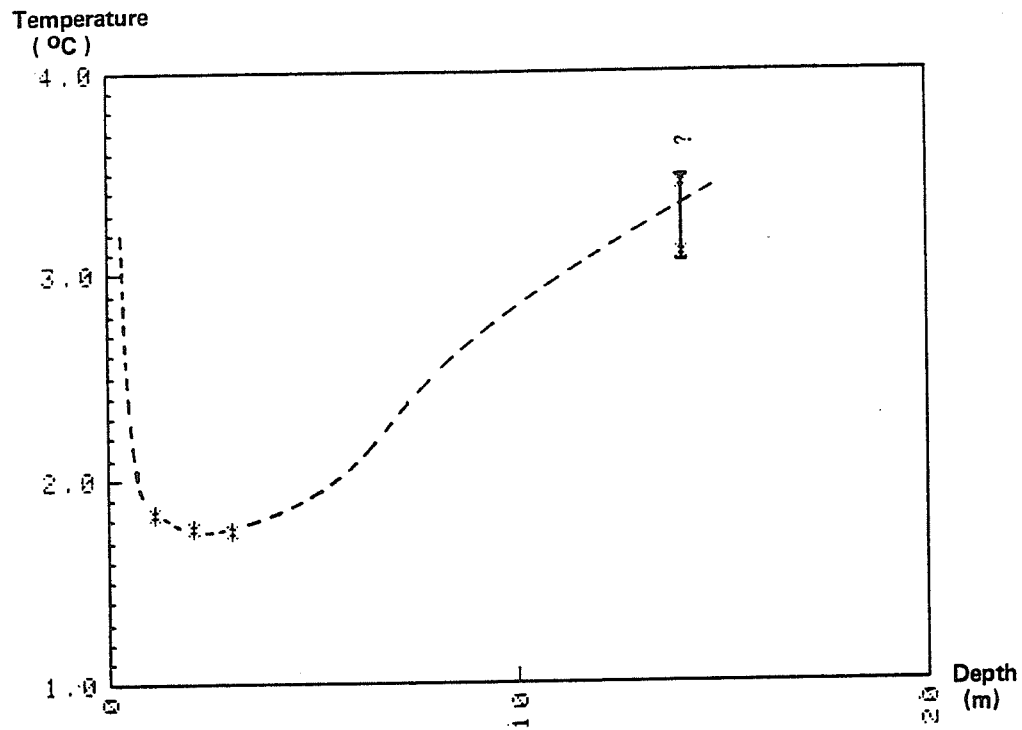


Fig. 4.2.4.4. Plot of temperature versus depth and interpolation curve for site D85-H.

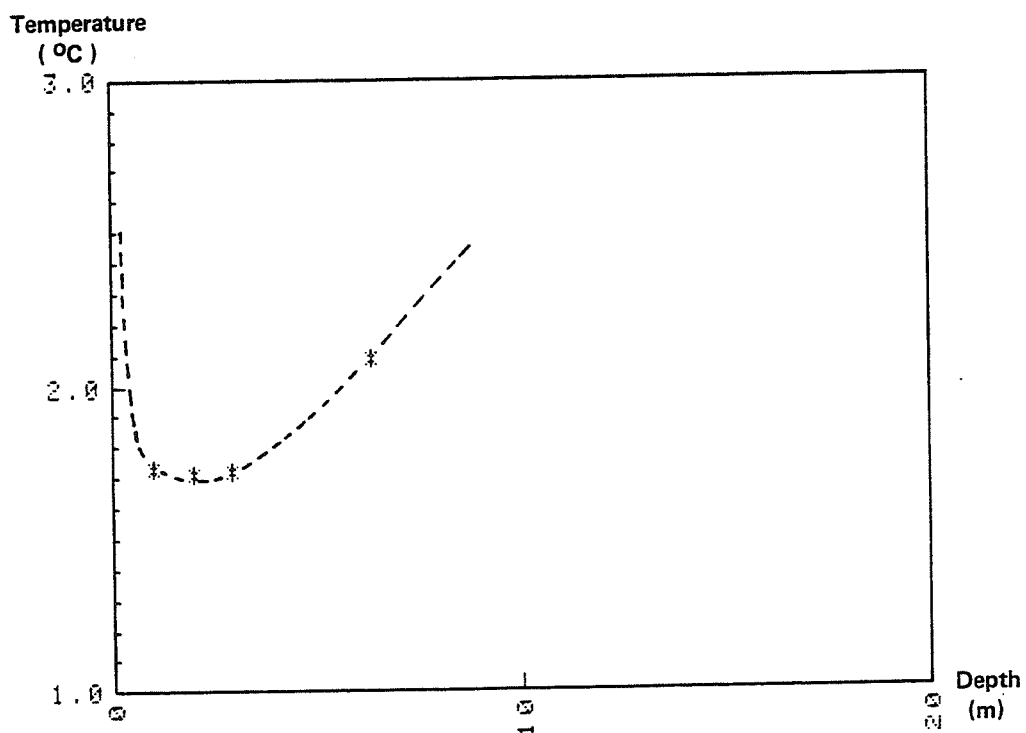


Fig. 4.2.4.5 Plot of temperature versus depth and interpolation curve for site D85-I.

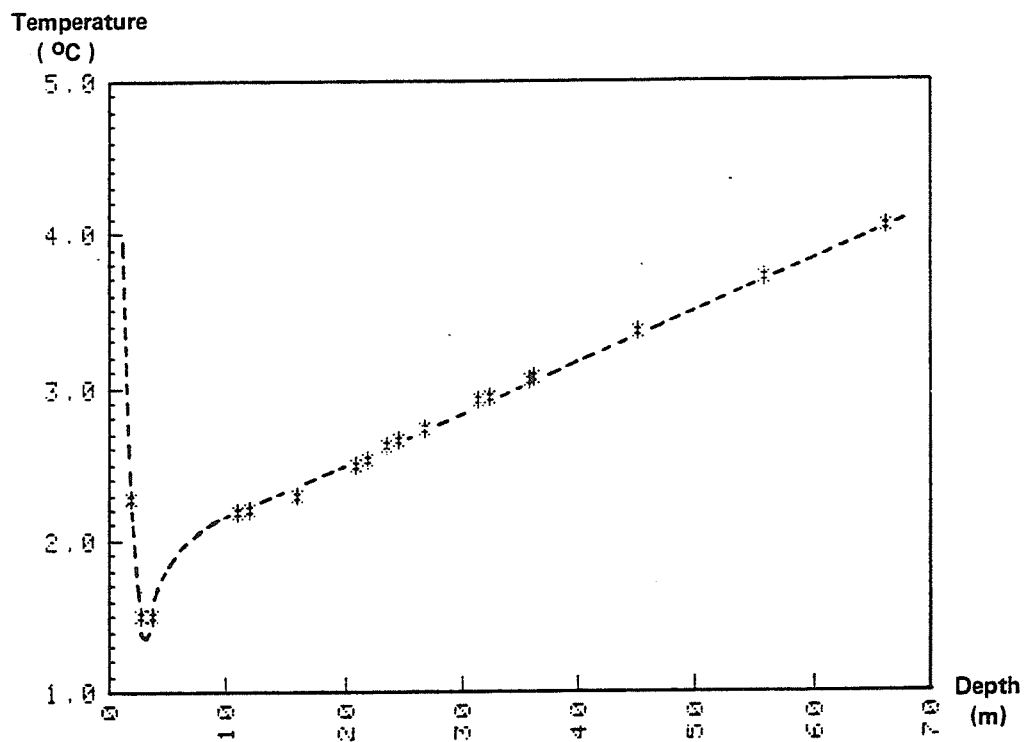


Fig. 4.2.4.6. Plot of temperature versus depth and interpolation curve for site D85-K.

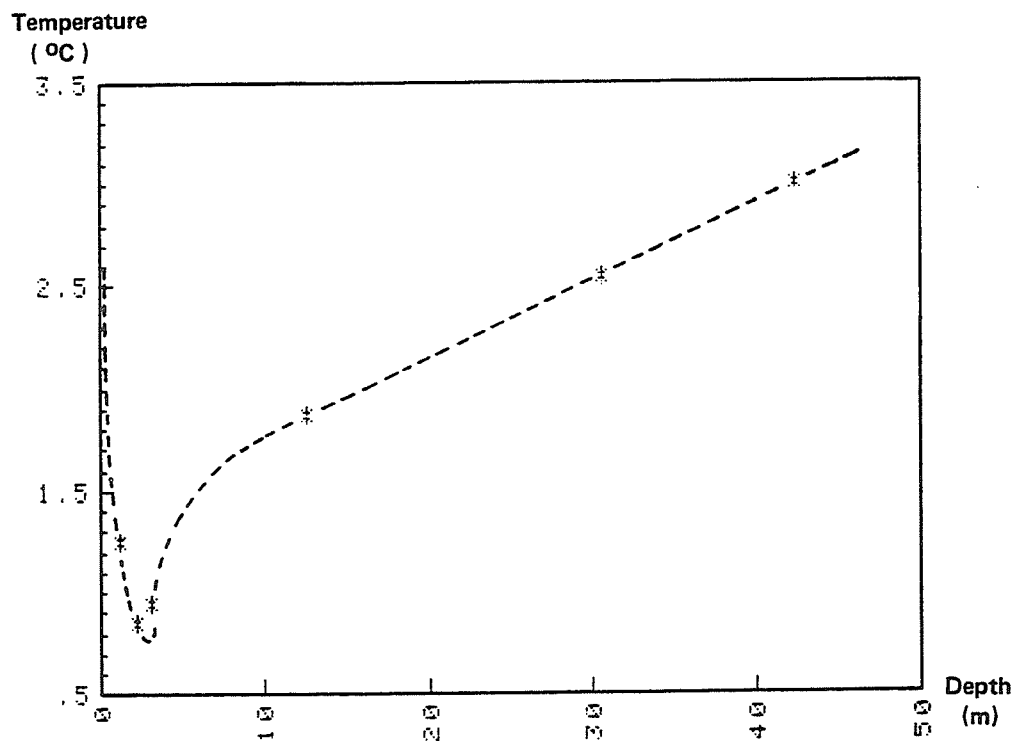


Fig. 4.2.4.7 Plot of temperature versus depth and interpolation curve for site D85-N.

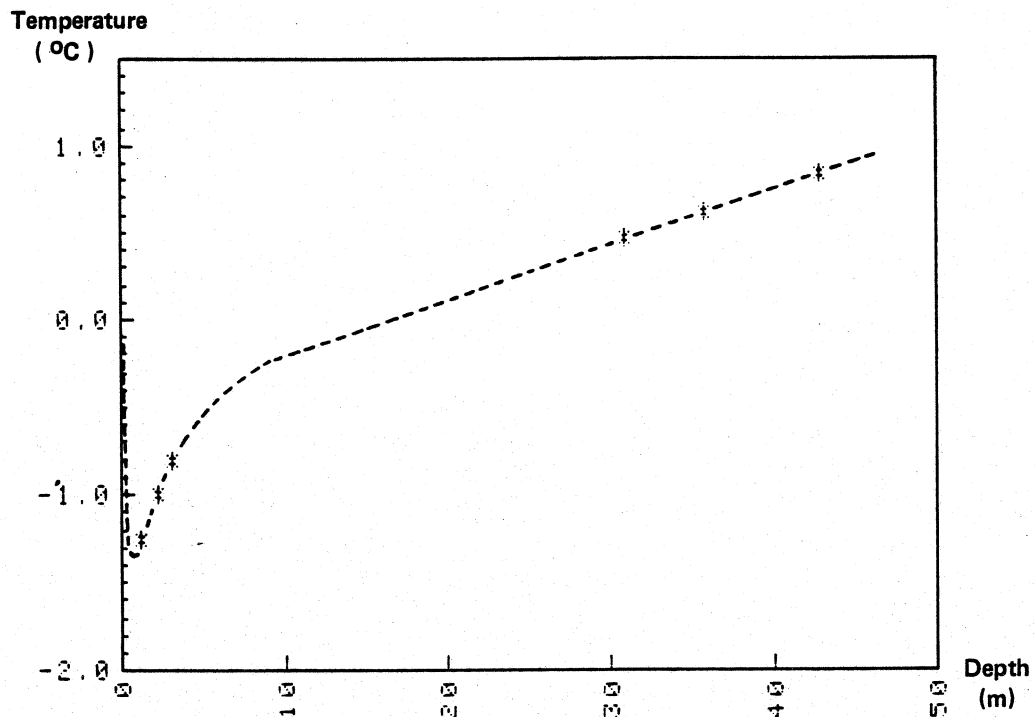


Fig. 4.2.4.8 Plot of temperature versus depth and interpolation curve for site D85-0.

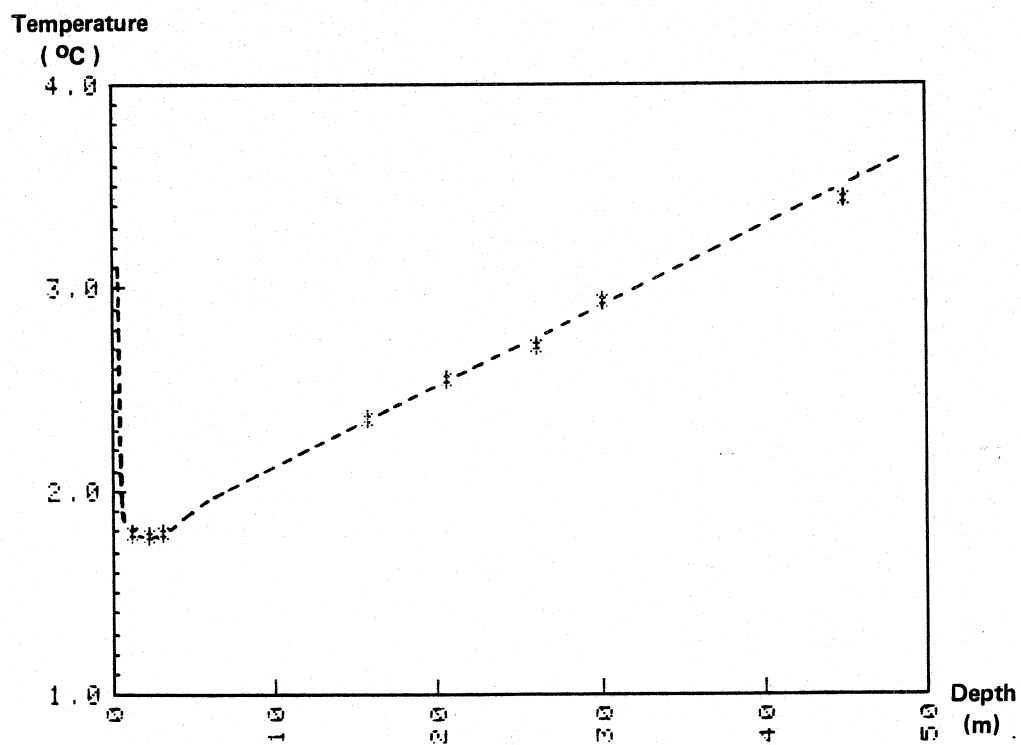


Fig. 4.2.4.9 Plot of temperature versus depth and interpolation curve for site D85-V.

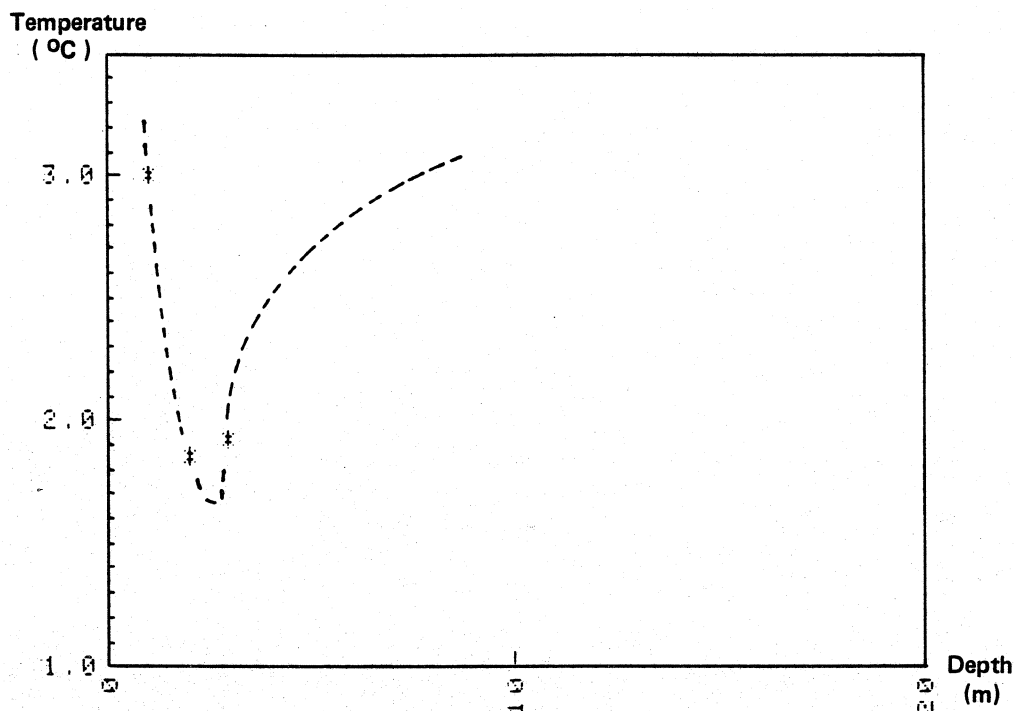


Fig. 4.2.4.10 Plot of temperature versus depth and interpolation curve for site D85-W.

4.2.5 Discussion of field data results

A significant factor contributing to the reliability of the presented heat flow data is the uniformity of the thermal conductivities measured at each site. Such uniformity tends to lessen errors normally associated with a finite sampling of thermal conductivity. Not only are the conductivity values uniform, they are also uniformly low. For marine sediments, the prime factor influencing on variation in thermal conductivity is water content (Ratcliff, 1960). It is perhaps somewhat surprising at first glance that for some of the encountered stiff overcompacted clays, measured conductivities imply 40 to 50 per cent water content compared with most sea-bottom sediments. This leads us to suspect that some lithologic component is contributing to the low values or that the fine-grained clays contain more water than simple observations reveals.

This theory is also supported by the pattern revealed by a cross plot of thermal conductivity versus water content in Fig. 4.2.5.1 which shows that especially for the population of plots with natural water content between 15% and 23% the correlation between water content and thermal conductivity is poor. This pattern may probably be an effect of variations in mineralogy or content of organic material. However, this can not be treated further before more sample analyses are carried out.

The importance of the outcome arises from the fact that the thermal conductivity measurements were made on board the ship at a temperature that was about 12 degC higher than sea bed conditions. The increase of temperature with 12 degC from in situ conditions to testing conditions would normally imply a correction on the measured thermal conductivities of about -3% (Ratcliff, 1960). This anticipated correction is largely due to the temperature effect on the thermal conductivity of the pore water. The mineral grains will have an increased thermal conductivity with increased temperature, but even though these two temperature effects are of opposite signs the effect on the water is stronger, and thus a negative total correction would normally apply for a sediment sample. However, the samples from the Barents Sea apparently have unusually low water content in relation to the measured thermal conductivity. The effects above will thus tend to cancel even more, and temperature corrections are therefore not applied to the thermal conductivity values given in this report. This item will be addressed further at a later stage of the project.

The effect of pressure (+1% per 2000 metres depth below sea level) on the measurements (Ratcliff, 1960) can be neglected.

Several environmental corrections sometimes applicable to heat flow measurements should be mentioned. These include topography and sedimentation rate corrections which normally apply to extreme conditions. For example it can be shown by a simple model that a sedimentation rate of 1 mm/year depresses heat flow by less than 4%. The effects of glacial uplift and long term climatic temperature change have been discussed by Swanberg et al. (1974) in relation to heat flow on mainland Norway. It was argued that these effects (each producing a maximum of 0.2 HFU correction) were of opposite sign and likely to cancel. Hence no correc-

tions were applied to that data. This is, however, very dependant upon the input model for glacial history that is applied, and we refer to the discussion in the next chapter. A more thorough treatment of these effects will be subject to subsequent research within our heat flow project.

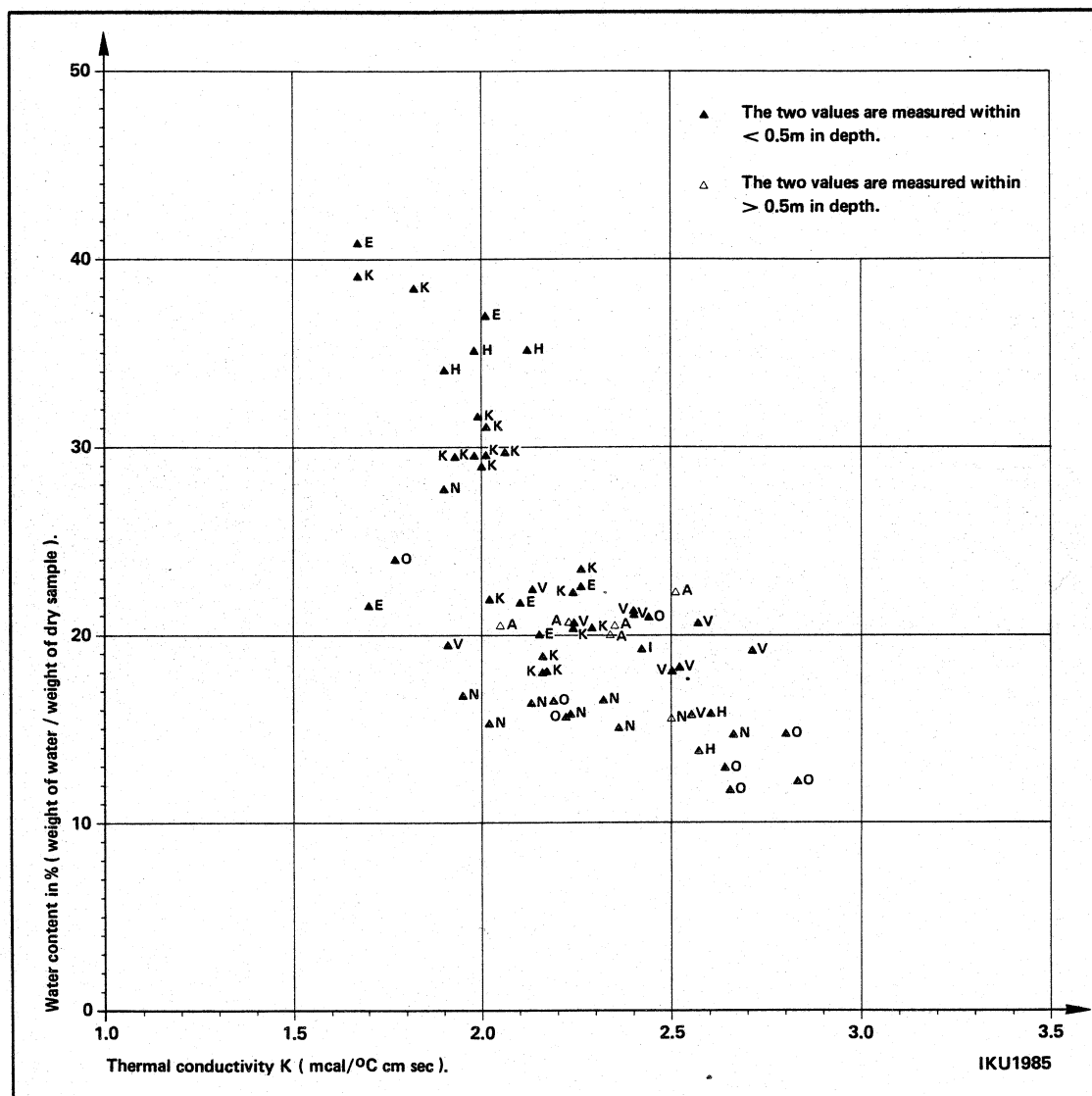


Fig. 4.2.5.1 Thermal conductivity versus water content for Quaternary samples obtained during the 1985 IKU drilling cruise.

5. POSSIBLE PERTURBATIONS IN THE MEASURED HEAT FLOW DATA DUE TO THE LATE QUATERNARY GLACIAL HISTORY

5.1 Objective and main findings

In the present chapter we try to outline the effects the glacial history may have caused on the measured heat flow data. The discussion is no attempt to treat this subject fully, but rather to establish a first order qualitative evaluation of what would be the likely palaeoclimatic effect on the calculated heat flow data.

The results so far indicate that a correction in terms of a slight increase of the measured heat flow values perhaps should be applied. However future work will treat this in detail. These corrections may vary from one site to another and because of this, we would recommend careful considerations before any corrections are applied.

5.2 The late Quaternary glacial history of the Barents Sea

5.2.1 Periods of glaciations and non-glaciations

It has not been possible within the time constraints to study all available relevant literature (of which a considerable amount only is published in the Russian language). It should therefore be noted that the selection of references and the presented models may be somewhat immature. However, with these restrictions given, we believe that the glacial history models outlined may be regarded as a proper basis for a preliminary evaluation of temperature history and serve as a basis for a continued research on this subject.

The theory about no glaciation at all in the study area (e.g. Boulton, 1979) is excluded because it is contradicted by the findings during the IKU drilling projects in the Barents Sea. Our documentation of the presence of stiff to hard silty clay containing fragments of gravel and pebble size clearly support the original suggestion of De Geer (1900) that an extensive grounded ice has existed in the Barents Sea. The diversity of ideas about the extent and presence of glaciations in the

Barents Sea is largely a result of sparse dating of the Quaternary succession in the area. Solheim and Kristoffersen (1984) regard 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. Still they are 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.

Elverhøi and Solheim (1983) summarized the different views of the late Weichselian glacial history as follows:

- I Total glaciation of the Barents Sea.
- II Glaciations of the shallower regions with Bjørnøyarennå and Storfjordrenna as calving bays.
- III No glaciation significantly beyond the coasts of Svalbard.

Model III above is regarded as unlikely and is not assumed as a realistic model for the maximum late Weichselian glaciation except for the western coast of Spitsbergen. Contradictions to this model are the supposed presence of a Late Weichselian ice sheet margin extending to the shelf edge off Troms (e.g. Rokoengen et al., 1979; Vorren and Kristoffersen, in press) and moraine ridges overlying organic material giving radiocarbon ages of 22,000-45,000 years BP in northwestern Siberia, that are supposed to be deposited along the margin of a Barents - Kara Seas icesheet (Grosswald, 1980).

Model I and Model II above are believed to represent different authors' opinions of the maximum ice sheet extension during the Late Weichselian. The maximum glaciation model presented by Andersen (1981) and Hughes et al. (1981) is consistent with model I. However, Andersen also discussed evidences from shore level studies in Finnmark and northwestern Kola that pointed against an extensive iceload (and thus an extensive ice sheet?) during late Weichselian time. This latter situation would agree with model II above, and also with the situation outlined by Elverhøi and Solheim (1983) and Solheim and Kristoffersen (1984).

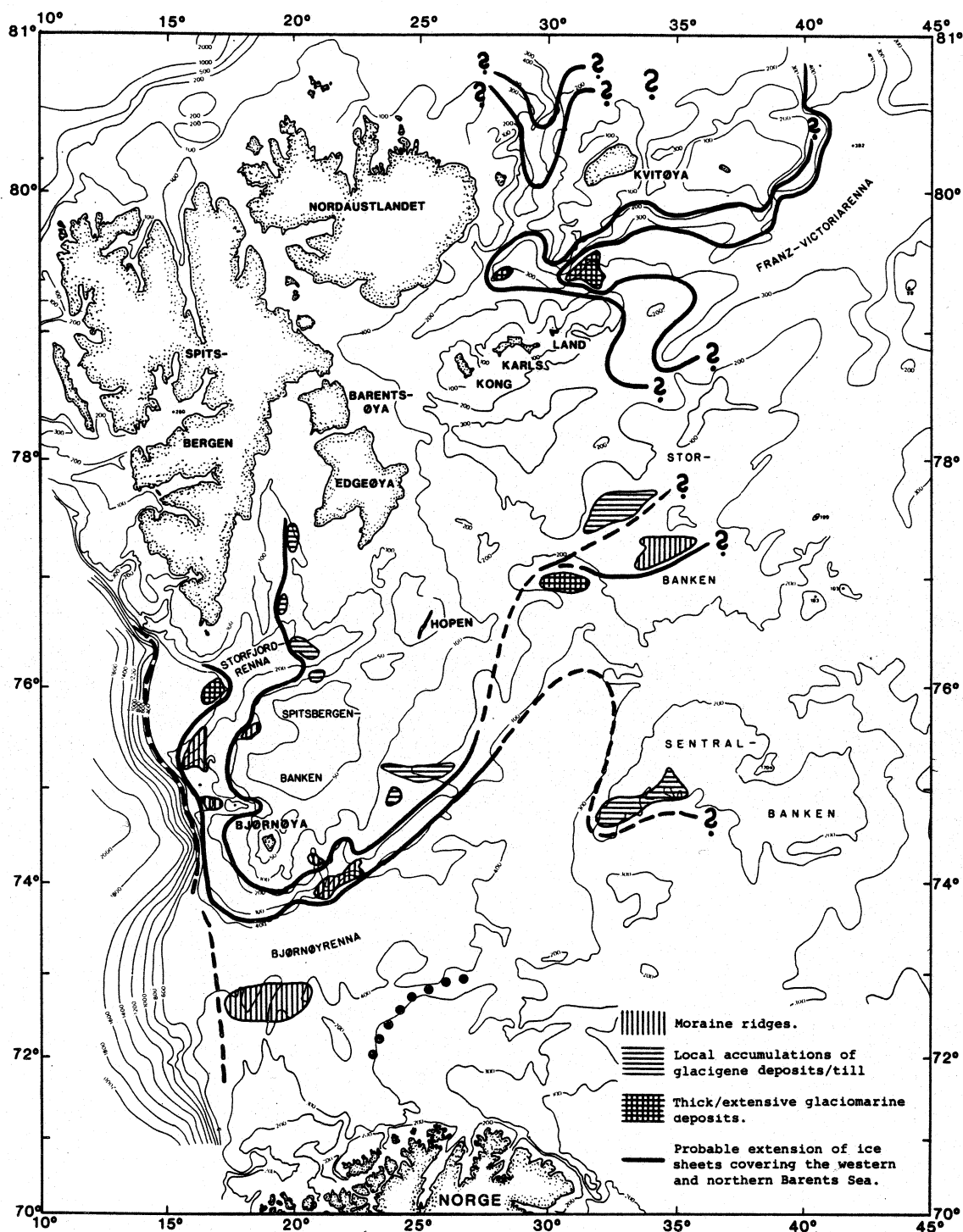


Fig. 5.2.1.1 Bathymetric map showing features related to former ice margins in the Barents Sea. Modified after Elverhøi and Solheim (1983). The heavy, dotted line shows approximately western termination of a wedge shaped sediment thickening interpreted from IKU sparker data.

Sparker data collected within the IKU Barents Sea Mapping Program shows evidences of a wedge shaped (in NW-SE cross section) deposit north of Nordkapp. The northwestern limitation of this deposit surparallels the present 300 m water depth contour on the map in Fig. 5.2.1.1

(Elverhøi and Solheim, 1983) and could tentatively be correlated with their ice margin at 300 - 400 m water depth on the northern flank of Bjørnøyrenna, thus supporting the Bjørnøyrenna calving bay theory. It should, however, be noted that this depositional wedge broadly corresponds with the boundary between a frozen base ice sheet and a wet base ice sheet according to the maximum Late Weichselian Barents Sea ice sheet reconstruction by Hughes et al. (1981) and that it also may be interpreted as a response to temperature zonation under such an ice sheet.

From the discussions above we have arrived at the following two suggestions for glacial history models for the southwestern Barents Sea:

Maximum glaciation:

Glaciations with ice sheets extending to the shelf edge occurred during Saale, Early Weichselian and late Weichselian time.

Minimum glaciation:

1. Saalian glaciation with an ice sheet extending to the shelf edge.
2. Early and late Weichselian glaciations with ice sheets grounded on the shallow banks (limited approximately by the present day 300 m water depth contour?) and an iceberg calving bay in the deep waters of Bjørnøyrenna.

With these two models established, the problem of the duration of the different events still remains. This problem is two-fold:

1. The duration of the different glacial periods.
2. The duration of the maximum glaciation situation within each glacial period.

For the purpose of establishing extreme temperature history models we have made the following simplification:

1. Full ice sheet advance according to the respective models occurred during the whole glacial periods.
2. Maximum and minimum duration of glacial periods are according to literature.

References for the different age alternatives are given in Figs. 5.3.1-5.3.2. Several of the works referred are general studies of Quaternary palaeoclimatology and general glacial geological history. The models presented here may therefore not be in accordance with the different authors' view upon the glacial history of the Barents Sea.

5.2.2 Temperatures underneath the Barents Sea ice sheets

This chapter gives a discussion of the possible temperature conditions under a Barents Sea ice sheet in relation to the IKU 1985 heat flow sites. The discussion serves as a background for the temperature history model used.

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 , at all our heat flow sites except from C85-A and C85-E. Though Orheim (pers. comm., 1985) tends to assume that most of the large Barents Sea ice sheet (sheets) had temperatures equal to T_M .

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

We have plotted the heat flow sites on an ice flow map for the maximum glaciation situation in the Barents Sea compiled by Hughes *et al.* (1981), and by estimating ice flow length for each site from this map and plotting these values into the calculated idealized surface profile (Fig. 5.2.2.1) (Hughes, 1981), we have calculated pressure melting temperatures corresponding to the maximum glaciation model for each site (Table 5.2.2.1).

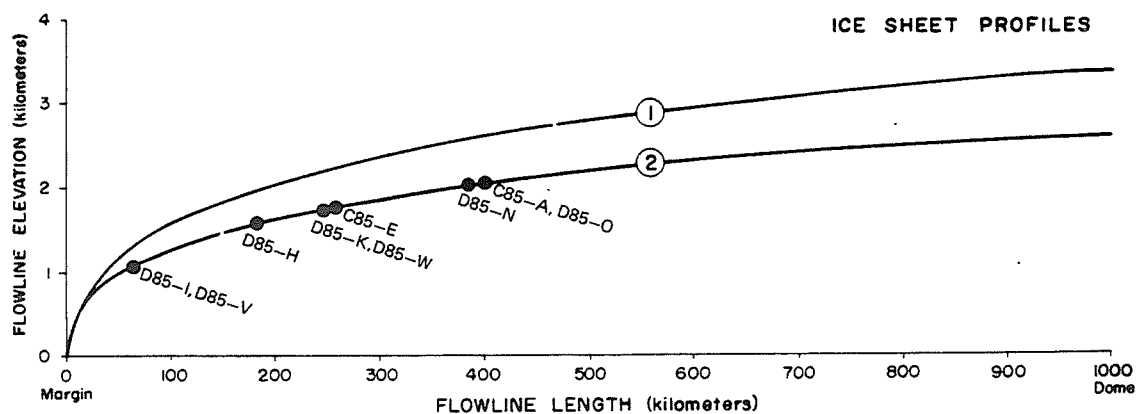


Fig. 5.2.2.1 Surface profiles for an ice sheet lying on (1) a frozen bed and (2) a melted bed, after Hughes (1981). The 1985 IKU heat flow sites are tentatively plotted along this curve assuming maximum glaciation (i.e. an ice sheet extending to the continental shelf break).

The curve results in a somewhat thicker ice cap estimate than would be the case for an ice sheet ending in an ice shelf as assumed by Hughes *et al.* (1981) to be the case for the Barents Sea ice sheet.

However, the Barents Sea ice sheet was probably somewhat buttressed by an ice shelf in the Norwegian Greenland Sea and this would have the opposite effect. Thus the thickness assumption seems reasonable.

By using a pressure melting point temperature gradient of 0.7 K/1000 m ice thickness we have thus ended at the following values for T_M for the heat flow sites.

Table 5.2.2.1 Pressure melting point temperature, T_M , underneath an ice sheet at the IKU heat flow sites assuming the maximum glaciation model.

Site	T_M °C
C85-A	-1.4°C
C85-E	-1.2°C
D85-H	-1.1°C
D85-W	-1.2°C
D85-K	-1.2°C
D85-I	-0.8°C
D85-V	-0.8°C
D85-N	-1.4°C
D85-O	-1.4°C

Table 5.2.2.2 Pressure melting point temperature, T_M , underneath an ice sheet for the IKU heat flow sites assuming the minimum glaciation model (no glaciations of the sites D85-H, D85-K and D85-W).

Site	T_M °C
C85-A	-1.1
C85-E	-0.7
D85-H	-
D85-W	-
D85-K	-
D85-I	-0.7
D85-V	-0.7
D85-N	-0.7
D85-O	-1.0

The same calculation procedure has been applied for the minimum duration of glaciation considered in the present study. In this model an ice sheet surrounded Bjørnøyrenna whereas the deepest parts of Bjørnøyrenna either was a calving bay with drifting icebergs or it was covered by an ice shelf. This model implies that locations D85-H, D85-K and D85-W were not glaciated, D85-O and C85-A were some 100 km, respectively 170 km from the ice sheet margin whereas locations C85-E, D85-I, D85-V, D85-N and D85-O were a few tens of kilometres away from the ice sheet margin. The corresponding basal pressure melting points are listed below.

The basal temperatures of a frozen bed marine ice sheet may differ largely from the basal temperatures of a terrigenous frozen bed ice sheet. In the latter case the ice sheet may have advanced over a permafrost terrain with very low temperatures in the underground. A marine ice sheet in the Barents Sea, however, most likely have originated from freezing of water from the sea underneath an ice shelf (Denton and Hughes, 1981b). Such a marine frozen bed ice sheet initially can not have a temperature below approx. -2.1°C at its sole.

The most effective way of lowering the temperatures within an ice sheet mass is by ablation of cold ice at the ice sheet surface. This can result in internal ice sheet temperatures equal to the surface temperature several hundreds of metres below the ice sheet surface. The consequence may be a further lowering of the temperature at the base of the ice sheet.

In the southwestern Barents Sea, however, we believe that the growth and thickening of the ice sheets probably occurred as mass flow of ice in a confluencing pattern from surrounding domes.

If so, this argues against a significant lowering of the initial temperature in frozen bed ice sheet zones of the Barents Sea, and thus the temperatures probably never were more than maximum a few of degrees below the pressure melting point under these ice sheets.

Towards the end of a glaciation a marine ice sheet will tend to move fast upon its base. This will create frictional heat and basal temperature will increase towards the pressure melting point.

5.2.3 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 on Figs. 4.2.4.2-4.2.4.10. The effect of different average thermal conductivity above and below 10 m is ignored.

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 temperature 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. comm., 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.

-0.5°C may probably be chosen as an average value under such conditions, and if this approximation also is valid for site D85-0 it implies that the sea water temperature at this site has been roughly the same since the deglaciation as it is today.

5.3 Preliminary temperature history models

In order to study possible temperature effects caused by late Quaternary glaciations, we have constructed two glaciation models which we regard as realistic alternatives deduced from the discussions in Chapters 5.1 and 5.2. These models are presented in Figs. 5.3.1 and 5.3.2 and show temperature events as a function of time for each site.

The models are considerably simplified by assuming that the study area was glaciated during the entire glacial periods. This is probably not correct and will result in an over-estimate of the effect on the present day measured heat flow.

Cold based ice sheets are not included in our models, but would probably imply slightly lower temperatures than those used in our models.

5.4 Discussion

In a study of temperature gradients and heat flow in Norway, Swanberg et al. (1974) concluded that corrections of the measured temperature gradients due to palaeoclimatic temperatures were less than $+1.8^{\circ}\text{C}/\text{km}$. In this study was also a correction due to effects from the post glacial isostatic uplift of Scandinavia discussed. The correction for isostatic uplift was found to imply a reduction of the measured gradients of less than $2^{\circ}\text{C}/\text{km}$. As the two corrections were of the same magnitude but with opposite signs, they were both ignored in the final values in the study by Swanberg et al. (1974).

The temperature models presented in Chapter 5.3 are regarded as too immature as a basis for expressing correction values for the different sites. However, we have run some preliminary correction calculations at the Geophysical Laboratory of the University of Aarhus in Denmark. Based on these results and a general evaluation of the possible temperature history (Chapters 5.2 and 5.3), similar corrections for the earth surface temperature history, might apply for our sites in the Barents Sea as for the Norwegian heat flow sites.

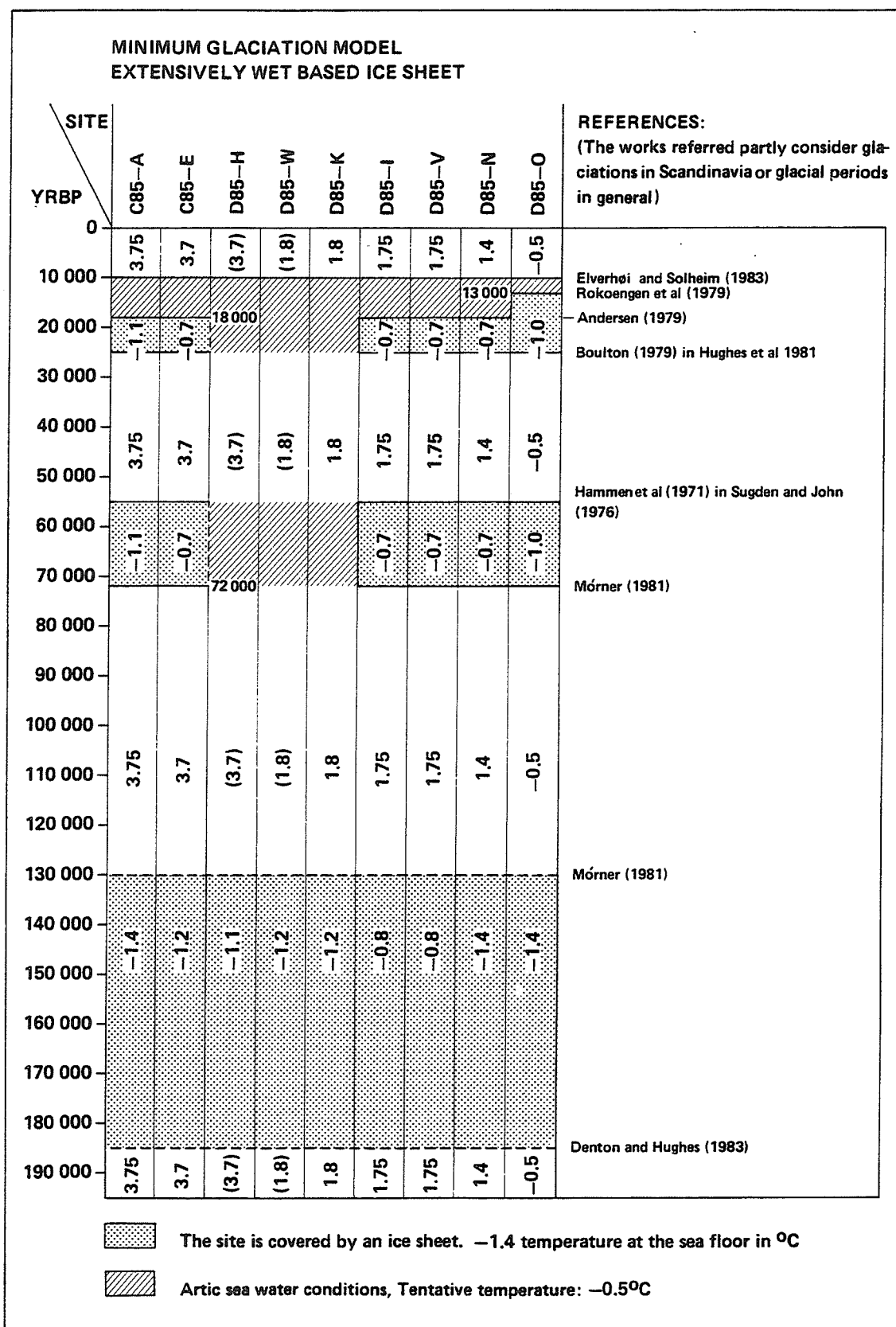


Fig. 5.3.1 Minimum glaciation model.

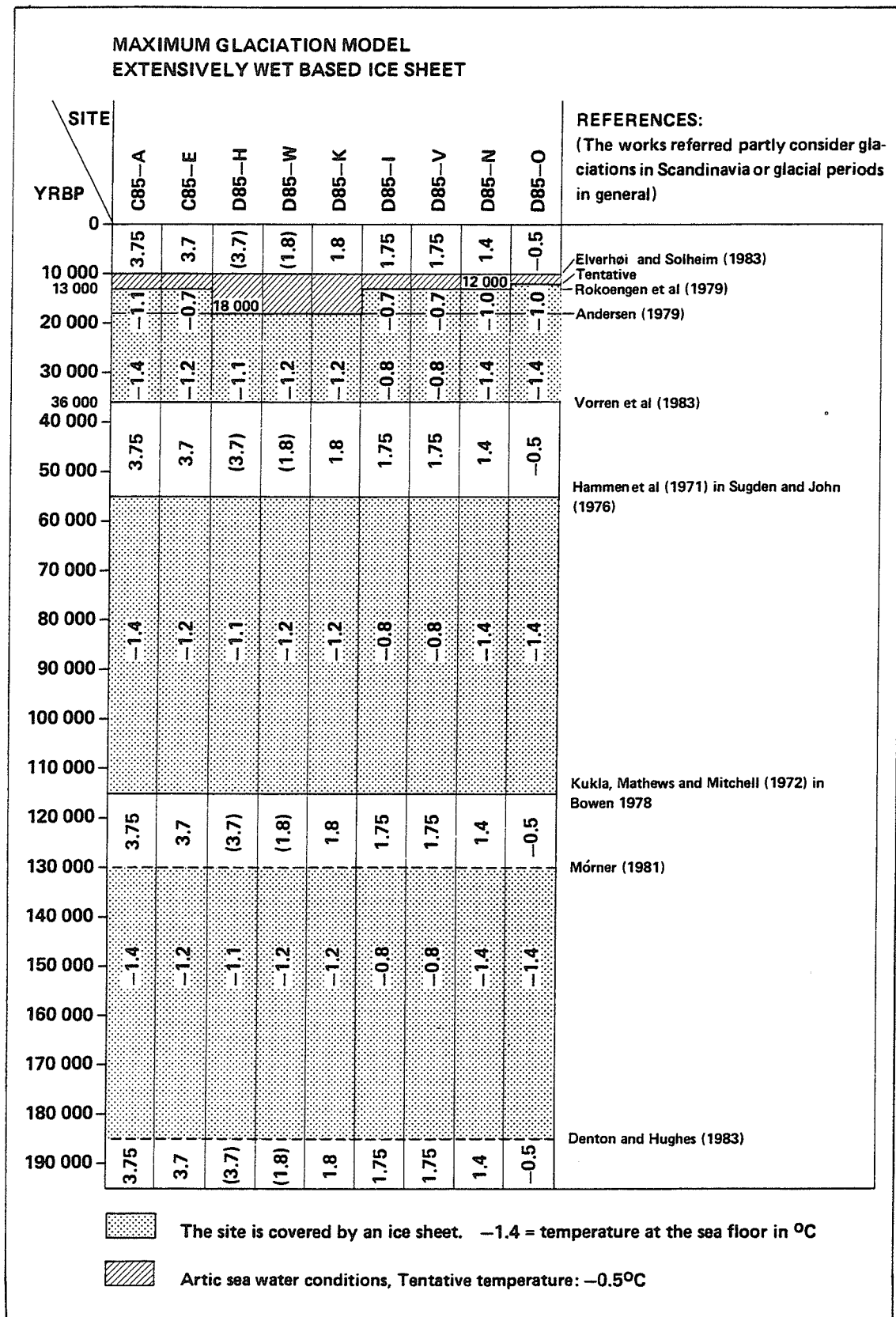


Fig. 5.3.2 Maximum glaciation model.

The correction for isostatic uplift applied by Swanberg et al. (1974) is, however, probably not applicable in our study. This correction followed a scheme presented by Birch (1950) and was based on the assumption that isostatic uplift of the sites resulted in a lowering of temperature at the earth surface of each site since the deglaciation as temperature generally decreases with increased altitude. This situation can not directly be applied to the sites in the Barents Sea where for instance the present day water depth in some places exceeds 400 m.

From the above discussion it may be suggested that effects of late Quaternary glaciations in the area would give slight positive corrections that should be added to the measured heat flow values. It may, however, be expected that a better and more detailed understanding of the late Quaternary glacial history of the region will have the following effect upon our temperature history models:

1. Temperature models will be modified, and the modifications are likely to reduce their effect upon heat flow values measured in shallow boreholes.
2. Future, refined temperature models are likely to imply a differentiated temperature history throughout the area.

6. PLANS FOR FURTHER WORK

Utilization of shallow boreholes for measuring heat flow has proven highly successful in the southwestern Barents Sea. The potential of this method may be even further improved through the experience gained during the 1985 survey, and the combination of shallow drilling with bedrock coring and measurement of temperature and thermal conductivity is regarded as ideal for mapping the thermal regime of the area.

The distribution of the 1985 sites is, however, limited mainly to structural highs, and similar mapping of basin areas is necessary in order to obtain a complete first order documentation of the heat flow in this region. This, and a denser grid of data points will be main aims for the planned field work in 1986.

The present report (Chapter 5) indicates a possible need for a slight positive correction (probably not for all the sites) of the measured heat flow values. A tentative quantification of this effect will be an item for further research within the project.

Information about thermal conductivity at different levels of the sedimentary succession is necessary in order to model temperature as a function of depth. This information is published for various lithologies and ages of rocks from different parts of the world. However, testing of bedrock samples from the actual study area will improve the confidence level of this modelling, and such sampling and testing will be given priority in the project.

As a part of this testing we also will pay special attention to the anisotropy in thermal conductivity which seemed to be present in some of this years claystone samples (Table 4.1.2).

The final aim for the heat flow measurements is to model temperatures as a function of depth within the study area and to relate this present day situation to the development of the different structural elements in the southwestern Barents Sea. This work will be commenced during 1986, but will rely on input of more data during the planned field work of 1986.

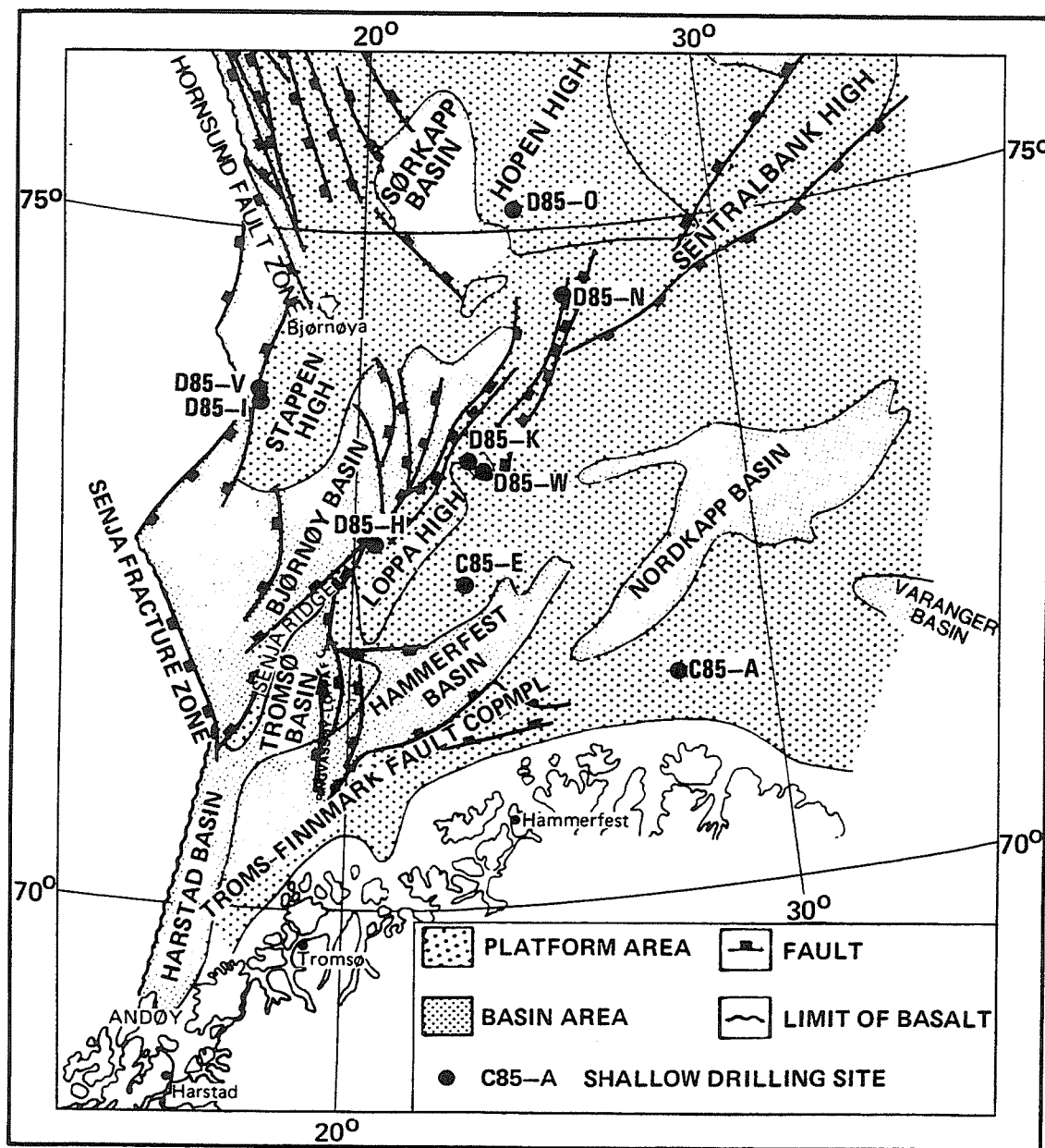


Fig. 6.1 Structural distribution of IKU shallow drilling and heat flow measurement sites 1985.

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