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Deep Heatflow Measurements in Quaternary Sediments on the Norwegian Continental Shelf

by G.W. Zielinski, *Omegalink*; T. Gunleiksrud and J. Saettem, *I.K.U.*; and H.M. Zuidberg and J.M. Geise, *Fugro Geotechnical Engineers B.V.*

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ABSTRACT

A heat flow measurement technique used in shallow boreholes on the Norwegian Continental Shelf in water depths from 105 to 440 m is described.

A thermistor probe was mounted on a downhole jack normally used for geotechnical investigations, and connected to an onboard recording unit via amplifiers and an umbilical cable. Measurements of in-situ temperature in Quaternary sediments were obtained to 70 m below the seabed with a resolution and accuracy of the measured temperatures of 0.008°C and 0.02°C, respectively.

In order to establish heat flow values, thermal conductivity was measured on high quality push samples obtained from the depth interval covered by temperature measurements.

The method described can be applied in conjunction with normal shallow drilling marine geotechnical programs and thus provides an opportunity for extensive collection of heat flow data to be used in the modelling of present day thermal conditions and fluid flow in offshore sedimentary basins.

INTRODUCTION

The vast majority of measurements comprising world heat flow data base are confined to either the Abyssal oceans or deep (greater than 500 m) boreholes on land. Largely due to the disturbing effect of bottom water temperature fluctuations in shallow water environments and the general lack of availability of reliable thermal measurements from deep production boreholes, continental margins remain grossly undersampled with respect to heat flow. In light of the increasing attention being given to shallow water sedimentary basin areas by explorationists and petroleum geologists, this appears an unfortunate situation. With this in mind an effort was launched to develop an operationally practical system to obtain heat flow data by measuring temperature and thermal conductivity in Quaternary sediments beneath the seafloor in continental shelf areas.

Heat flow data measured as described here has to be subjected to corrections for several effects like isostatic uplift, sedimentation and erosion and late Quaternary temperature fluctuations as described by several authors (i.e. Birch, 1950 and Beck, 1977). This will not be discussed further in the present paper.

In the summer of 1985, the Continental Shelf and Petroleum Technology Research Institute (IKU) of Trondheim, Norway performed a stratigraphic bedrock drilling and heat flow programme in the North Norwegian Continental Shelf. The survey was conducted from the geotechnical drill ship M.S. Bucentaur (figure 1). Heat flow values were measured in 9 boreholes with water depths varying between 105 and 440 m. As part of the survey Fugro B.V. of Leidschendam, The Netherlands and Omegalink International Ltd. of New York, U.S.A. were subcontracted to perform temperature measurements in the Quaternary sediments and to measure thermal conductivity on samples recovered from corresponding levels in the boreholes.

Vertical conductive heat flow through the underground can be described by the following equation:

$$q = k_t \cdot \frac{dt}{dZ}$$

where q is the heat flow, k_t is the thermal conductivity of the sediment and dt is the temperature difference across a depth

References and illustrations at end of paper difference dZ. An accurate heat flow measurement thus requires accurate recording of all the three parameters on the right side of the equation.

For the temperature measurement, a thermistor probe was attached to a remotely operated downhole jack, which pushed the probe in thermally undisturbed sediments below the bottom of the borehole. (In several respects this procedure was similar to that of Sass et al., 1979.). High quality samples were obtained during the survey by a hydraulic push sampler and thermal conductivities were measured on these samples in the onboard laboratory via the needle-probe method (von Herzen and Maxwell, 1959).

THE HEATFLOW PROBE

For the survey, a new thermistor probe was developed through a joint research and development effort of Fugro B.V. and Omegalink International Ltd. The principle design considerations for the temperature probe were so as to achieve the required accuracy and resolution of nominally 0.01°C and 0.001°C with an optimum compromise between fast thermal response time (low thermal mass) and high breaking strength (high thermal mass).

For deployment, an existing remotely operated downhole jack was chosen. Consequently the heat flow probe had to be thermally isolated from the jack in order to keep stem (heat) transfer within acceptable limits, while the probe had to withstand insertion into stiff to very hard clayey sediments without breakage. As a result of the foregoing design criteria, a small stainless steel tube with a diameter of 4.7 mm (3/16 inch) and a length of about 80 mm was chosen. The termistor was mounted in the tip of the small tube. This tube was then mounted in a plastic (nose) housing of high strength and good thermal insulation properties (figure 2).

In order to transmit the thermistor output from measurement depth to the surface vessel without loss of accuracy and resolution, a temperature stable two-stage amplifier was built and mounted in a water tight amplifier housing immediately above the plastic nose. In this manner the thermistor output is transmitted via the downhole jack umbilical, with a length of 750 metres, as amplified voltages to a precision strip chart recorder and a mini-computer system aboard the vessel.

THE DOWNHOLE JACK

A downhole jack was used to push the heat flow probe into the soil below the bottom of the borehole. This jack, having a maximum stroke of three metres, is normally used in geotechnical site investigations (figure 3). The downhole jack latches into a special bottom hole assembly located immediately above the drill bit. The jack itself is connected to a remote measuring and control unit, which contains sensors for monitoring downhole mud pressure, oil pressure, probe penetration and tool location. The system affords the opportunity to push the heat flow probe in a controlled fashion into unconsolidated sediments ahead of thermal disturbances associated with drilling operations. The use of a remotely operated downhole jack for downhole temperature measurements has several advantages:

- full control over heatflow probe penetration
- control of the penetration force
- direct and continuous readings of the heatflow probe output
- exact penetration measurement
- providing fixity of the heatflow probe during thermal equilibration.

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 10°C. The corresponding outputs of the thermistors were measured with respect to NBS traceable reference resistors (0.015 percent accuracy) by curve-fitting the resulting calibration data to a standard logarithmic function (Steinhart and Hart, 1965). The mean residuals for the thermistors employed were found to be nominally 0.001°C.

Amplifier calibration consisted of inputting NBS traceable resistances while recording the voltage output over the anticipated operating range.

Similar calibrations were performed on all probe assemblies returned after the survey (only one thermistor probe failed to return). Based on these pre- and post-cruise calibrations, we estimate the overall instrument accuracy and resolution to be within 0.02°C and 0.008°C, respectively.

TESTING PROCEDURES

Based on previous surveys in the area, some gravel content in the Quaternary sediments was anticipated at the locations where temperature measurements were to be made. The following procedure was established in order to reduce the risk of breaking the heat flow probe on gravel: Prior to each temperature measurement, a push sample was obtained. Upon retrieval of the sampler, visual inspection of the sample tube gave sufficient indication as to whether a test with the heatflow probe could be undertaken (figure 4). The sample was extruded in the laboratory on board the vessel for thermal conductivity measurement, classification and other physical and chemical properties measurements.

In case a measurement could be undertaken, the downhole jack was lowered on its umbilical in the drill string until it was seated on the drill bit and the tool was then latched in place. The heat flow probe was allowed a few minutes to equilibrate with downhole temperature prior to the push. The jack was then activated and the probe advanced. Normally the jack pushes the sensor ahead at a speed of 20 mm/s, a standard rate of penetration for cone penetrometer testing (CPT), however, in this case the control during penetration of the fragile probe was of extreme importance. Thus the hydraulic control valve in the control cabin was used to reduce the speed of penetration. While continuously monitoring the oil pressure (thrust), heat flow probe output (temperature) and the probe displacement (penetration), the equipment operator was able to embed the probe such that frictional heating was reduced to a minimum.

In order to avoid drill string movement by the vessel moving in the waves, which could seriously hamper the measurements, the drill string was immobilized during testing by clamping the seabed template to the drill pipe (figure 5).

DEPTH MEASUREMENT

Recording of the depth below sea bed for each temperature measurement had to be carried out with an accuracy corresponding to the accuracy of the temperature measurements. Assuming a temperature gradient of 40°C/km, a temperature accuracy of 0.01°C would correspond to a depth accuracy of 0.25 m. This accuracy could not be achieved by measurement relative to the vessel which moved vertically due to swell and tidal variations which both occasionally had amplitudes exceeding 2 to 3 m.

To overcome this problem the penetration of the drill bit with reference to the seabed was measured from fixpoints on the heave-compensated heavy lift wires from the seabed template. With careful measurement between drillstring and the heavy lift wire and with the system's inherent high degree of accuracy for determining the position of the heat flow probe relative to the drill bit, the degree of accuracy is believed to be on the order of ± 0.1 m.

MEASUREMENT RESULTS

The basic measurements results of the downhole heat flow probe are summarized in figures 6 and 7, illustrating the real-time output from the onboard mini-computer. Digital data sampling (in addition to the analog strip chart records mentioned earlier) was at a rate of one measurement per second. Figure 6 shows a plot of the basic voltage output of the downhole probe plotted as a function of time in seconds during the measurement. The final push into the sediments occurs a little more than 200 seconds on the plot, after which the steady dissipation of excess heat occurs as equilibration toward formation temperature progresses. The temperature response time of the probe is such that about 15 minutes are required for a valid estimate of equilibrium temperature to a comparable level of resolution as was stated for the instrument calibration.

In figure 7 the vertical axis has been converted to temperature via the appropriate transfer functions (voltage to resistance and resistance to temperature) and the time axis has been transformed to reciprocal time. Based on the theory of equilibration of cylindrical conductors (Jaeger, 1956) a plot of this type can be used over an appropriate interval of figure 6 to perform an extrapolation to equilibrium. The data points in this particular case span the time interval from about 500 seconds to the end of the measurement (1800 seconds). A linear least-squares fit to the data in figure 5a has been performed and the corresponding intercept value computed. According to the scheme, as 1/time tends towards zero, time tends toward infinity. Hence the intercept temperature value provides an estimate of the true equilibrium formation temperature. The generation of figure 7 and associated data reduction to equilibrium formation temperature can routinely be performed on ship immediately after each measurement (i.e. after each subsequent generation of a figure 6).

CONCLUSIONS

We feel that the equipment and methods chosen for the survey have proven well suited for shallow water heat flow mapping. The requirements as to accuracy and resolution of the temperature measurements were fulfilled and only one of the rather fragile heatflow probes was damaged during the survey.

Normally surface heat flow measurements are affected by annual temperature fluctuations, however, the downhole measurements afforded the opportunity to obtain data below this thermally disturbed zone.

The method used can be combined with routine geological and geotechnical survey work. Compared with standard downhole oil well temperature measurements the method described here has the advantage that temperature is measured in sediments with no disturbance from drilling operations. It should, however, not be regarded as an alternative but rather as an optional addition to deep well temperature measurements.

ACKNOWLEDGEMENTS

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Fig. 1- Drillship M.S. Bucentaur

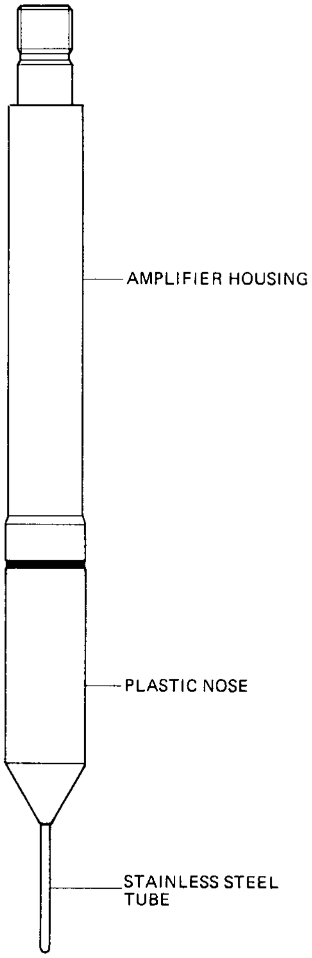

Fig. 2- Heatflow Probe

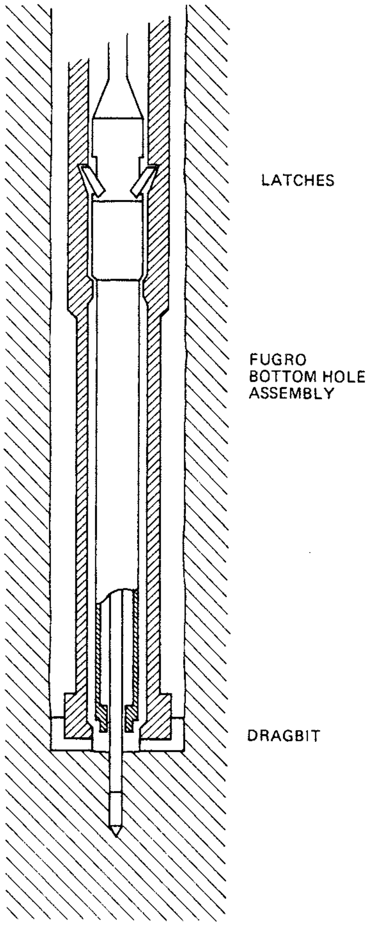

Fig. 3- Wison Downhole Cone Penetrometer

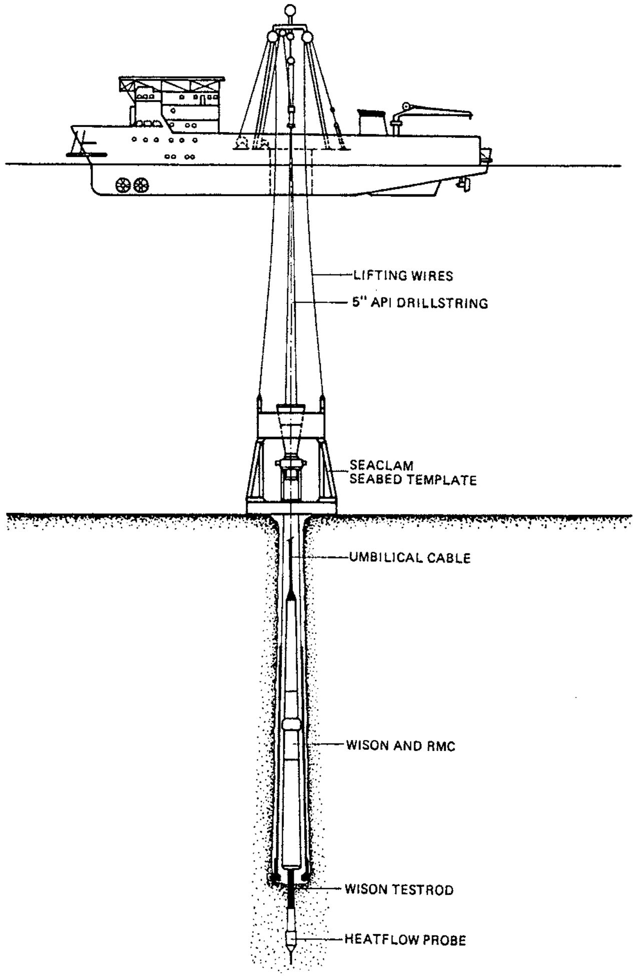

Fig. 5- Testing Set-up

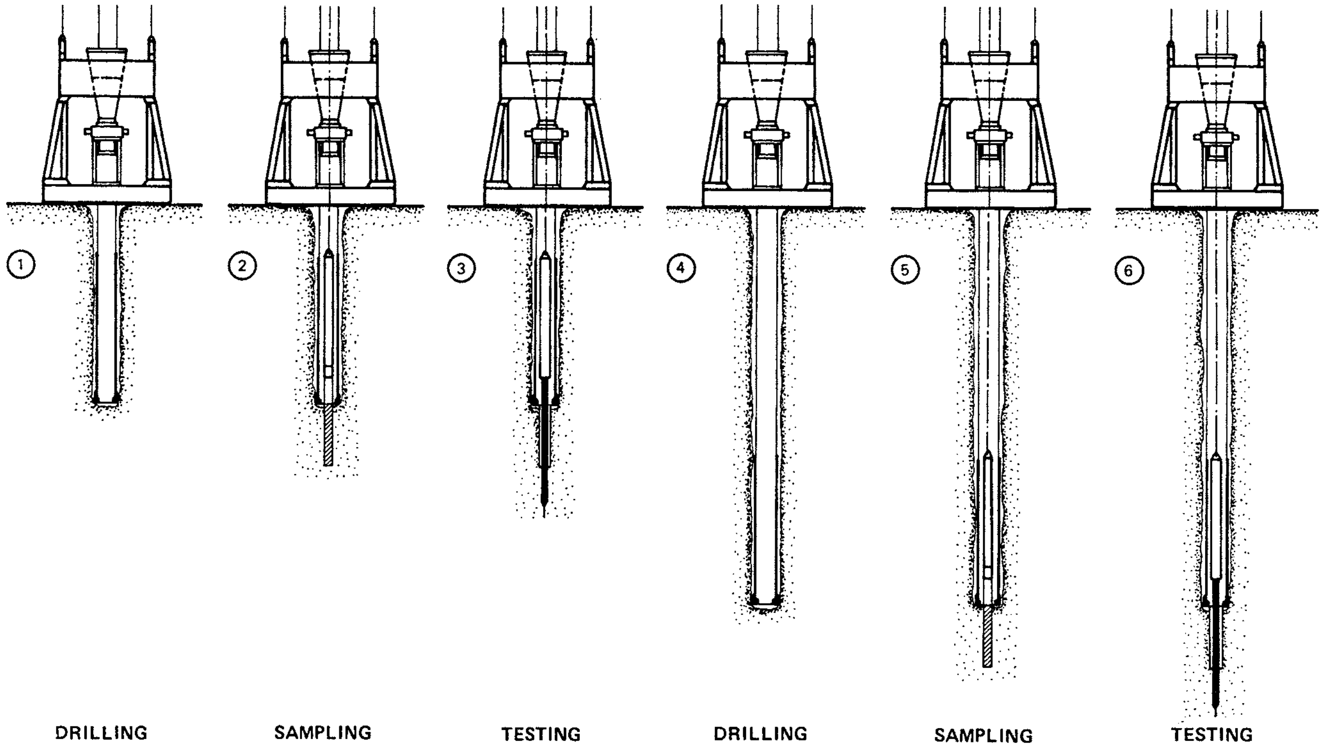

Fig. 4- Operational Procedures

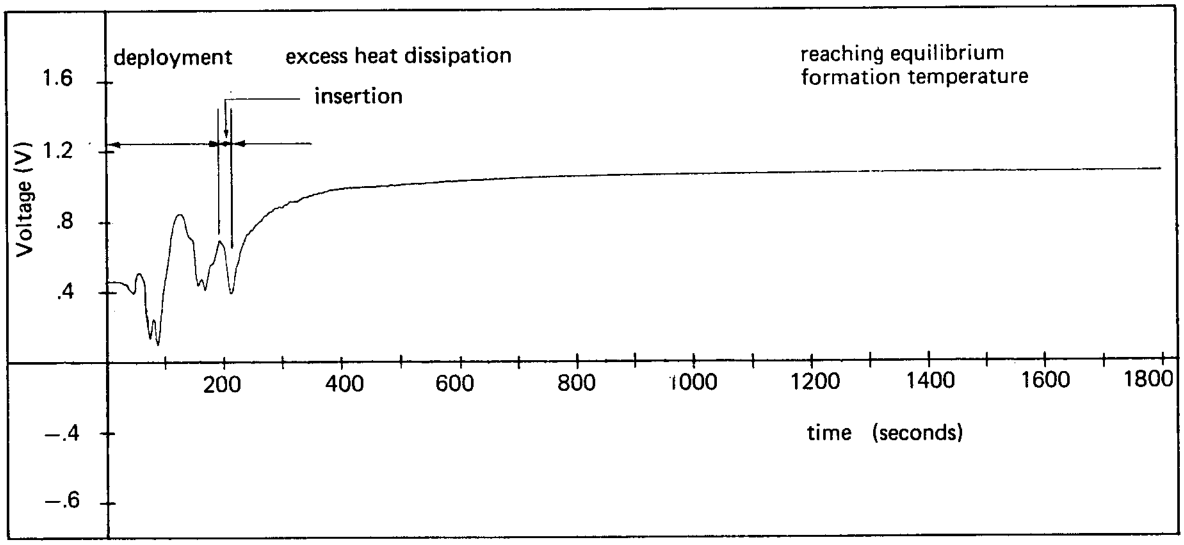

Fig. 6- Measurement result

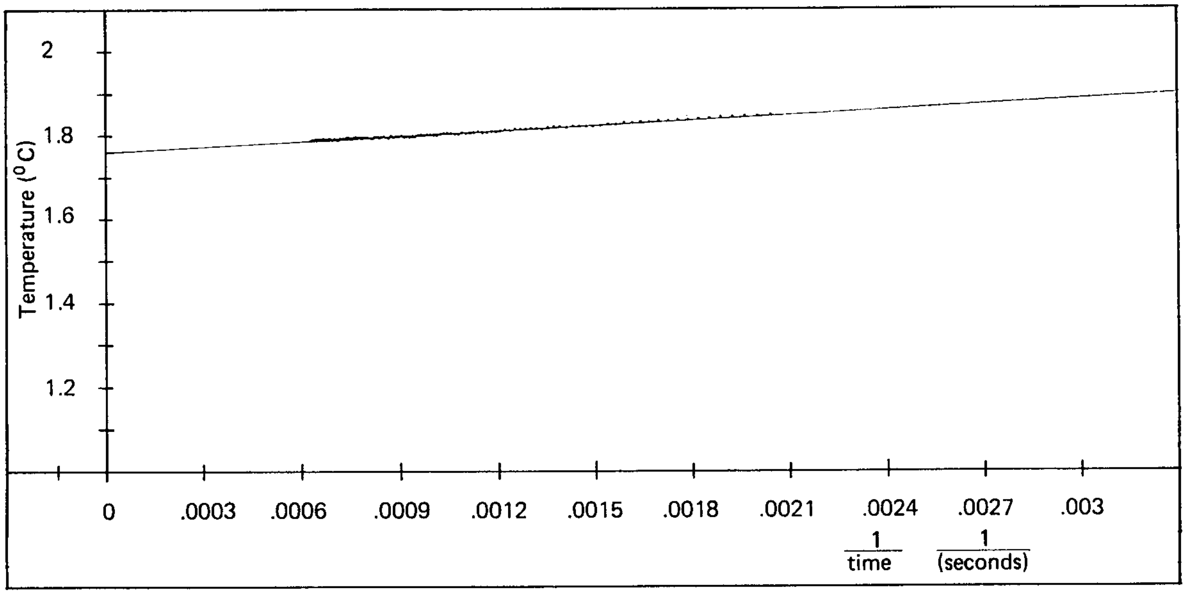

Fig. 7- Processed Measurement