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# The Temperature and Salinity Profile in CRP-2/2A, Victoria Land Basin, Antarctica

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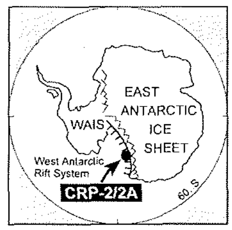
**Abstract** - In the northern part of McMurdo Sound (Ross Sea, Antarctica), drillhole CRP-2/2A targeted the western margin of the Victoria Land basin to investigate Neogene to Palaeogene climatic and tectonic history by obtaining continuous core and downhole logs. The background of the project and its detailed aims, methods used and results so far are summarized in Cape Roberts Science Team (1999). The CRP-2A drillhole extended to 625 mbsf (meters below seafloor) with an average of 95 % recovery of Oligocene to Quaternary sediments. Most of the downhole logging tools were run to the bottom of the hole. The first measurement after drilling operations was the temperature and salinity measurements, which were completed in two phases down to 166 mbsf and down to the bottom of the hole. Although an equilibrium temperature state had not been reached after drilling operations, the temperature profiles provide interesting and important data on formation temperature and fluid movement. The average overall temperature gradient is 24 K/km, somewhat lower than the temperature gradients found in the DVDP, MSSTS, and CIROS boreholes. Active permeable zones could be detected at least at two depths (150 and 580 mbsf) by falling temperatures and salinities, suggesting cold water influx. The driving forces for fluid movements detected by the anomalies in CRP-2 are still unknown.




## INTRODUCTION

### CAPE ROBERTS PROJECT

The main aims of the Cape Roberts Project are to document past variations in Antarctic ice cover and climate and to reconstruct the early uplift history of the nearby Transantarctic Mountains (TAM). The Cape Roberts boreholes CRP-1 (Cape Roberts Science Team 1998) and CRP-2/2A (Cape Roberts Science Team 1999) were drilled in a sedimentary basin just seaward of the edge of the present ice sheet, about 20 km offshore Cape Roberts, a small Cape *c.* 125 km NE of McMurdo, Ross Island. The time period assumed to have been drilled (10 Ma to more than 50 Ma) is of interest because present knowledge suggests it covers the time when Antarctica changed from an ice-free continent to an ice-covered continent. A detailed description of the geological setting is given by Cape Roberts Science Team (1998). Coring and downhole logging of the drillholes are prerequisites to reach the aims of the project.

The aim of this paper is to document and evaluate the temperature and salinity measurements carried out in CRP2/2A shortly after drilling operations. Drilling in Antarctica using the sea ice as a drilling platform is always a race against time. Due to the time and weather constraints, it was not possible to wait a reasonable time for temperature logging after drilling operations and repeated measurements were not possible. However, the measured temperature and salinity profiles provide important and interesting data on temperature gradient and fluid movement.

### DOWNHOLE LOGGING

A detailed description of the downhole logging tools used in CRP-2A and of the downhole logging techniques is given in the Initial Report on CRP-2/2A (Cape Roberts Science Team, 1999). The downhole logs provide a representative record of in situ physical properties of formations adjacent to the drillhole. A detailed description of the results of the standard downhole measurements is given by Bücker et al. (this volume).

Temperature measurements were made with a combined salinity/temperature tool (salct) with a Pt100 thermal resistor that records the mud temperature with a precision of 0.1 °C (Cape Roberts Science Team 1999). The same tool also records the electrical conductivity of the mud (1/mud R) with two adjacent electrodes. The drilling and mud circulation disturbs the natural temperature field. According to Bullard (1947), the time necessary for a drillhole to attain temperature equilibrium is at least as long as the time required for drilling. Due to the constraints mentioned above, the temperature measurements had to be made only hours after drilling operations. A continuous temperature log to detect fluid movement is the most commonly used in production logging, but the same principles can be used effectively in other open boreholes (Rider, 1996). Although the measured temperatures do not reflect true formation temperatures, temperature changes measured shortly after drilling completion may indicate fluid movement in the drillhole or in the formation, or changes in lithology.

## RESULTS

Mud temperature and resistivity measurements were completed in two phases. Phase one covered the depth interval from the seafloor to 166 mbsf and phase two the open (uncased) section of the borehole from 200 mbsf to the bottom of the hole at 624.15 mbsf. During phase one, the depth section from the seafloor down to 63 mbsf was measured inside the casing; during phase two, measurements were made through the drillstring in the section above 200 mbsf. The combined and spliced temperature profile of the two measurement phases is shown in Figure 1 together with a linear regression curve for the entire borehole section. The average temperature gradient from the seafloor to the bottom of the hole is 24 K/km with large local deviations. The highest temperature reading at 624.15 mbsf was 17.2 °C. Using this measurement method, temperatures below 0 °C are not recorded, but obviously the seafloor temperature and the water column close to the seafloor was below the freezing point.

At least two negative temperature anomalies are observed at 155 mbsf and at 580 mbsf. Both anomalies have an amplitude of more than 1 K with respect to the overall temperature gradient. The two temperature anomalies are different. The upper anomaly shows a rapid change in temperature and extends over about 20 m, whereas the lower anomaly extends over more than 50 m in depth (Fig. 1) and seems to be a combination of several (up to four) temperature anomalies. The temperature gradient below the lower anomaly at about 590 mbsf increases from 24 K/km to 50 K/km, approximately a factor of two.

The original unshifted and unspliced temperature profile is shown in figure 2, along with other physical properties. The top part of the temperature profile ("temp" in Fig. 2) from seafloor to 63 mbsf was measured inside

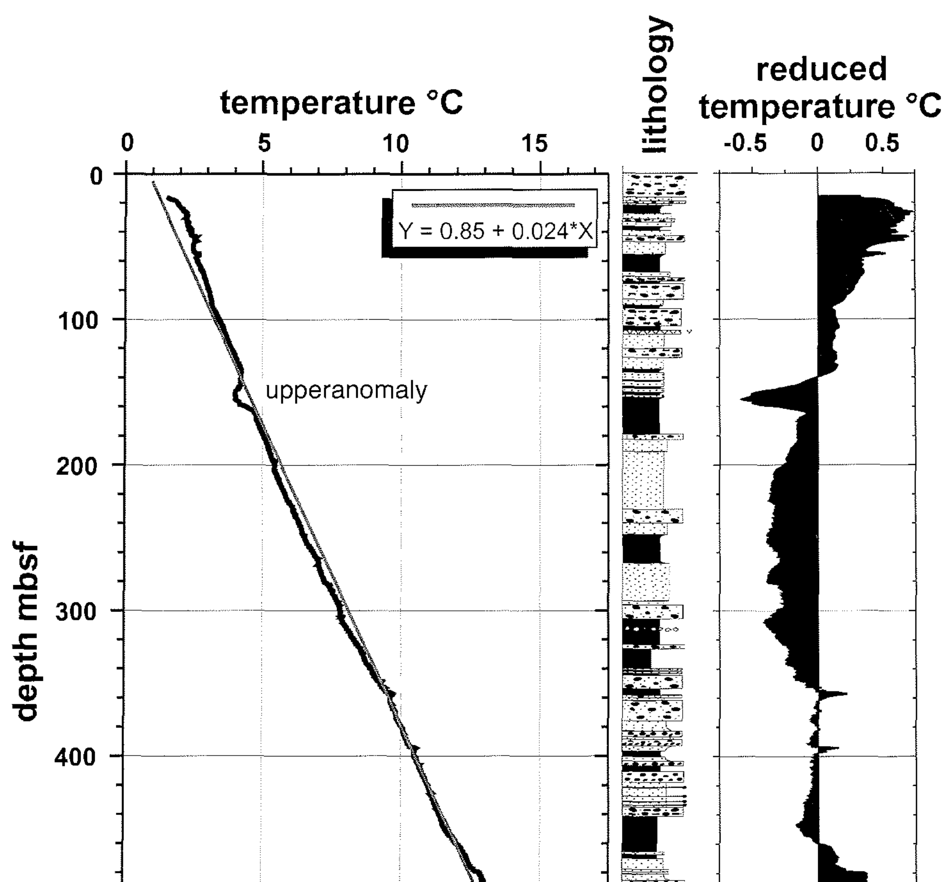



*Fig. 1* - Temperature profile of the CRP2/2A hole, spliced and shifted on the basis of the measurements during phases one and two. The regression line was calculated using all temperature data, yielding an overall temperature gradient of 24 K/km over the entire borehole. Two distinct temperature anomalies are observed at 150 mbsf and 580 mbsf. The right column shows the reduced temperature profile calculated using the average temperature regression line (temp = 0.85 °C + 0.024 °C/m · depth). A simplified lithology log is given between the two temperature logs.

the drillstring. At the top of the open borehole section, the temperature decreases sharply by 2 K. The temperature log from 63 – 165 mbsf is shifted lower by this amount. At 165 mbsf the profile shifts again about 2 K higher, continuing the gradient to about 500 mbsf. This shift is presumed to be caused by the thermal conductivity and insulation properties of the drillstring that prevents the mud column inside the drillstring from rapid cooling by fluid movement in the sediments. The temperature gradient from 200–500 mbsf is 26 K/km, in agreement with the

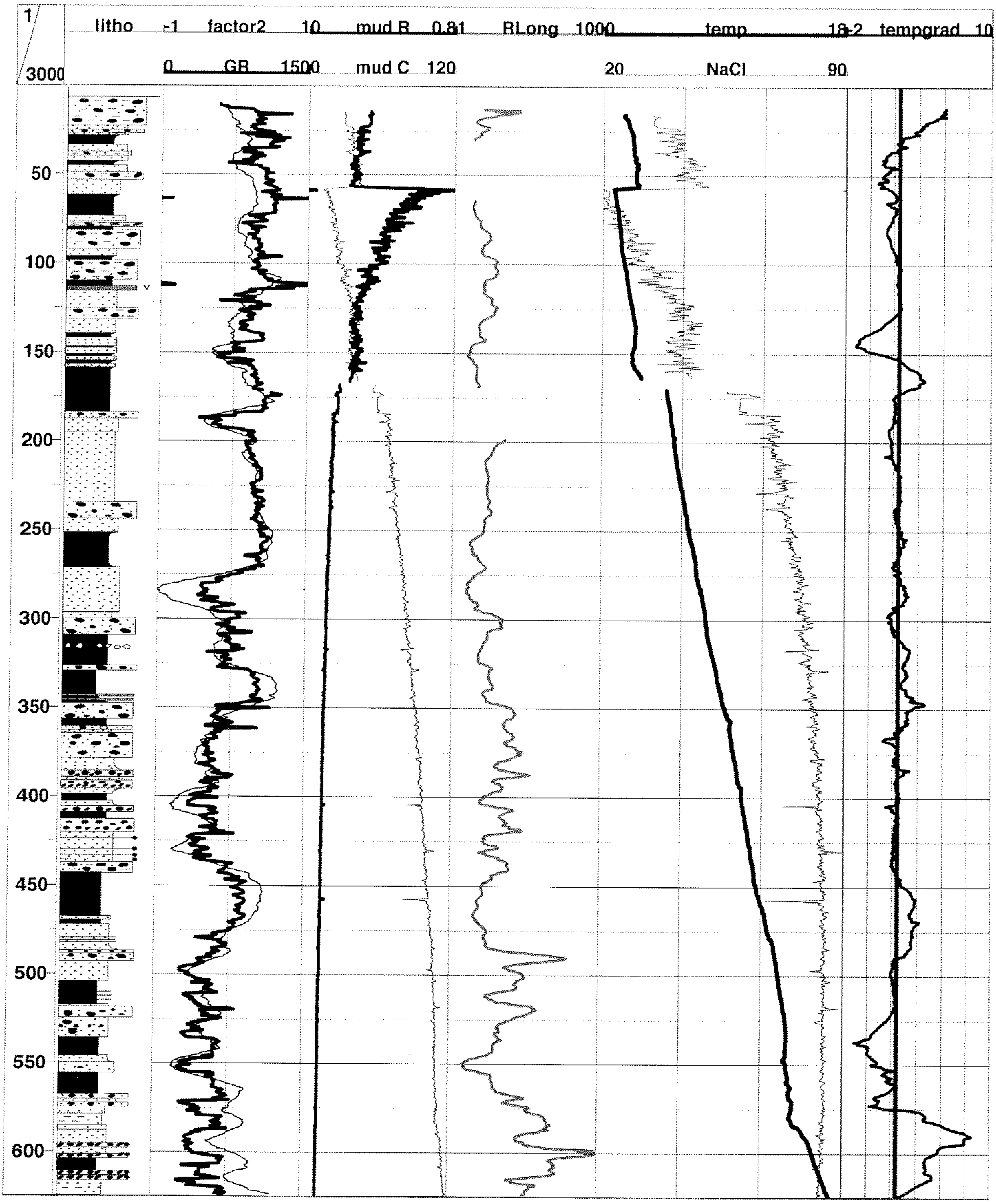



*Fig. 2* - Original temperature profile together with other physical properties. From left to right the columns show the following logs: litho: simplified lithology profile derived from core descriptions; factor2: factor2 log, as defined by Bücker et al. (this volume). This parameter is based on multivariate analysis and the log indicates changes in grain size: high factor2 values indicate fine-grained sediment, low values indicate coarse-grained; GR: gamma ray from 0 to 150 API; mud R: mud resistivity from 0 to 0.8 Ohm·m (logarithmic scale); mud C: mud conductivity from 0 to 120 mS/cm; Rlong: long-spaced formation resistivity from 1 to 100 Ohm·m (logarithmic scale); temp: temperature from 0 to 18 °C; NaCl: NaCl equivalent salt concentration in g/L; tempgrad: temperature gradient from –2 to 10 K/100 m, the average temperature gradient of 2.4 K/100 m is indicated by the gray, vertical line. To reduce noise, the temperature gradient was filtered by a moving average over 201 samples (20 m).

overall gradient of 24 K/km and the gradient from 63–165 mbsf. The calculated temperature gradient (tempgrad in the far right column in Fig. 2) clearly indicates temperature anomalies over short depth intervals. Besides these anomalies, the gradient shows only small variations around the average value of 2.4 K/100 m.

NaCl equivalent salinity concentrations S(z) in g/L (Fig. 2) were calculated based on the mud conductivity log (1/mud R(z), in mS/m), the temperature log (T(z)), and on resistivity charts (Schlumberger 1986), by using a formula after Kessels & Pusch (1990):

$$S(z) = 4 * \left(\frac{61.5}{T(z) + 21.5\ °C}\right) \frac{1}{\text{mud } R(z)} \qquad \text{(g/L)}$$

Conductivities of the seawater and the drilling mud were independently measured with logging tools (salct and aind) that were lowered through an hole in the ice at the drilling site, and by laboratory measurements on samples taken through the icehole and from the mud container. The results of these measurements are given in table 1. The values for the seawater salinity are all in close agreement with an average of 30 g/L NaCl equivalent. In contrast to the seawater, the mud shows a much higher conductivity, resulting in a NaCl equivalent concentration of more than 100 g/L. The NaCl log (Fig. 2) shows a steady increase over the entire borehole (besides the measurements inside of the drillstring) from seawater values of 20–30 g/L in the upper section to a constant value of 85 g/L in the lower section. The high value of 85 g/L is close to the pure mud value. As can be seen in the mud conductivity log (mud C in Fig. 2), as well as in the NaCl log, the temperature anomaly at 155 mbsf is accompanied by a decrease in salinity. The lower anomaly at 580 mbsf does not show a significant drop in salinity within the precision of the measurement. This decrease in salinity suggests influx of water with a lower electrical conductivity, possibly seawater or fresh water.

## DISCUSSION

A complete and continuous temperature profile and mud conductivity profile was recorded down to a depth of 624 mbsf in Antarctica for the first time. The average temperature gradient over the entire borehole section is 24 K/km, somewhat lower than those calculated from previous temperature measurements in the CIROS-1, MSSTS, and DVDP boreholes. Temperature gradients between 35 K/km and 41 K/km determined by point measurements have been reported for these boreholes (Decker 1974; Pruss et al. 1974; Decker et al. 1975; Bucher & Decker 1976; White 1989). All the Dry Valley Drilling Project holes on the Antarctic continent showed permafrost conditions with temperatures below 0 °C.

The lower temperature gradient at CRP-2 may be it is further from the active volcanoes at Mt. Erebus and Mt. Discovery than the other drillholes mentioned above, which still may influence the temperature field of the surrounding area. But also the fact that temperature equilibrium was not reached during the CRP-2 measurements may have an effect on the temperature gradient. However, a temperature gradient higher than 30 K/km would not be surprising, because of the active tectonic regime in the Victoria Land Basin.

Two temperature anomalies of different character were detected at 155 mbsf and at 580 mbsf. A typical geothermal gradient, which steadily increases downhole, may be disturbed by an inflow of formation fluid (flow into the borehole) or outflow of drilling mud (flow into the formation) (Rider 1996). Coarse-grained, porous and highly permeable sediments permit such fluid flow into or out of a formation. As can be inferred from the low values of the gamma ray and factor2 logs (Bücker et al., this volume; see caption Fig. 2), both of the major temperature anomalies in CRP-2 occur in or just below borehole sections with very coarse grained and loose sands. Major drilling problems and mud loss into the formation were recorded near 155 mbsf, indicating very permeable sediments. Low formation resistivities are also recorded (Rlong in Fig. 2) at both 155 and 580 mbsf, indicating high formation porosities. Brink et al. (this volume) calculated resistivity

*Tab. 1* - Conductivities of seawater and drilling mud.

| | conductivity measured | conductivity @ 20 °C (mS/cm) | resistivity (Ohmm) | NaCl (equ. g/l) |
|---|---|---|---|---|
| *downhole logging tools* | | | | |
| salct (@8°C) | 25 | 33 | 0.3 | 30 |
| aind (@0°C) | 22 | 37 | 0.27 | 35 |
| | | | | |
| *laboratory* | | | | |
| mud sample (@24°C) | 119 | 110 | 0.09 | 110 |
| seawater sample (@24°C) | 32 | 29 | 0.34 | 27 |

Seawater and mud conductivities measured by downhole logging tools in the seawater column through a hole in the ice and in the laboratory. ***Salct*** denotes the salinity and temperature logging tool and ***aind*** denotes the electrical induction tool. The mud sample was taken on 3 October 1998 from the mud container. The mud was prepared as follows: 1800 L seawater, 3 bags KCl, 2 tins of Pac R & Polymer, yielding a viscosity of vis 35 and a density of 1.07 g cm$^{-3}$). The seawater sample was taken through a hole in the ice in the video monitor hut. Laboratory measurements were carried out using a commercial conductivity device. The NaCl equivalent concentration was calculated using the formula of Kessels & Pusch (1990).

porosities of greater than 50 % at these depth sections. The lower temperature anomaly at 580 mbsf seems to be constrained between high resistivity beds at 490 mbsf and at 600 mbsf.

Normally, if there were a direct, continuous flow of warm formation water into the borehole, the temperature log would show a marked increase at the inflow point (Hill 1990). The reason for this is that the inflowing fluid is at formation temperature, which is higher than the mud temperature in newly drilled wells. However, the CRP drilling mud was heated to about 20 °C to prevent it from freezing in the supercooled saltwater column, which was below 0 °C. The small diameter of the borehole and the high mud circulation rates resulted in little loss of heat as the mud flowed downhole. Thus, a cool temperature anomaly would be expected to result from inflowing formation fluids.

However, in the same way as inflow produces temperature anomalies, outflow or loss of drilling fluid can have an effect on the temperature log (Hill, 1990). Typically, a cool temperature anomaly is encountered when cooler drilling fluid enters the formation. Because these temperature measurements could not be repeated however, the reason for the observed temperature anomalies in CRP-2 is still unclear. We cannot exclude the possibility that an existing aquifer system was stimulated by drilling, resulting in cold water inflow into the borehole.

The occurrence of gas hydrates can be excluded. There was no evidence for any gas hydrates in the cores, and gas hydrates would produce a positive anomaly in the temperature log.

## ACKNOWLEDGEMENTS

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