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Downhole Temperature, Radiogenic Heat Production, and Heat Flow from the CRP-3 Drillhole, Victoria Land Basin, Antarctica

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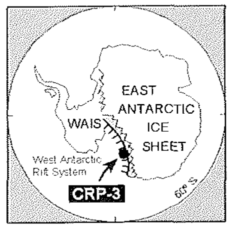

Abstract - Cape Roberts drillhole CRP-3 in the northern part of McMurdo Sound (Ross Sea, Antarctica) targeted the western margin of the Victoria Land basin to investigate Neogene to Palaeogene climatic and tectonic history by obtaining continuous core and downhole logs (Cape Roberts Science Team, 2000). The CRP-3 drillhole extended to 939.42 mbsf (meters below seafloor) at a water depth of 297 m. The first downhole measurements after drilling were the temperature and salinity logs. Both were measured at the beginning and at the end of each of the three logging phases. Although an equilibrium temperature state may not have been fully reached after drilling, the temperature and salinity profiles seem to be scarcely disturbed. The average overall temperature gradient calculated from all temperature measurements is 28.5 K/km; remarkably lower than the temperature gradients found in other boreholes in the western Ross Sea and the Transantarctic Mountains.

Anomalies in the salinity profiles at the beginning of each logging phase were no longer present at the end of the corresponding logging phase. This pattern indicates that drilling mud invaded the formation during drilling operations and flowed back into the borehole after drilling ceased. Thus, zones of temperature and salinity anomalies identify permeable zones in the formation and may be pathways for fluid flow.

Radiogenic heat production, calculated from the radionuclide contents, is relatively low, with average values between 0.5 and 1.0 $\mu W/m^3$. The highest values (up to 2 $\mu W/m^3$) were obtained for the lower part of the Beacon Sandstone below 855 mbsf. The heat flow component due to radiogenic heat production integrated over the entire borehole is 0.7 mW/m^2. Thermal conductivities range from 1.3 to 3 W/mK with an average value of 2.1 W/mK over the Tertiary section. Together with the average temperature gradient of 28.5 K/km this yields an average heat flow value of 60 mW/m^2.

INTRODUCTION

The main aims of the Cape Roberts Project are to document past variations in Antarctic ice cover and climate and to reconstruct the tectonic history of the nearby Transantarctic Mountains (TAM). A comprehensive overview of the project and a detailed description of the geological setting have been published by the Cape Roberts Science Team (1998, 1999, 2000). A cumulative stratigraphic thickness of 1500 m was drilled by the three CRP boreholes. CRP-3 cored 821 m of Lower Oligocene and possibly Upper Eocene sedimentary rocks and 116 m of the underlying Devonian sandstone (Cape Roberts Science Team, 2000). Drilling and coring was done in two phases: HQ-size 3" drill rod (6.1 cm core diameter) was used for coring the interval from 3 to 346 mbsf, followed by NQ-size 2" coring (4.5 cm core diameter) of the interval from 346 to 939 mbsf. Average core recovery was 95 %. The mid-Tertiary section consists primarily of sandstones and muddy sandstones, which are intercalated with conglomerate beds and less common sandy mudstones and diamictites (Cape Roberts Science Team, 2000).

It is possible that anomalous thermal conditions are associated with the crustal thinning and subsidence of the Ross Embayment and the Cenozoic uplift of the Transantarctic Mountains of up to 55 m/Ma (Blackman et al., 1987). Temperature logs exist for only a few drillholes in Antarctica, and all of the older measurements consist of discontinuous point measurements. An overview of existing downhole temperature data for this area of Antarctica is given in table 1, the locations of the drillholes are shown in figure 1. The Dry Valley Drilling Project (DVDP) drillholes have been described by Bucher & Decker (1976), Decker (1974, 1975), Decker et al. (1975), McGinnis et al. (1981), Mudrey et al. (1973), Pruss et al. (1974), and Treves & McKelvey (1974). Information about the MSSTS (McMurdo Sound Sediment and Tectonic Studies) drillhole (depth 220 mbsf) has been published by Sissons (1980), and

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Tab. 1 - Compilation of downhole temperature measurement results in the Transantarctic Mountains and Victoria Land Basin. The most reliable determinations are shown in boldface type. The temperature gradients of 24 and 28.5 K/km for the Cape Roberts boreholes are lower than those for all the other boreholes. The highest temperature gradients were determined for the DVDP boreholes 8, 10, 11 and 12, which are located in the Taylor Valley (see location map, Fig. 2). The offshore drillholes MSSTS-1, CIROS-1, and DVDP-15 at New Harbour show overall temperature gradients of about 35 K/km. The third column ("*temperature °C*") gives the temperature at the depth given in the second column. Large negative gradients at Don Juan Pond (DVDP 13) and at North Fork (DVDP 14) are interpreted as a result of fluid convection in the permafrost (Decker et al., 1975).

Location	Depth m(bsf)	Temperature °C	Gradient K/km	Depth range m	Lithology	Reference
DVDP-2, -3, McMurdo			30-33	40-180	volcanics, pyroclastics	Decker, 1974
DVDP-2, -3, McMurdo			**42**	180-270	volcanics, pyroclastics	Decker, 1974
DVDP-2, McMurdo	20	-16.1			volcanics, pyroclastics	Decker, 1974
DVDP-2, McMurdo	135	-12.9	28	20-135	volcanics, pyroclastics	Decker, 1974
DVDP-3, McMurdo	10	-16.9			volcanics, pyroclastics	Decker, 1974; Pruss et al., 1974
DVDP-3, McMurdo	270	-7.3			volcanics, pyroclastics	Decker, 1974; Pruss et al., 1974
DVDP-3, McMurdo			**36.3**	90-260	volcanics, pyroclastics	Decker et al., 1975
DVDP-4, Lake Vanda	70	22.1			basement	Decker, 1974; Pruss et al., 1974
DVDP-4, Lake Vanda	85	24			basement	Decker, 1974; Pruss et al., 1974
DVDP-6, Lake Vida	10	-25			basement	Decker, 1974; Pruss et al., 1974
DVDP-6, Lake Vida	305	-16	31	10-305	basement	Decker, 1974; Pruss et al., 1974
DVDP-8, New Harbor			50-80	30-135	glacial & marine sediments	Decker, 1974; Pruss et al., 1974
DVDP-8, New Harbor	10	-16.4			glacial & marine sediments	Decker, 1974; Pruss et al., 1974
DVDP-8, New Harbor	135	-8.7	62	10-135	glacial & marine sediments	Decker, 1974; Pruss et al., 1974
DVDP-8, New Harbor			63	30-135	glacial & marine sediments	Decker et al., 1975
DVDP-10, New Harbor	10	-16.6			glacial & marine sediments	Decker et al., 1975
DVDP-10, New Harbor	160	-6.9	76	10-160	glacial & marine sediments	Decker et al., 1975
DVDP-11, Com. Glacier	10	-18.7			clastic sediments	Decker et al., 1975
DVDP-11, Com. Glacier	300	-5.4	46	10-300	clastic sediments	Decker et al., 1975
DVDP-11, Com. Glacier			**47**	60-300	clastic sediments	Decker et al., 1975
DVDP-12, Lake Leon	10	-14.5			clastic sediments	Decker et al., 1975
DVDP-12, Lake Leon	180	-5.6	52	10-180	clastic sediments	Decker et al., 1975
DVDP-13, Don Juan Pond	10	-8.9			basement	Decker et al., 1975
DVDP-13, Don Juan Pond	75	-13.5	-70	10-75	basement	Decker et al., 1975
DVDP-14, North Fork	10	-9.6			basement	Decker et al., 1975
DVDP-14, North Fork	80	-14.4	-69	10-80	basement	Decker et al., 1975
DVDP-15, McMurdo Sound			35	10-60	glacigenic sediments	Bucher & Decker, 1976
MSSTS-1, Butter Point			35	20-220	glacigenic sediments	Sissons, 1980
CIROS-1, Butter Point	672	24			glacigenic sediments	White, 1989
CIROS-1, Butter Point			**35**	150-600	glacigenic sediments	White, 1989
CIROS-1, Butter Point			**40**	280-450	glacigenic sediments	White, 1989
CRP-2/2A, Cape Roberts	624	17	**24**	20-620	glacigenic sediments	Bücker et al., 2000
CRP-3, Cape Roberts	900	24	**28.5**	20-920	glacigenic sediments	this paper

investigations on drillhole CIROS-1, which reached a depth of 700 mbsf, have been described by Barrett (1987) and White (1989).

All temperature data besides the measurements in the Cape Roberts drillholes indicate temperature gradients greater than 30 K/km. In particular, the downhole measurements in the drillholes of the Dry Valley Drilling Project (DVDP) onshore and offshore of the Transantarctic Mountains show temperature gradients up 80 K/km for some depth intervals. Since the Transantarctic Mountains are relatively young, elevated temperature gradients and heat flow values would be expected. Blackman et al. (1987) found "minimum possible" heat flow values in the western Ross Sea of 66 to 73 mW/m^2, which are significantly higher than the continental mean of 57 mW/m^2 (Sclater et al., 1980). Other values in the area are similar (*i.e.* Della Vedova et al. 1992). Bucher and Decker (1975) give onshore heat flow values of 67 and 79 mW/m^2 at Ross Island (near McMurdo Station) and Lake Vanda (Transantarctic Mountains), respectively. These data are in agreement with other studies suggesting regionally high heat flow in the Western Ross Embayment because of crustal thinning during Cenozoic rifting (Cooper & Davey, 1985).

Our new geothermal studies in the Cape Roberts drillholes presented here will be used to examine the role of thermal conditions in determining the tectonic history of the Ross Embayment.

MEASUREMENTS AND RESULTS

DOWNHOLE TEMPERATURE AND MUD CONDUCTIVITY MEASUREMENTS

A detailed description of the downhole logging tools used in CRP-3 is given in the Initial Reports (Cape Roberts Science Team, 1999, 2000). Temperature measurements were made with a combined salinity/temperature tool at a sampling rate of 0.1 m. The accuracy of the temperature

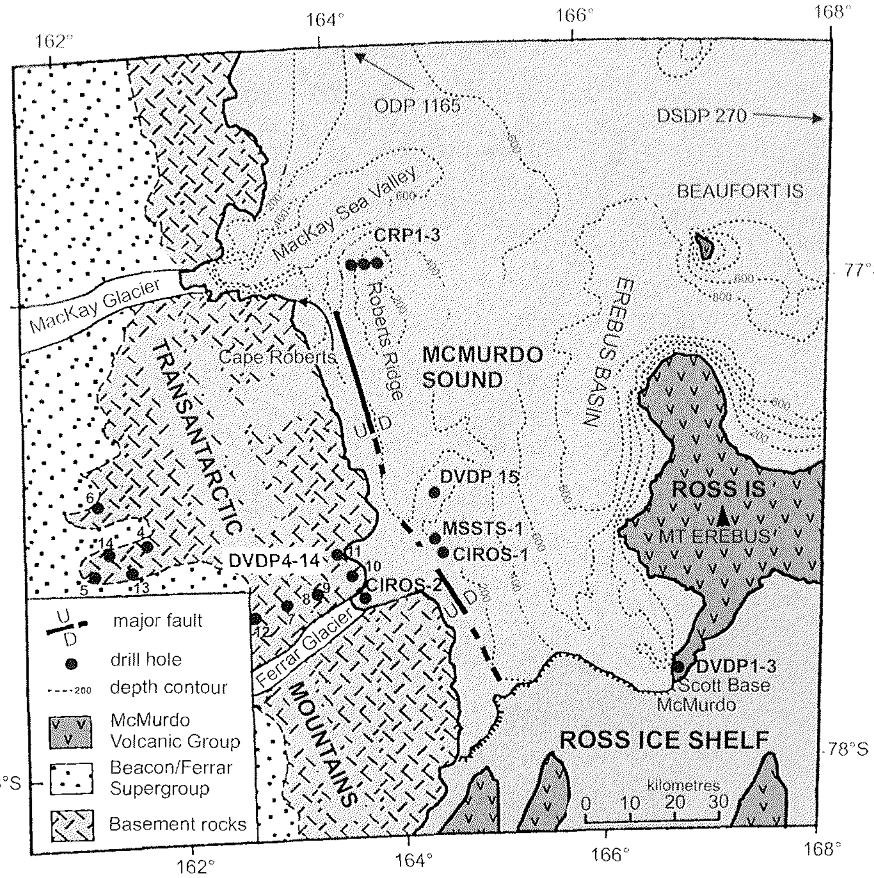


Fig. 1 - Location map of bedrock drillholes in McMurdo Sound and the adjacent Transantarctic Mountains (TAM). The major fault between the Victoria Land basin (VLB) and TAM is indicated; U = upthrown side, D = downthrown side. ODP drillhole 1165 from Leg 188 in Prydz Bay is the deepest drillhole in bedrock in Antarctica (999 m below sea floor (mbsf)); CRP-3 reached a depth of 939.42 mbsf in November 1999.
All Dry Valley Drilling Project (DVDP) drillholes are in the TAM except DVDP 15 in McMurdo Sound and DVDP 1 – 3, which are on Ross Island. The CRP drillholes are at the northern tip of Roberts Ridge. Figure modified from Barrett et al. (1986).

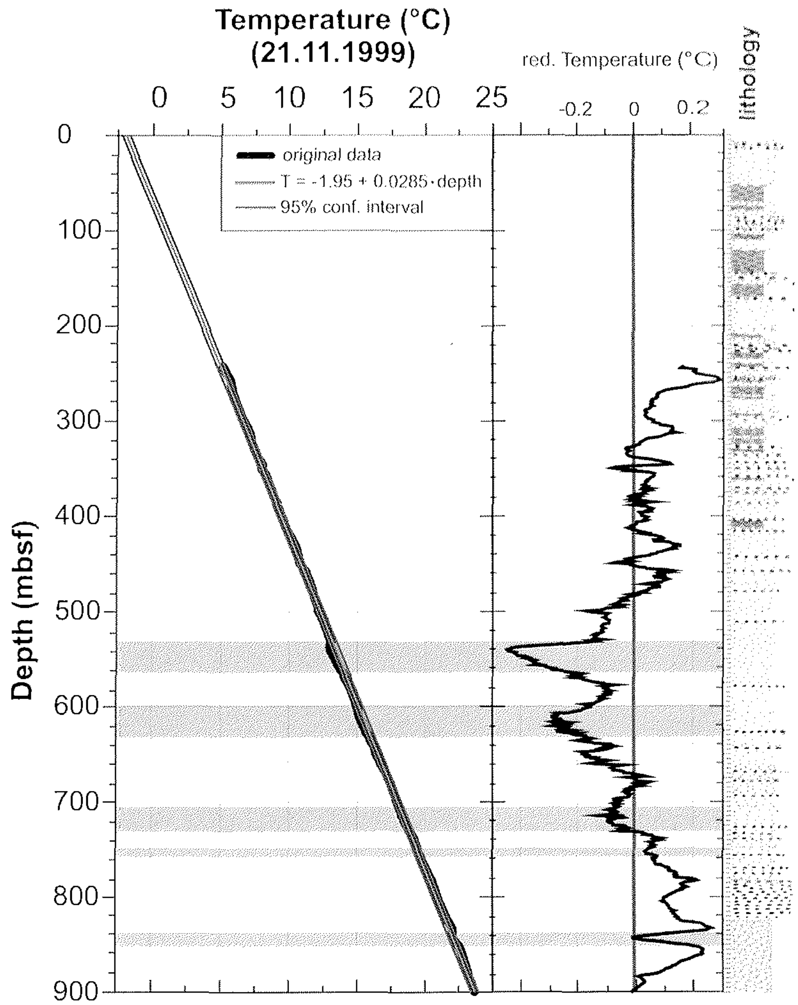
measurements is about 0.1 °C (Cape Roberts Science Team, 1999). The same tool also records the electrical conductivity (salinity) of the mud with two adjacent electrodes.

Downhole logs in CRP-3 were recorded in three phases of CRP-3 drilling. Due to time and weather constraints, it was not possible to wait a reasonable time for temperature equilibrium after drilling operations, and measurements had to be made only hours after drilling was concluded. Because of the cold conditions and to prevent freezing, the drilling mud was heated to 20 °C in the circulation system before it was pumped down-hole (Bücker et al., 2000). Downgoing temperature measurements were made at the beginning and at the end of each downhole-logging phase, with about two days between each pair of temperature logs. These sets of temperature measurements provide a unique chance to observe transient effects in mud conductivity and downhole temperatures.

Although the measured temperatures may not reflect undisturbed formation temperatures due to the constraints mentioned above, temperature and salinity changes measured shortly after drilling completion may indicate fluid flow and thus permeable zones (Rider, 2000; Serra, 1986). Since the circulating mud presumably cooled the drillhole, the calculated temperature gradients and heat flow values must be regarded as "possible minimum values".

An example of a continuous downhole temperature log taken at the end of the third logging phase after two days of logging operations is shown in figure 2. The temperature ranges from −1.95 °C at the sea floor (freezing point of sea water) to 23.7 °C at the bottom of the hole. The average temperature gradient over the entire measured section from 250 to 910 mbsf as calculated by linear regression is 28.5 K/km; deviations from this average are very small as indicated by the 95 % confidence interval shown in the figure. However, these small deviations from the linear temperature gradient are enlarged in the reduced temperature curve (right column in Fig. 2), produced by subtracting the linear temperature gradient from the measured temperature curve. The anomalies in this reduced temperature curve (marked with Grey shading) occur at the same depths as anomalies in previous logging runs, but the amplitudes are smaller than in those logs. These negative anomalies indicate an influx of cold fluids into the borehole. They can be detected mainly in the sand-dominated section of the borehole below 500 mbsf and occur in conjunction with lonestones and/or conglomerates. The Tertiary section of the borehole from 500 to 780 mbsf seems to be cooled, the reduced temperature curve shows mainly negative values, in contrast to the section above 500 mbsf. The dolerite thrust zone at about 800 mbsf and the underlying Beacon sandstone show mainly positive

Fig. 2 - Example of a downhole temperature log down to 920 mbsf from the end of the last logging phase on 21 November 1999, two days after drilling was concluded and after all other downhole measurements. The average overall temperature gradient is 28.5 K/km; the 95 % confidential interval is very small. The anomalies (marked by Grey shading) in the reduced temperature curve (right part of the figure) are at the same depths as in the previous logs, but with lower amplitudes. An additional anomaly can be seen at 845 mbsf in the Beacon Sandstone. The lower amplitudes in the temperature anomalies may be due to a rebound effect of the formation. For lithology (right column) see Barrett (this volume).



values for reduced temperature with one distinct negative anomaly at 840 mbsf.

All downhole measurements taken in CRP-3, together with the temperature log taken in CRP-2, are shown in figure 3 in the middle column. Temperature variations over the entire borehole are only minor and occur in a narrow band along the linear temperature gradient. Only the temperature log from CRP-2 shows a systematic offset of about 1 K to higher temperatures, possibly due to different borehole conditions and a different time between the end of drilling and the starting of logging operations. In CRP-2, the temperature was logged first in the last logging phase after drilling was concluded in December 1998 and is shown for comparison with the CRP-3 logs. The deviations of the downhole temperatures from the linear temperature gradient are enlarged in the reduced temperature curves (Fig. 3), produced by subtracting the average temperature gradient of 28.5 K/km. All reduced temperature curves show negative anomalies, which indicate cold fluid inflow into the borehole. Enlarged peaks can be seen at depths of 265 mbsf, 535 mbsf, 605 mbsf, 750 mbsf, and at 840 mbsf. In CRP-2, a large negative anomaly can be seen between 520 and 600 mbsf. This anomaly has already been described by Bücker et al. (2000). The temperature anomalies at 605 mbsf and 750 mbsf in CRP-3 are accompanied by anomalies in the mud conductivity. But these mud conductivity anomalies (which can be inverted to salinity anomalies) from the first measurements at the beginning of the logging phases are no longer present at the end of the corresponding logging phases. Unfortunately, there was no time to conduct any active fluid flow measurements or to take fluid samples at depth.

A closer look at the temperature profiles and their variation with time shows that for each logging phase, the first temperature log has lower temperatures than the second temperature log, which was run about two days later. The second temperature run is always warmer than the first one, confirming the argument that observed gradients are minima and negative thermal spikes are from mud influx. This occurs despite the fact that equilibrium temperatures for most of the borehole are < 20°C, indicating that mud passage through the –2°C water column cools it to near freezing (after having been heated at the surface). The difference between the temperature runs proves that equilibrium was not reached by the first

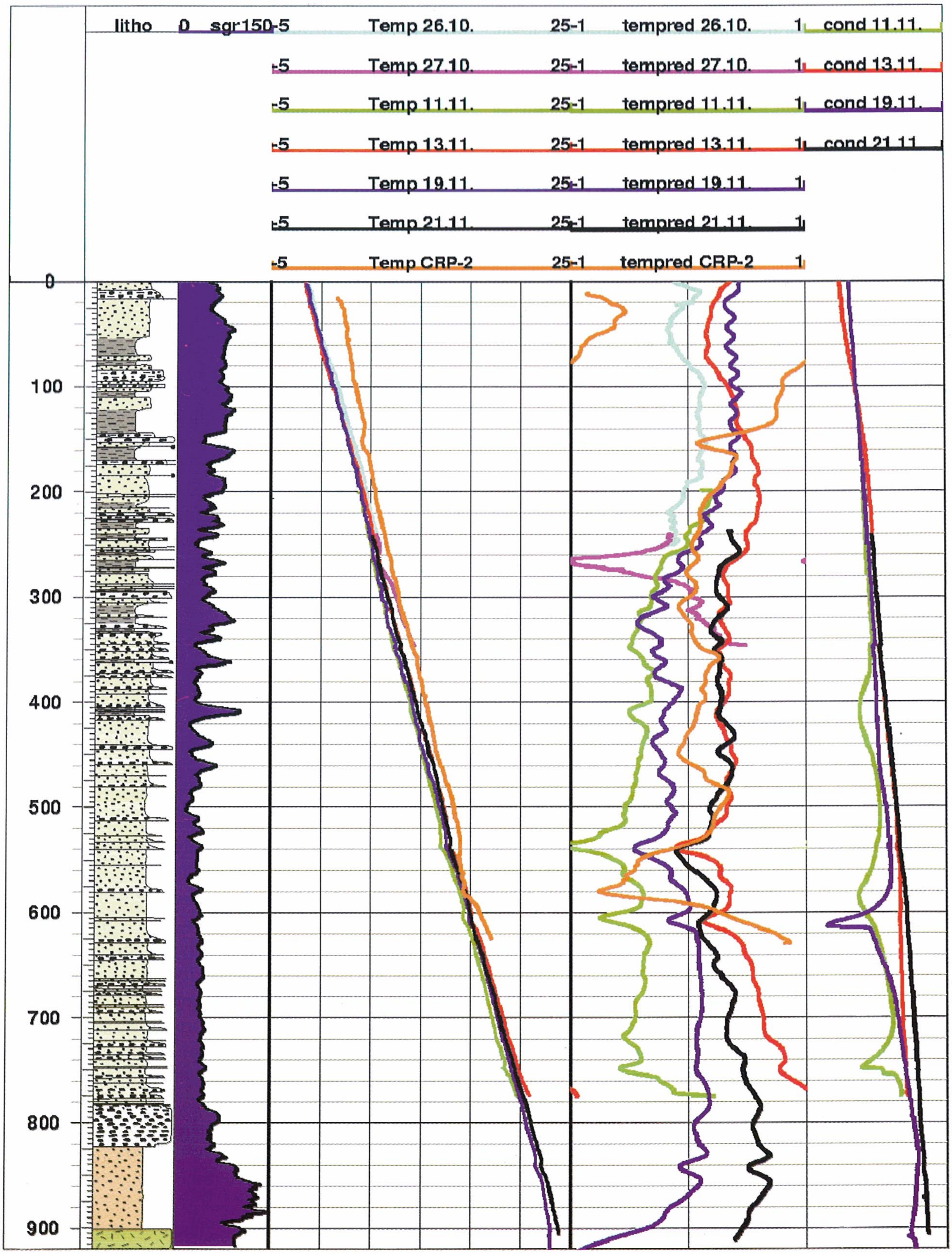


Fig. 3 - Downhole temperatures and salinities. From left to right: (i) lithology, (ii) gamma ray (0 – 150 API, see Bücker et al., this vol.), (iii) temperatures measured on the indicated dates (-5 to +25 °C), (iv) reduced temperatures (-1 to +1 °C) calculated from temperature curves with an average temperature ~~gradient~~ of 28.5 K/km (the reduced temperature curve of borehole CRP-2/2A was calculated using the thermal gradient of 24 K/km), and (v) mud conductivities (salinities) (50 – 150 mS/cm).

All reduced temperature curves show anomalies that indicate inflow of cold fluid into the borehole. Distinct peaks can be seen at 265 mbsf, 530 mbsf, 610 mbsf, 750 mbsf, and at 840 mbsf. The temperature anomalies at 605 mbsf and at 750 mbsf are accompanied by anomalies in the mud conductivity. But these mud conductivity (salinity) anomalies from the first measurements at the beginning of the logging phases are not present at the end of the corresponding logging phases.

run, but it may have been reached by the second run. Obviously temperature equilibrium is achieved many times faster in small-diameter holes such as the Cape Roberts boreholes than in large-diameter holes. The maximum difference between two corresponding temperature measurements is about 1 K. However, since the approach to temperature equilibrium is nonlinear, with decreasing temperature differences with time, it cannot be expected that the true formation temperature will be much higher than the logged temperatures. As a result, the temperature curves and temperature gradients presented here must be considered as minimum possible values. By taking into account the highest temperatures in CRP-3 as recorded on 13 Nov. 1999 (red curve in Fig. 3), a temperature gradient of 30 K/km can be estimated.

RADIOGENIC HEAT PRODUCTION

Radiogenic heat production is controlled by the decay of the radionuclides of potassium, thorium, and uranium. It can be determined by two different methods. The first method uses the spectral gamma ray measurements of the contents of potassium, thorium, and uranium (Bücker et al., this volume). Radiogenic heat production is then calculated using the following formula (Rybach, 1986):

$$A = 10^{-5} \cdot \rho \cdot (9.52 \cdot c_U + 2.56 \cdot c_{Th} + 3.48 \cdot c_K),$$

Where A is heat production in $\mu W/m^2$, ρ is rock density in kg/m^3, and c_U, c_{Th}, and c_K are the radioactive element concentrations in ppm for thorium and uranium, and in percent for potassium.

The second method simply uses the correlation between the measured gamma ray values and the heat production of Bücker & Rybach (1996):

$$A = 0.0158 \cdot (GR-0.8),$$

where GR is the gamma ray in API units. Although this formula was originally set up for hard rocks, it is also valid for the sediments drilled in CRP-3 with considerable reliability.

Since radiogenic heat production shows a close correlation to gamma ray, its depth pattern can be compared to the gamma ray curve shown in figure 4. Overall, a bimodal distribution of heat production values was observed with peaks at 0.5 and $1.0 \mu/Wm^3$. These values can be attributed to sandstones and mudstones, respectively. Diamictites and conglomerates show intermediate heat production values. The highest heat production was calculated for the lower part of the Beacon Sandstone below 855 mbsf with values greater than $2 \mu/Wm^2$, due to elevated thorium values (Bücker et al., this volume).

The depth integrated heat production rate gives the amount of heat produced by radioactive elements in the drilled sediments and is shown in figure 4. Integrating the radiogenic heat production over depth yields a value of $0.7 mW/m^2$, which is about 1 % of the measured surface heat flow (Bucher & Decker 1975; McGinnis et al., 1981). Thus, the radioactive heat production in the drilled sequences has no significant influence on heat flow.

THERMAL CONDUCTIVITY AND HEAT FLOW

Thermal conductivity was measured on core samples from the Tertiary section of drillhole CRP-3 with a high precision, noncontact method using an optical scanning device (Popov, 1997). The theoretical model for this kind of measurement is based on scanning a sample surface with a focused, mobile and continuously operated heat source in combination with infrared temperature sensors. For these measurements no polishing or sawing is necessary, and flat and cylindrical surfaces of the cores are acceptable. The measurements were calibrated against standards; replicate measurements were made on all samples. The relative error in thermal conductivity is less than 15%.

Thermal conductivities range from 1.3 to 3 W/mK with an average value of 2.1 W/mK over the Tertiary section of CRP-3 (Fig. 4). In the upper part of the borehole, where the lithology consists of sandstones, mudstones, diamictites, and conglomerates, a reasonable correlation between quartz content and thermal conductivity can be seen (Fig. 4, SiO_2 measurements by Sproveri et al., this volume). In the lower part of the borehole below 500 mbsf, where clean sandstones dominate the lithology, thermal conductivities show an excellent correlation with quartz content. Since quartz has a high thermal conductivity of 7 W/mK, it is evident that quartz controls the thermal conductivity in this depth range. The few non-correlating data points, with very high thermal conductivities up to 3 W/mK, can be attributed to high-density conglomerate sections. Despite these few high values, thermal conductivity is generally low below about 630 mbsf. This is remarkable because the sandstones below and above 630 mbsf show distinctly different sediment provenance (Bücker et al., this volume; Smellie, this volume).

Heat flow was then calculated by multiplying the average thermal gradient of 28.5 K/km with the results of thermal conductivity measurements (Fig. 4). Because of the linear relationship, heat flow shows the same trend as thermal conductivity. The average heat flow is 60 mW/m^2, insignificantly higher than the average continental heat flow of 57 mW/m^2 (Sclater et al., 1980). However, two sections with elevated heat flow values can be observed. The first is

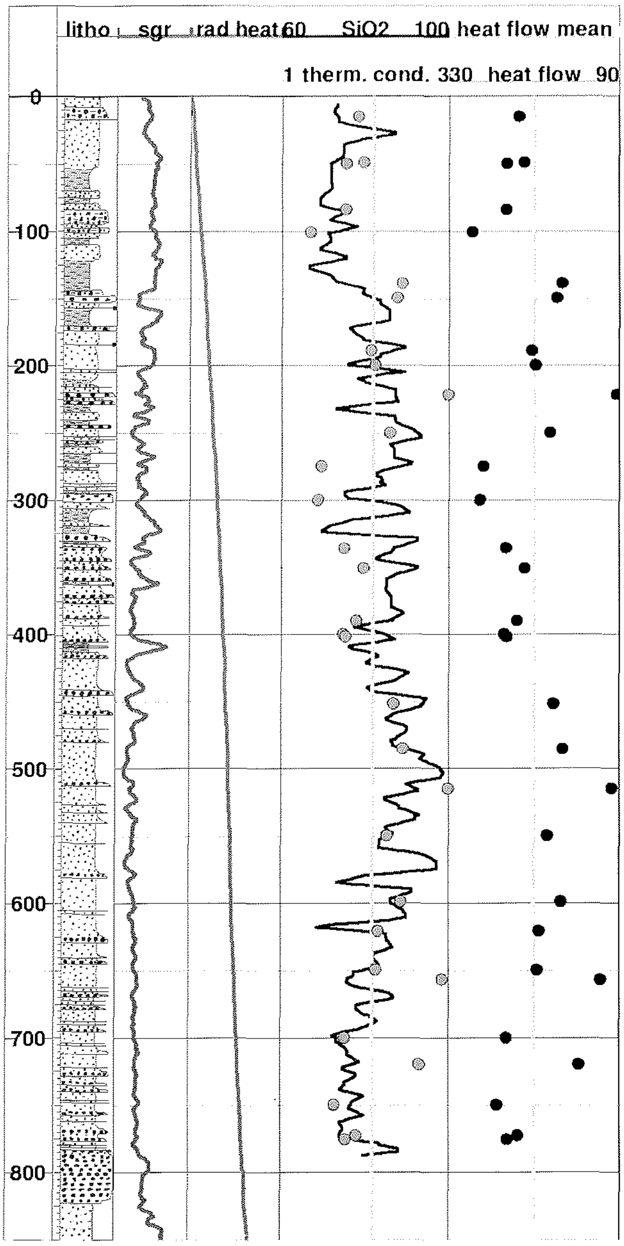


Fig. 4 - Thermal properties of the rocks in the CRP-3 drillhole. From left to right: (i) lithology, (ii) gamma ray log (0 – 150 API), (iii) log of integrated radiogenic heat production (0 – 1 mW/m^2), (iv) thermal conductivity measured on core samples (dots) (scale from 1 to 3 W/mK, mean thermal conductivity is shown as vertical grey line at 2.1 W/mK) and SiO_2 content taken at 1 m core intervals (scale 60 – 100 %, data from Sproveri et al., this volume), (v) heat flow (dots) (scale 30 – 60 mW/m^2) calculated from thermal conductivity and a constant thermal gradient of 28.5 K/km, mean heat flow is shown as vertical Grey line at 60 W/mK. The integrated radiogenic heat production was calculated from the uranium, thorium, and potassium contents. The highest heat production values were calculated for the lower part of the Beacon sandstone below 855 mbsf. The integrated radiogenic heat production is 0.7 mW/m^2, which is about 1 % of the measured surface heat flow (Bucher & Decker 1975).
The mean heat flow for the CRP-3 drillhole of 60 mW/m^2 is indicated as a vertical grey line.

at about 130-250 mbsf and the second is below about 500 mbsf, with peak values up to 90 mW/m^2. These peak values may be attributed to conglomerates and maybe also affected by local convection effects.

DISCUSSION AND CONCLUSIONS

Downhole temperature logs were run during three logging phases in drillhole CRP-3 in order to obtain reliable data about the true formation temperature and temperature gradient. Altogether, six downhole logs in CRP-3 and one downhole log in CRP-2 provide the basis for the interpretation of the temperature field at the Cape Roberts drill sites. However, due to Antarctic constraints it was not possible to wait for temperature equilibrium after drilling ceased. Usually the first log was run shortly after the drill bit was taken out of the drillhole. The second temperature log of one logging phase was taken at the end of the phase, about two days later. The advantage of having several downhole temperature logs taken at different times after drilling allows a differentiated interpretation of the logs and an estimate of transient effects.

An example of a downhole temperature log on 21 November 1999 is given in figure 2. Although the log was taken only a few hours after drilling was stopped, it shows a very linear trend with depth. The 95 % confidential interval of the linear regression is very small, indicating only small temperature fluctuations. Anomalies from the linear regression can be seen in the reduced temperature curve in figure 2. The zones of negative values for reduced temperature marked in figure 2 indicate permeable zones from which cold mud flowed back from the formation into the borehole. All other downhole temperature logs show behavior similar to this one. Even the temperature anomalies, which are enlarged in the reduced temperature curves, occur at the same depth in each temperature log. These negative temperature anomalies indicate inflow of cold fluid into the borehole and mark the locations of permeable zones. However, on the basis of an individual temperature curve it cannot be decided whether these anomalies indicate an aquifer or if mud is simply flowing back from the formation into the borehole.

In general, the temperature curve run first during a logging phase shows about 1 K lower temperatures than the temperature curve taken at the end of a logging phase. This can be attributed to a temperature rebound effect. The temperature field, which was disturbed by the drilling activities, is rebounding to the true undisturbed formation temperature. This temperature rebound is not a linear process. Most temperature changes occur during a short time after the disturbance of the temperature field ceases. Presumably there will be only minor temperature changes after the second log run of one logging phase.

The effects of the small diameter of the borehole (3" in the lower part, see Cape Roberts Science Team, 2000) are rapid formation rebound and rapid cooling of mud while traversing the water column. However, due to the temperature rebound effects, the temperature curves must be taken as minimum possible values. The same is true for the calculated temperature gradients. A careful look at the reduced temperature curve in figure 3 shows that the gradient also changes slightly with time. The temperature curve logged on 13 November 1999 shows the highest temperature measured in CRP-3 (Fig. 3) at that time. The temperature gradient calculated on the basis of this temperature curve is 30 K/km, which can be estimated as an upper value for the temperature gradient at the Cape Roberts drill site CRP-3. However, at the Cape Roberts drillsites CRP-2/2A, a temperature gradient of 24 K/km was estimated Bücker et al., 2000). This lower temperature gradient may be result of fluid flow, which might give a bigger effect in the more unconsolidated sediments with higher porosities in the upper sections of CRP-2/2A.

The mud conductivities (Fig. 3), which were measured with the same probe as the downhole temperatures, are directly related to the mud salinity. KCl was added to the mud to prevent it from freezing, the borehole from collapsing, and the clays from swelling, resulting in a mud conductivity of 130 mS/cm, whereas the seawater salinity was about 30 mS/cm. The temperature anomalies at 610 mbsf and 750 mbsf are accompanied by negative anomalies in the mud conductivity indicating lowered salinity. But these mud conductivity (salinity) anomalies from the first measurements at the beginning of a logging phase are no longer present at the end of the corresponding logging phase. This observation clearly indicates that the observed temperature anomalies are not related to an aquifer but to backflow of mud invaded the formation during drilling. However, temperature and salinity anomalies indicate permeable zones in the drilled formation. The temperature anomalies at 260 and 530 mbsf also correlate with fracture zones determined by Wilson et al. (this volume).

A heat flow profile was calculated using thermal conductivity measurements made on core samples and an average thermal gradient of 28.5 K/km (Fig. 4). The resulting average heat flow of about 60 mW/m^2 is only slightly higher than the average continental heat flow. If the estimated higher thermal gradient of 30 K/km is used, a higher average heat flow of 63 mW/m^2 is obtained. These heat flow values are considerably lower than all the other published values mentioned above. The rifting event of the Transantarctic Mountains about 40 m.y. ago would have caused increased heat flow and thermal gradient at the CRP borehole sites over the entire borehole compared to normal continental crust. Obviously this is not the case, which may result in the interpretation that the tectonic activity ceased a long time ago.

As the Cape Roberts drillholes are at the northern end of Roberts Ridge, which is truncated by the Mackay Sea Valley, the measured relatively low temperature gradient and thus low heat flow values at the Cape Roberts sites may be a result of ice that flowed through the Mckay Sea Valley during periods of more extensive glaciation. During the last glacial maximum, the entire thermal gradient would have been offset to much lower temperatures, and subsequent warming acts like a heat spike propagating downward from the seafloor and taking thousands of years to reach 500-1000 m depth. The observed linear thermal gradient indicates that a new equilibrium temperature profile has been established and thermal memory of the cooling event has been lost.

The topographic location of the Cape Roberts drillholes and the lithologic contrast of crystalline rocks in the Transantarctic Mountains and sedimentary rocks in the Victoria Land Basin may also have an effect on the measured heat flow values. Calculations by Delisle (pers. comm.) indicate that this effect is small: only 3 mW/m^2, which would have to be added to the heat flow value given above.

In summary, the heat flow estimates given here for the Cape Roberts drillsites, based on repeated downhole temperature and thermal conductivity measurements on samples, are lower than expected. But they confirm the estimates by Smellie (this vol.) regarding timing of the uplift of the Transantarctic Mountains and subsidence of the Victoria Land basin. Blackman et al. (1987) has already pointed out that the thermal conditions play an important role in the tectonic history of the region. However, we still need more information on the temperature field and it must be recognized that we are still at the beginning of Antarctic geothermal exploration.

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