Radwaste

Thermal Studies at Pinawa, Manitoba

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Introduction

Lewis (1979 a, b) has reported on initial temperature logs of three boreholes at Pinawa, WN-1, -2 and -4. Since those reports were prepared WN-2 and WN-4 have been logged twice (on 12.10.79 and 07.05.80). The log of October 1979 in WN-4 was at 3m intervals, and is the only detailed log of that hole. Unfortunately WN-1 was unavailable for logging on both occasions. It is interesting to note the reason for the unavailability of WN-1 on 07.05.80. - the hole had been blocked near the surface during an attempt to repair a perforation in the casing. Lewis (1979 a) had pointed out that water was flowing down the hole from near the surface, after making a careful interpretation of the temperature logs. It is hoped that this hole will be logged with the micrologger system in the Spring of 1981, as it will be useful to have information on the thermal effect of blocking off the downward water flow.

In addition to the temperature logs over 200 measurements of thermal conductivity, density and porosity have been made on core samples from WN-4 alone. Sixteen conductivity, density, porosity, heat generation and mineralogical determinations have also been performed on core samples from WN-1 and WN-2. These latter data (except heat generation) and most of the WN-4 data are presented in Drury (1980).

The purpose of logging temperatures down the boreholes is to detect water flow. Lewis (1979b) has given a description of the thermal effects of direct water flow within boreholes, and Lewis and Beck (1977) discussed the effects of sub-horizontal regional water flow in fractures. Mansure and Reiter (1979) described the effects of vertical groundwater flow in the bulk porosity on temperature gradients observed in a borehole. The study of hydrogeological patterns in plutons is of primary importance for the Radwaste programme, as possible pathways for radionuclide migration in the event of a postburial disruptive failure must be predictable.

Temperature logs

As this study of the thermal regime in a pluton requires the calculation of vertical heat flow, it is necessary to correct downhole lengths in the dipping boreholes to true vertical depths. In this report all depths will be given as true vertical depth, followed by the downhole length in parentheses. The method of obtaining downhole temperature data, and the associated accuracies, has been described by Judge (1980).

Lewis (1979 a, b) presented data obtained from the early logs of WN-1 and WN-4. The logs of 12.10.79 and 07.05.80 of WN-4, and a log of WN-2 temperatures with depth are shown in Fig. 1. As noted by Lewis (1979b) a large volume fracture zone occurs between 435 (460) and 460 (480) m depth. In the later logs of WN-4, e.g. 12.10.79, the form of the temperature disturbance around this zone has changed from that initially observed by Lewis (1979b), to become a smoothly varying temperature anomaly with a sudden change in gradient at 440 (465) m. The temperature gradient below the fracture zone is lower than that above in all logs of WN-4.

The successive logs of WN-4 show that the rock surrounding the hole is cooling as temperatures return towards equilibrium. In the lower part of the hole measured temperatures are the same, within the limits of resolution, in the logs of 12.10.79 and 07.05.80. However, above the fracture zone the latest log reveals noticeably lower temperatures below approximately 100 (102)m. Temperature gradients are equal in the two logs between 150 (155) m and the fracture zone, and are the same as the gradient observed in WN-1 (Fig. 2).

All the logs show a temperature minimum and gradient reversal, at a depth of approximately 50m for WN-2 (Fig. 1) and 60-70m for WN-4 and WN-1. The minimum is best defined for WN-2.

Between 150 (156) and 430 (453)m, the gradient measured in WN-4 on 07.05.80 is 14.4 mKm^{-1}, with a surface temperature intercept of 3.96°C. Below the fracture zone, between 470 (497) and 810 (902)m the same log gives a gradient of 12.4 mKm^{-1}, with a temperature intercept of 5.08°C.

The temperature log in WN-2 can be extrapolated below the bottom of the hole. This is the dashed line in Fig. 1. The gradient is the same as in WN-4 in this section, and the extrapolated temperature in WN-2 is the same as the observed temperature in WN-4 at the bottom of the step in the log of WN-4.

Physical properties of core samples

Judge (1980) has described the laboratory measurement techniques for determining thermal conductivity, density and effective porosity of core samples. Fig. 3 shows the variation of these parameters with depth for a large suite of samples taken at approximately 8m intervals from the entire length of WN-4. In some cases two adjacent discs, of different thickness, were measured. Between about 50m and 90m there is a zone of tonalites, characterised by lower thermal conductivities and higher densities than the granites above and below, both reflecting a higher proportion of mafic minerals. Below the tonalite zone, conductivity and density are quite uniform, with means of $3.44 \pm 0.19\ Wm^{-1}K^{-1}$ and $2.63 \pm 0.05\ Mgm^{-3}$ respectively. The samples with low conductivity and higher density at 485 (513)m are from a narrow band of amphibolite, about 1m wide.

Porosity increases slightly with depth from approximately 0.2 - 0.3% at the top of the basement to 0.5 - 0.6% at the bottom of the hole. The lithology changes at approximately 695 (755)m from pink granites above to grey granites below. Detailed mineralogical analyses have been done for 16 samples from WN-1 and WN-2 and 17 samples from WN-4, to sample the full depth of the study zone (see Drury, 1980). There appears to be no major difference mineralogically between the pink and grey granites. However there is some suggestion in Fig. 3 that below the transition zone conductivity decreases and porosity increases. The mean conductivities of the pink and grey granites are 3.44 $\pm$ 0.20 and 3.36 $\pm$ 0.08 $Wm^{-1}K^{-1}$ respectively.

Interpretation

Lewis (1979 a) interpreted the temperature measurements in WN-1 as indicating water flow down the borehole. The water entered the borehole at a depth of approximately 15m and flowed down to depths between 399 (418) and 432 (454)m. The thermal signatures of such downward flow is seen clearly in Fig. 2. Water starts to flow out of WN-1 into a broad zone starting at approximately 385 (403)m. Increased water flow out of the hole at depths of 430 (452)m and 446 (469)m is indicated by sharp gradient changes. In WN-4 water is flowing down from near the surface (as indicated by the equality of temperatures in WN-1 and WN-4, Fig. 2) and leaving the hole in a narrow zone starting at approximately 430 (453)m. The log of 12.10.79 shows that flow out of WN-4 has ceased at a depth of 440 (464)m (Fig. 2). In May of 1980 the log of WN-4 shows a lower temperature minimum and lower temperatures down to the fracture zone (Figs. 1, 2). Temperatures in the two logs (12.10.79 and 07.05.80) of WN-4 begin to diverge at about 60 (62)m, suggesting an inflow at about that depth of near-surface water. Such water will be cooler in May than in October. The apparent broadening of the zone of discharge in WN-4 in the log of 07.05.80 (Fig. 2) is probably a reflection only of the greater spacing of measurement points.

The log of WN-2 (Fig. 1) shows temperatures quite different from those at the same depths in WN-1 and WN-4. The minimum temperature in WN-2 is lower and at a lesser depth, and the gradient reversal more pronounced. The logs of WN-2 and WN-4 cross at 22 (23)m and 83 (86)m. Water at a higher temperature than the minimum temperature of WN-2 is, therefore, entering WN-1 and WN-4 above 22m. Such water flow down the hole accounts for both the higher minimum temperature and less pronounced gradient reversal seen in WN-1 and WN-4. No water flow is indicated in WN-2.

The change in gradient in WN-4 below the fracture zone cannot be explained by the downhole water flow above it. The effect of such downward flow would be either to reduce, or to maintain, with a constant temperature reduction, the gradient in the flow zone. However, the mean gradient in the flow zone is about 16% higher than the gradient below. The gradient change at the fracture zone is clearly not related to any change in mean conductivity (Fig. 3). This is confirmed by Fig. 4, which is a Bullard plot. Temperature is plotted as a function of integrated vertical thermal resistance (thermal depth). If gradient variations arise from a change in conductivity such a plot will still yield a straight line, the slope of which is a measure of the constant vertical conductive heat flow in the rock surrounding the hole. It is clear from Fig. 4 that the conductive heat flow is higher above the fracture zone than below it. The Bullard method of calculating vertical heat flow yields the following:

interval 320-420m (335-442m):

heat flow 46.1 $\pm$ 0.01 mWm^{-2}

interval 470-816m (496-910m)

heat flow 42.1 $\pm$ 0.05 mWm^{-2}

Mair (1979) recorded seismic reflection profiles in the region of the boreholes and located a reflector, dipping at about 45-50° to the west, at the depth of the fracture zone. If warm water from a greater depth were flowing up an inclined fracture it would provide an additional source of heat to the rock above. Conductive heat flow would then be higher above the dipping fracture. Lewis and Beck (1977) have observed a similar phenomenon, in which cool water flowing down a dipping fracture was invoked to explain regional variations of heat flow. They showed that, for a simple model, if the heat lost (or gained) by a vertical column of rock were equal to the heat gained (lost) by the water flowing across it, the difference in heat flow is given by:

$$\left| Q_u - Q_l \right| = f\ c\ G \sin\theta \qquad (1)$$

where c is the thermal capacity of the water per unit mass, G the normal gradient, θ the angle of dip of the flow plane, f the water flow rate, and Q_u and Q_l the conductive heat flows above and below the flow plane.

Taking the gradient below the fracture zone, 12.4 mKm^{-1}, to be the "normal" gradient and the dip angle to be 48°, then a difference in heat flow of 4 mWm^{-2} implies a water flow rate of ≈ 1 $mgs^{-1}m^{-1}$.

A quantitative estimate of the velocity of water flowing directly down WN-4 can also be made, using an equation developed by Ramey (1962) and discussed by Mansure and Reiter (1979):

$$T = T_o + Gz + \{ \exp(-z/A) - 1 \} AG \qquad (2)$$

where T is the observed temperature, G the normal gradient, T_o the temperature at the point of entry of the fluid into the borehole, z the vertical distance from the point of entry, and A is a measure of the rate of heat transfer between the flowing fluid and the rock around the borehole. A is proportional to u, the velocity of fluid up or down the borehole.

Assuming that the water enters the borehole at a depth of 20m, at which the temperature is 5.7°C, and that the normal gradient above the fracture zone is 14.4 mKm^{-1}, an estimate of A can be made by taking the temperature at 400m (9.8°C on 12.10.79) and substituting in equation 2. This gives A $\simeq$ 100, which implies a flow velocity of approximately 4 mms^{-1} (Mansure and Reiter, 1979), or a flow rate down the hole of approximately $2 \times 10^{-5}\ m^3s^{-1}$.

Some smaller scale anomalies in the logs of WN-4 show that water may also be flowing in the borehole below the fracture zone. For example, water appears to be entering the hole at 555 (592) m, flowing down and leaving at three levels: 670 (726)m, 697 (758)m and 713 (778)m. These true depths correspond to thermal depths, calculated for the log of 12.10.79., of 149, 182, 189 and 194 m^2KW^{-1} respectively. Anomalies are seen in the Bullard plot (Fig. 4) at these thermal depths.

Heat flow and heat generation

T.J. Lewis (Geothermal Service of Canada, Pacific Geoscience Centre) has measured the heat production of core samples from WN-1 and WN-2. Measurements on samples from WN-4, to extend the depth range, are in progress. Lewis (1974) has described the measurement technique. Very simply, the uranium, thorium and radioactive potassium contents of core samples are determined by γ-ray spectrometry, and the heat production A in μWm^{-3} is obtained from the expression:

$$A = (0.0963U + 0.0264Th + 0.0358K).\ \rho \qquad (3)$$

where U and Th are in ppm, K is % and ρ is the density in Mgm^{-3}.

The mean heat production of 12 granites is $5.28 \pm 1.50 \mu\ Wm^{-3}$, and of 2 tonalites $1.72 \mu\ Wm^{-3}$ (Lewis, 1980, personal communication).

The Pinawa boreholes are in the Superior Province of the Canadian Shield. It has long been recognized that a linear relationship between heat flow Q and heat generation A exists over large areas known as heat flow provinces. The relationship is:

$$Q = Q_o + A\ d \qquad (4)$$

where Q is the observed heat flow, and Q_o the "reduced" heat flow. The constant d has the dimensions of length and is always less than crustal thickness. Physically, d represents the distribution of heat producing sources in the crust and Q_o represents the heat flow from beneath the layer of radiogenic heat production. For the Superior Province Jessop and Lewis (1978) found values of Q_o and d of 21 mWm^{-2} and 14 km respectively, for heat flow data that were uncorrected for Pleistocene climatic changes. Taking the heat flow below the fracture zone in WN-4 as representing true local conductive heat flow, i.e. 42 mWm^{-2}, it is seen that the heat flow and heat generation data do not fit the relationship (equation 4) for the Superior Province. A heat flow of 42 mWm^{-2} would be expected if surface heat generation were $1.5 \mu\ Wm^{-3}$. In other words, the surface heat generation is apparently too high, by a factor of almost four, to explain the site heat flow. Jessop and Lewis (1978) reported a similar phenomenon elsewhere in the Superior Province. Heat generation at their English River heat flow site was higher than expected. The site was close to the Indian Lake batholith, a shallow (2-3 km), potassium-rich body. Jessop and Lewis (1978) suggested that the batholith represents a remnant of a thin (2-4 km) Archean surface layer having relatively high heat production. It is possible that the body from which the borehole core samples were taken reflects a similar condition at Pinawa. The maximum thickness of the granite layer of high heat generation can be estimated. Taking Q_o as 21 mWm^{-2} a crustal heat flow Q_c of 21 mWm^{-2} is postulated at the site. If the heat generation of the granite layer is A_g and of the rest of the crust zero, the thickness of the granite layer is Q_c/A_g, or approximately 4 km. If the effective heat generation of the rest of the crust is 1 μWm^{-3}, a value typical of borehole sample measurements from the Superior Province (Jessop and Lewis, 1978), the thickness of the granite layer would be approximately 1.5 km.

The tonalites, however, have a heat production that is close to that expected for the Superior Province for a heat flow of 42 mWm^{-2}. Hence the tonalite layer may represent an erosional surface of the original Archean crust, with the granitic batholith being considerably younger. Age dating of samples, and detailed gravity and seismic surveys to delineate the batholith should be undertaken.

Summary

Thermal studies in three of the boreholes at Pinawa indicate that:

1. water is flowing down WN-1 and WN-4 from near the surface to the fracture zone at approximately 440m.
2. there is no water flow in WN-2.
3. regional water flow up a dipping fracture zone provides an additional source of heat to the formation above.
4. A reliable heat flow for Pinawa is 42.1 $\pm$ 0.05 mWm^{-2}, uncorrected for Pleistocene glaciation effects.

5. The granite layer of high heat generation is probably thin, not more than 4 km thick, and possibly only approximately 1.5 km thick.

Acknowledgement

Determinations of physical properties of the core samples were made by D.V. Sharma.

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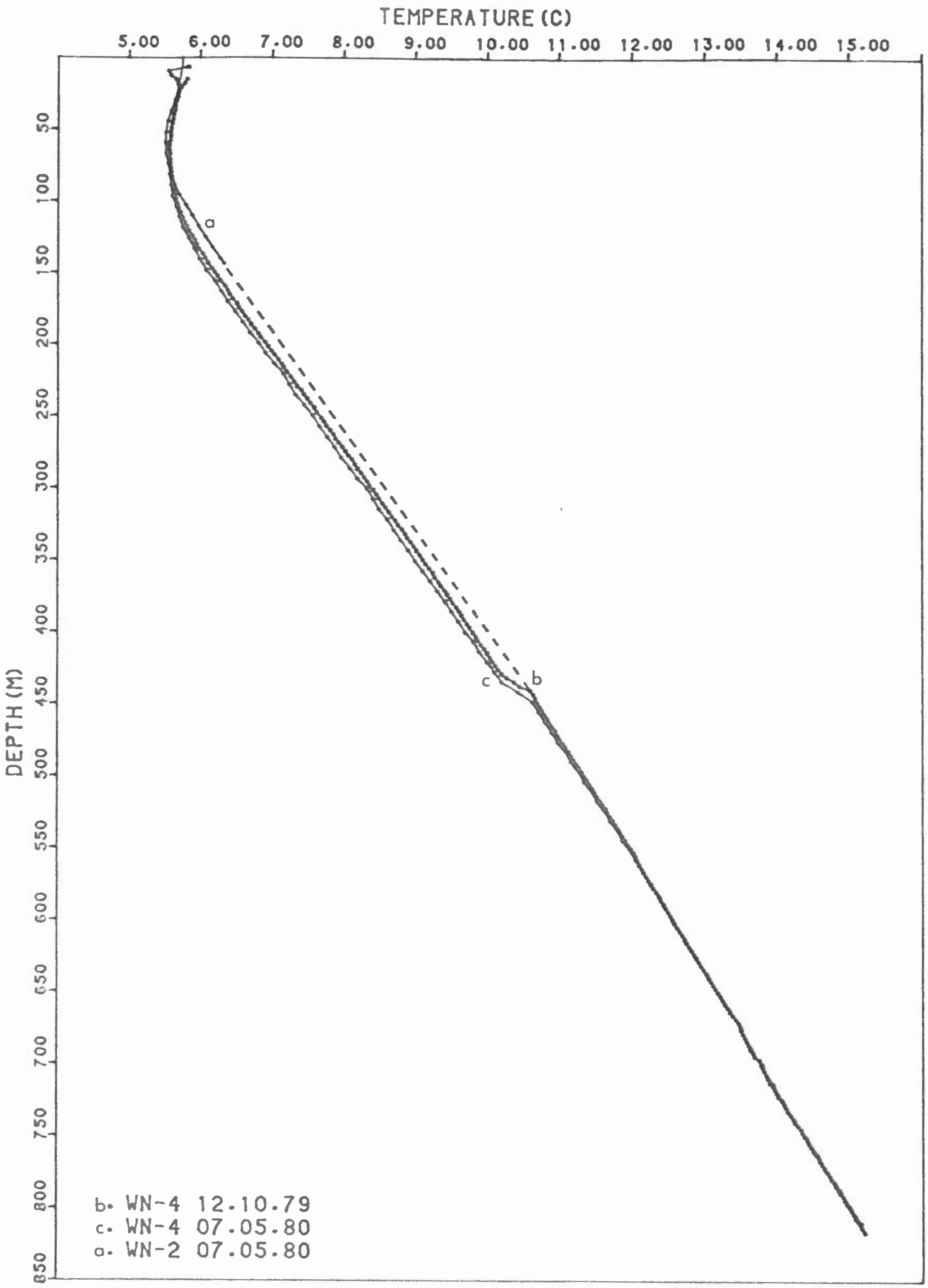

Fig. 1 Temperature logs of WN-2 and WN-4

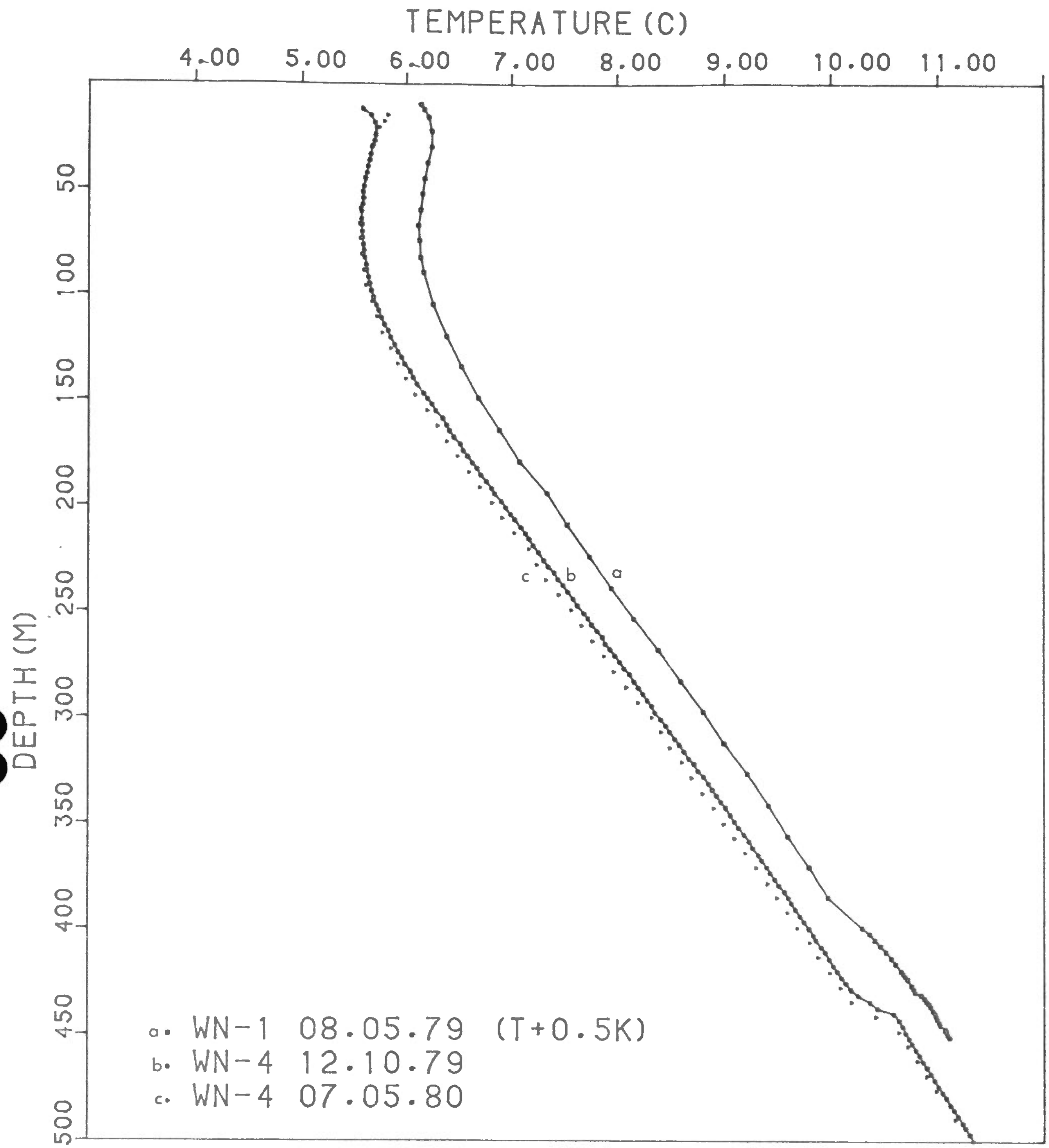

Fig. 2 Upper part of WN-4 temperature logs with log of WN-1. In the latter, temperatures have been offset by 0.5K for clarity.

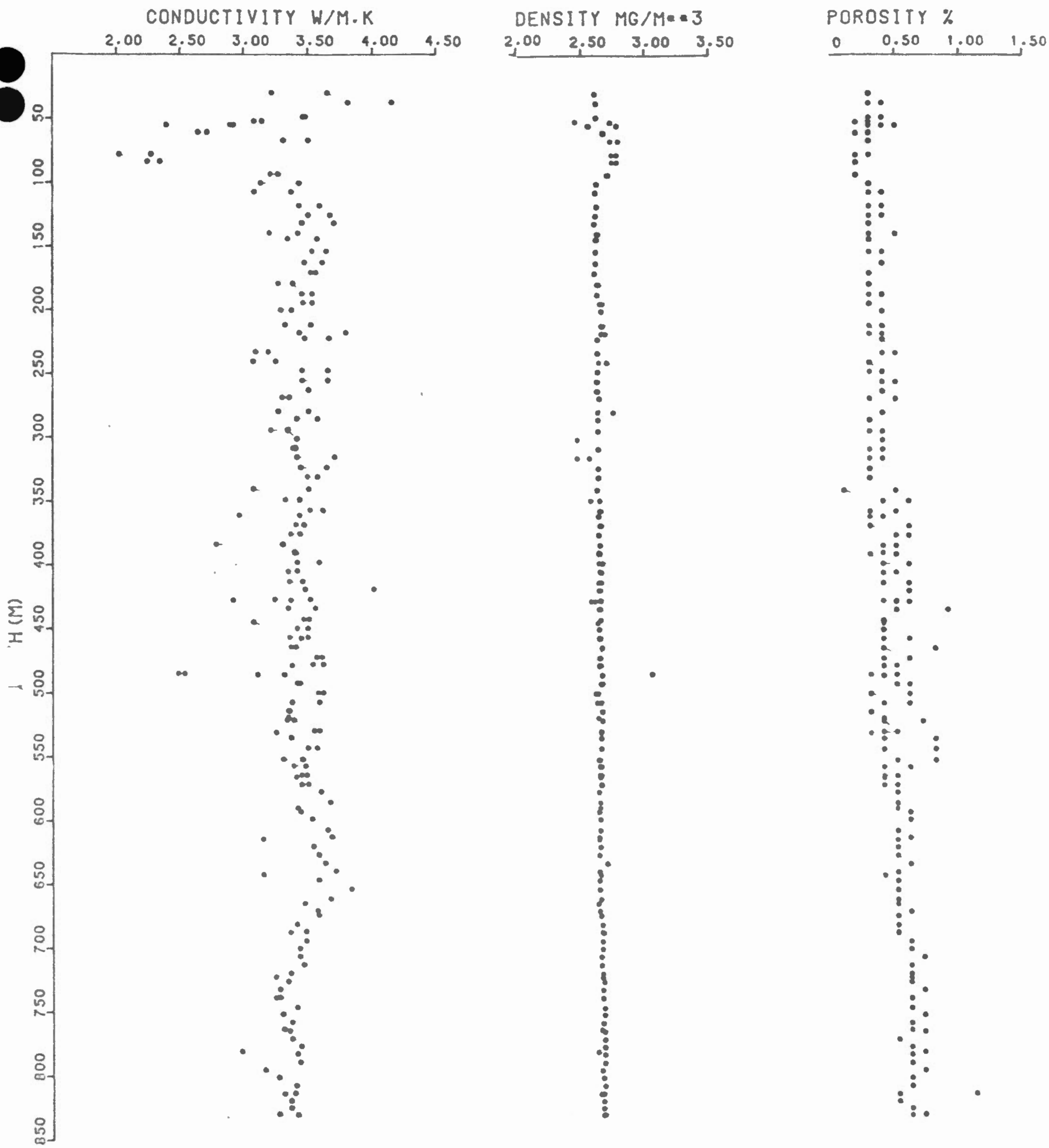

Fig. 3 Variation with depth of thermal conductivity, density and porosity in WN-4.

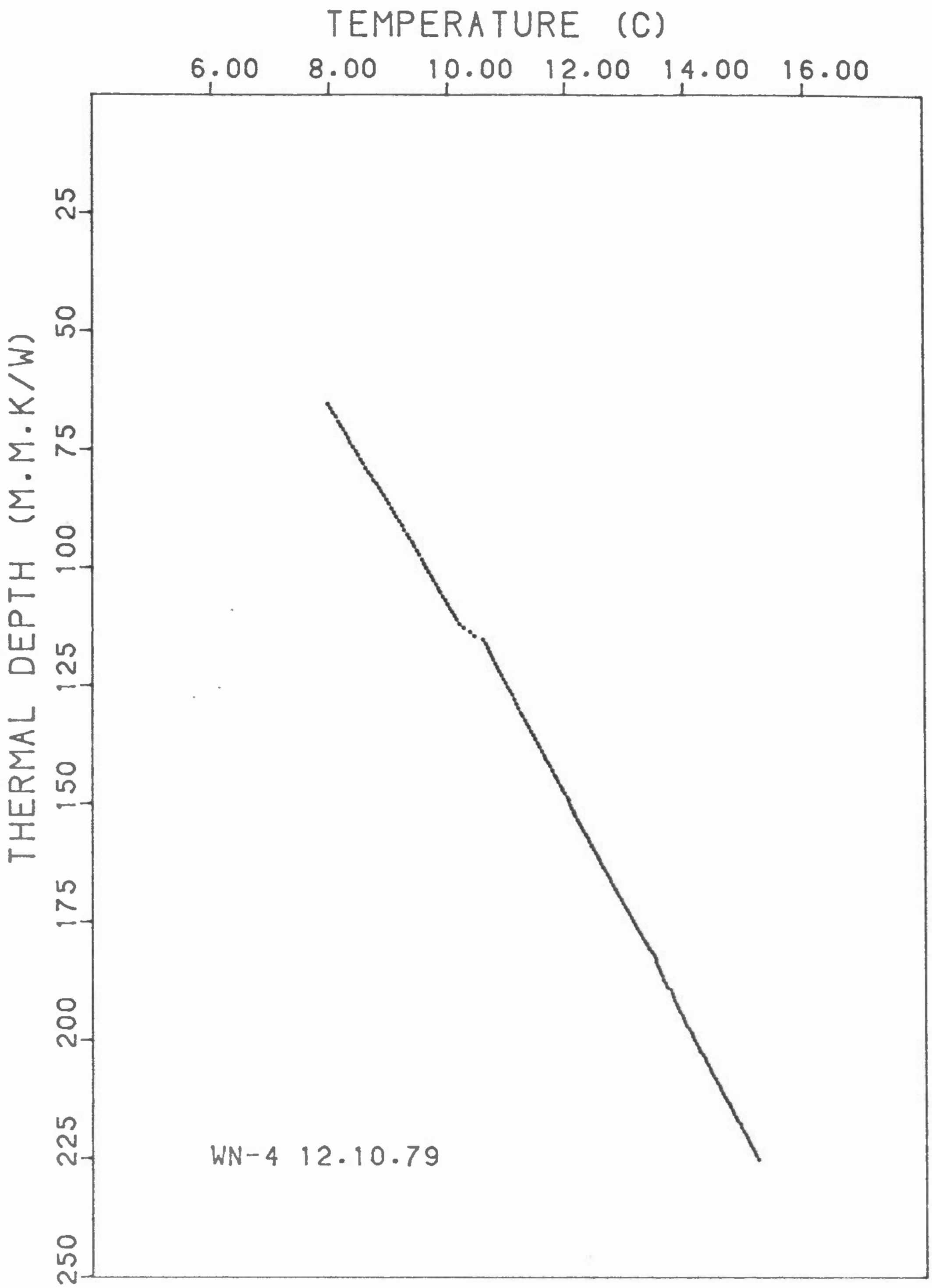

Fig. 4 Bullard plot of temperature log data of 12.10.79 for WN-4.