Geothermal logging of URL boreholes, 1981

Malcolm J. Drury

Internal Report 82 - 2

Geothermal Studies Group

Division of Seismology and Geothermal Studies

Earth Physics Branch

Energy, Mines and Resources Canada

1982

In 1981 five boreholes were drilled to varying depths at the proposed underground research laboratory site in the Lac du Bonnet batholith, Manitoba. Early results of geothermal logging of boreholes URL-1 were presented by Drury and Tomsons (1981). Since that report was distributed all URL holes have been logged at least once with the portable logging system described by Judge (1980). Holes URL-3 and URL-4 intersected wide fracture zones at shallow depths. Cavities had apparently formed in the fractures, and it was not possible to lower the thermistor probe below the fractures. Those holes have, therefore, been abandoned, at least for the present, for geothermal logging purposes. All holes were drilled into bedrock that, according to surface electrical surveys (Paterson and Watson, 1981), was uniformly highly resistive, with no indication of subsurface faults or fracture zones.

Geothermal logging permits the detection of water flow within boreholes and along fractures (e.g. Drury and Lewis, 1982), and can also be used to identify passive fractures, i.e. those in which there is normally no water flow, but which accept relatively warm fluid during drilling (Drury and Jessop, 1981). Time variations in an observed thermal anomaly provide useful information on the cause of that anomaly, so geothermal logs are repeated, whenever possible on well-defined schedules.

This report presents data from URl-1, -2 and -5, all of which have been logged at least three times. Interpretations are made: these can be summarised briefly as indicating that water is flowing either between or along fractures that are intersected by all three boreholes. As in previous reports, depths are given as true vertical depth and downhole length in parenthesis.

URL-1

Data from four logs are displayed in Fig. 1. Drury and Tomsons (1981) concluded, from analysis of the first three logs taken 3, 9 and 32 days after the end of drilling, that there was no water flow within the hole, nor was there any regional flow along fracture zones. An anomaly centred on 111m (115m) was ascribed to a passive fracture. By the time of the fourth log, 150 days after the end of drilling, the amplitude of this anomaly had decayed substantially (Fig. 1). The amplitude at this time is consistent with the estimate of the strength of the heat source, 0.1 μKms^{-1}, that produced it given by Drury and Tomsons (1981). This suggests that the amount of heat passed into the fracture was approximately 0.7 MJm^{-2}, assuming that the density and heat capacity of the rock into which the hole is drilled are 2.64 Mgm^{-3} and 950 Jkg^{-1} K^{-1} respectively and that its thermal diffusivity is 1.3 - 1.4 mm^2 s^{-1} (Jessop et al., 1981; Drury and Jessop, 1981). If it is further assumed that Q, the rate of heat input, was constant during the elapsed drilling time, i.e. the time between the drill bit encountering the fracture and the end of drilling (approximately 33 days in this case), the rate of heat input is estimated to be approximately 0.25 Wm^{-2}. The rate of heat input depends on several factors, but primarily on the ease of penetration of the fluid into the fracture (Drury and Jessop, 1981). Q is, therefore, a rough indication of the hydraulic conductivity of the fracture.

It was noted by Drury and Tomsons (1981) that there was no pronounced anomaly in the first three logs to coincide with the fracture zone at 312m (325m) that was detected during drilling. In the fourth log, however, a temperature anomaly at that depth is apparent. There is a sharp increase in thermal gradient over a very short vertical interval, above which temperatures are lower than those predicted by extrapolating upwards the temperature field immediately below 312m. Such an anomaly indicates the flow of water out of the borehole (e.g. Drury and Lewis, 1982). Curvature in the gradient above 312m means that the temperature offset above that depth cannot be uniquely defined. The maximum offset is approximately 0.15K. At 180m (186m) there is a sharp decrease in thermal gradient over a few metres, below which temperatures are lower by a maximum of approximately 0.15K, than those predicted by extrapolation downwards of the temperature field above 180m. This anomaly indicates the inflow of water from a fracture at 180m; the water flows down the hole and leaves at 312m. The flow rate can be estimated if the normal thermal gradient is known (Drury and Lewis, 1982). Taking the gradient between 312m and 340m (354m) as the normal one, 10.9 mKm^{-1}, gives an estimate of the flow rate of approximately 2×10^{-5} m^3 s^{-1}. Within the depth range of this downward flow, other anomalies indicate the efflux of water at 222m (230m), and influx of water at 250m (260m). At 178m there is an abrupt increase in gradient, seen in both the first and fourth logs, which indicates an outflow of water. There is no indication above 178m of the inflow depth; the water appears to be flowing from near the surface.

With the exception of the thermal anomaly at 312m, none of the anomalies between 180m and that depth coincide with mapped fractures (J. Dugal, unpublished data). The passive fracture at 111m (115m) occurs in a zone of fractures, and in a zone of pinkish-grey to grey granite, compared with grey granite below 150m (J. Dugal, unpublished data). R. Coles (pers. comm.) has suggested that the transition from grey to pink granite in core taken from borehole WN-4, some 15 km to the south of URL-1, may reflect increasing oxidation of magnetite to hematite, caused by groundwater circulation. It is reasonable to suppose that the same explanation holds for the observation of a zone of pink granites from the surface to approximately 150m in URL-1. There is also a narrow zone of pink granites at approximately 312-317m (325-331m), which suggests that the granite around the fracture zone at 312m has been altered by the effects of groundwater. A zone of pinkish-grey granite extends from approximately 202m to 220m (210 - 230m) (J. Dugal, unpublished data); the bottom of this zone coincides with one of the postulated depths of efflux of water from the borehole. There is, therefore, evidence that there is a fracture at that depth, although none is mapped.

There is also a gradient change at 312m. In the lower 30m of the zone of downhole water flow between 180m and 312m, the gradient is 13.1 mKm^{-1}. It is reasonable to assume that this represents the equilibrium gradient that would exist if there were no water flow down the hole (Drury and Lewis, 1982). In the 30m section immediately below 312m the gradient is 10.9 mKm^{-1}, i.e. the gradient increases by approximately 20% immediately above 312m. The change in gradient is shown more clearly in Fig. 2, which is a plot of temperature reduced by subtracting a gradient of 10.9 mKm^{-1}. The abrupt gradient changes at 180m and 312m show up clearly in Fig. 2. Gradual gradient changes below 350m probably reflect variations in conductivity and the non-equilibrium nature of the temperature field. Seismic reflection surveys indicate a dipping fracture zone at this depth in the vicinity of both URL-1 and URL-5 (A.G. Green, pers. comm., 1982). The zone, or zones, appear to dip down to the east at approximately 10-15°. The gradient change at 312m could be accounted for by regional water flow up this fracture zone, as is postulated for an anomaly in WN-4 (Drury and Lewis, 1982). The preliminary lithology log (J. Dugal, unpublished data) gives no indication that there is likely to be a difference in conductivity above and below the fracture zone. Assuming that the conductivity of the granite is 3.4 $Wm^{-1} K^{-1}$ (Drury, 1981), the vertical heat flux above and below the fracture zone is estimated to be 44 mWm^{-2} and 37 mWm^{-2} respectively. This allows an estimate of the flow rate to be made (Drury and Lewis, 1982). Assuming that the fracture plane dips at 15° to the horizontal, the flow rate is estimated to be 0.6 $gs^{-1} m^{-1}$, if the flow has persisted for thousands of years (Lewis and Beck, 1977). This rate is approximately double the postulated rate of flow up the fracture zone intersected at 400 - 450m by WN-4 (Drury and Lewis, 1982). Water flow up the fracture at 312m seen in URL-1 could account for the localised discoloration of the granite.

<u>URL-5</u>

URL-5 was started approximately 200m to the south-east of URL-1. As the hole is close to the dipping fracture zone postulated by A.G. Green, results from the hole will be discussed before those from URL-2.

Data from three logs, run 2, 11 and 56 days after the end of drilling, are displayed in Fig. 3. Prominent spike-like temperature anomalies are seen at depths of 100m (103m) and 252m (260m) on all three logs. Each decays with time and can be modelled as arising from a fracture that allowed the entry of drilling fluid. The anomaly at 100m can be reasonably well modelled as a plane fracture with a heat source strength of 2.3 μKms^{-1}, for a total heat input of approximately 7.5 MJm^{-2}, assuming that 15 days elapsed between the time the drill bit encountered the fracture and the time drilling ended. The heat input rate is estimated to be approximately 6 Wm^{-2}, or 24 times that estimated for the fracture at 111m in URL-1. The anomaly occurs in a zone of fractures between approximately 80m and 110m (J. Dugal, unpublished data).

The anomaly at 252m appears to be more complicated than that at 100m. The thermal gradient increases below 252m, from 9.7 mKm above (interval 200-250m) to 11.0 mKm below, an increase of 13%. A fault is mapped at approximately 250m (J. Dugal, unpublished data), and fractures are mapped between approximately 245 and 255m. Above this zone the granites are generally greyish-pink to pink, suggesting that they might have been altered by circulating groundwater. Below the fracture zone the granites are generally uniformly grey. The fractures and fault at approximately 250m appear, therefore to decouple the pink and grey granites hydrologically. It is unlikely that the thermal conductivity of the grey granites is 13% lower than that of the pink granites (Sharma, 1982). The change in gradient probably reflects the effect of water flowing down a dipping fracture system, thereby acting as a sink for heat flowing conductively towards the surface from greater depths (Drury and Lewis, 1982). Assuming that the conductivity of both pink and grey granites is 3.4 Wm^{-1} K^{-1} and that the fracture dips at 15° (A.G. Green, pers. comm.), a flow rate of approximately 0.3 gs^{-1} m^{-1}. would produce the observed gradient change. This rate is very similar to that postulated for flow <u>up</u> a fracture system intersected by borehole WN-4.

The spike thermal anomaly at 252m can be modelled by a uniform heat source of strength 1 μKms^{-1} acting for a period of 10 days, for a total heat input of 3 MJm^{-2}, or an average heat input rate of approximately 3.5 Wm^{-2}.

If the temperature field below 250m is extrapolated upwards, taking into account the gradient change, it is found that actual temperatures above the fracture zone are approximately 0.28K lower than those predicted. This phenomenon arises from water flowing down the borehole at a rate of approximately 2.5×10^{-5} m^3 s^{-1} (Drury and Lewis, 1982). There is no indication from the temperature logs of where the water enters the hole, which suggests that it is flowing from near the surface. In the two early logs approximately one third of the water leaves the hole at 210m (218m); this outflow is not indicated in the third log. Fractures are observed at this depth.

URL-2

The surface location of this hole is approximately 650m to the south east of that of URL-5. Four successive temperature logs of the hole run 4, 8, 39 and 97 days after the end of drilling are shown in Fig. 4. Between the surface and 170m is a zone of greyish-pink to pink granites, associated with a large number of fractures (J. Dugal, unpublished data). There is a peak in the number of fractures per metre at approximately 90m. There is no thermal anomaly that appears to be associated with this fracture zone; however, the discoloured granites occur in at least the upper hundred metres in all of the other URL holes (including 3 and 4), which perhaps indicates that this zone is hydrologically decoupled from the lower formation of generally grey granites.

Below 200m there are five zones of different thermal gradient, which are seen in both the third and fourth temperature logs. Gradients in the different sections are listed in Table 1. The most recent log is replotted in Fig. 5 with temperatures reduced by the removal of a regional gradient of $11.4 mKm^{-1}$, in order to show more clearly the zones of differing gradient. The breaks in gradient are not abrupt, but occur approximately at 344m (360m), 422m (440m), 570m (600m) and 650m (685m). Below the latter depth the temperature profile is disturbed, particularly on the fourth log. Fractures occur throughout the entire length of the borehole, some of them shear fractures, although there is no obvious correlation between the occurrence of fractures and the changes in temperature gradient. Between 170m (180m) and approximately 590m (620m) the lithology is generally uniformly grey granites; below this depth the granites are grey to pinkish-grey, and in discrete units, suggesting the possibility of a large number of fractures. The disturbed temperature profile perhaps reflects these fractures, the variability of the disturbances from one log to another possibly arising from the effects of hydrological pumping tests. Details of such tests are not known to the author.

It is difficult to account for the gradient variations. Changes of as much as 9% are observed (Table 1). If conductive heat flow over the depth of the borehole is constant gradient variations would arise from variations in thermal conductivity. There is no indication from the lithological log that conductivity changes of up to 9% are to be expected; no core samples are available for conductivity measurements, however, so conductivity changes cannot be ruled out.

Surface temperatures extrapolated from the intervals 200 - 340m and 430 - 560m are the same, to within the limits of error of measurement. The temperature and gradients in these intervals may, therefore, represent undisturbed conditions. The lower gradient in the interval 350 - 420m possibly reflects water flow down the hole, although the fact that there is no abrupt change in gradient suggests that water would be entering the hole over a relatively wide zone. The gradient between 650m and bottom hole is approximately 3% lower than that in the interval 430 - 560m; such a change could arise from a difference in conductivity between grey and pink granites (Drury and Lewis, 1982). However, temperatures in this lowermost section are approximately 0.1K lower than would be expected by downward extrapolation of the temperature field at 560m, taking into account the gradient change. This fact, and the lower gradient in the section 570 - 640m, suggests that there might be water flowing down the hole, at a rate of approximately $1 \times 10^{-5} m^3 s^{-1}$, entering in a broad zone starting at approximately 570m (600m). Further the alteration of the granites suggests that water might have been circulating below 570m (600m) for a considerable length of time, in interconnected fractures. If so, this is the first observation of such flow, in formation that is sufficiently permeable, in a pluton as part of the nuclear fuel waste management programme. Flow from a fracture to the bottom of the hole was observed in WN-4 (Drury and Lewis, 1982). A full analysis of the logging results from URL-2 must await the measurement of conductivity of core samples.

Summary

1. The upper 100m or so of the batholith in the area of the URL holes is possibly decoupled hydrologically from greater depths.
2. In URL-1 it appears that water is flowing up a dipping fracture zone that is intersected by the hole at 312m (325m), at a rate of approximately $0.6 \; gs^{-1} m^{-1}$.
3. In URL-5, it appears that water is flowing down a dipping fracture zone, encountered by the hole at 252m (260m), at a rate of approximately $0.3 \; gs^{-1} m^{-1}$.
4. The fracture zones detected in the logs of URL-1 and URL-5 may be connected (A.G. Green, pers. comm.). If so, hydrological flow is clearly complex, with both upward and downward flow.
5. There appears to be a zone of downhole water flow that coincides with altered granites in URL-2, from 570m (600m). Alternatively, the flow could be a general one through interconnected fracture systems. Water flow is also observed down sections of URL-1 and URL-5.

6. Although true equilibrium gradients had not been established at the time of the logs, it appears that the thermal gradient in the grey granites is approximately 11.5 mKm^{-1}. This is significantly less than that determined in borehole WN-4, where the equilibrium gradient is 12.4 mKm^{-1} (Drury and Lewis, 1982). Unless thermal conductivity variations in the grey granites of the Lac du Bonnet batholith account for this difference, the conductive heat flux at the URL area appears to be approximately 7% less than that at the location of WN-4, some 15 km to the south. There is, therefore, the possibility that there is a deep downflow of relatively cool water along a fractured zone beneath the greatest depths of the URL holes. Alternatively, up-dip flow of warm water could be enhancing the gradient measured in the lower zone of WN-4. The heat flux determined from measurements in WN-4 is 50 mWm^{-2}, at Winnipeg, it is 38 mWm^{-2} (Jessop and Judge, 1971), both values being corrected for the effects of Pleistocene glaciation (Jessop, 1971). Assuming a conductivity in the URL holes of 3.4 $Wm^{-1} K^{-1}$, a heat flux of approximately 48 mWm^{-2}, corrected for glaciation, would be expected. The Winnipeg value is considerably lower than that of the Lac du Bonnet batholith sites and cannot be used, therefore, to resolve the ambiguity in the postulated deep water flows beneath either WN-4 or the URL holes.

7. Passive fractures, or open fractures that store some drilling fluid, occur at 111m in URL-1, and 100m and 252m in URL-5. The heat input rates for these, assuming uniform heat source strengths, are respectively 0.25 Wm^{-2} 6 Wm^{-2} and 3.5 Wm^{-2}.

Table 1

Temperature gradients in hole URL-2, log of 23.10.81, obtained by least squares regression

Interval (m)	Gradient (mK/m)	No. of points	Correlation coefficient
200 - 340	11.8	15	1.00
350 - 420	10.9	15	1.00
430 - 560	11.9	15	0.99
570 - 640	10.7	15	1.00
650 - 800	11.4	15	1.00

Acknowledgements

D.K. Tomsons and D.V. Sharma assisted greatly with the field logging.

References

Drury, M.J. and Lewis, T.J. 1982. Water movement within La du Bonnet batholith as revealed by detailed thermal studies of three closely-spaced boreholes. In preparation.

Drury, M.J. and Jessop, A.M. 1981. The effect of a fluid-filled fracture on the temperature profile in a borehole. Geothermal Service of Canada, Internal Report 81-10, 18 pp.

Drury, M.J. and Tomsons, D.K. 1981. Results from the initial series of geothermal logs of borehole URL-1, Lac du Bonnet. Geothermal Service of Canada, Internal Report 81-12, 4 pp.

Jessop, A.M. 1971. Distribution of glacial perturbation of heat flow in Canada. Canadian Journal of Earth Sciences, 8, 162-166.

Jessop, A.M. and Judge, A.S. 1971. Five measurements of heat flow in southern Canada. Canadian Journal of Earth Sciences, 8, 711-716.

Jessop, A.M., Judge, A.S. and Drury, M.J. 1981. Existing data on specific heat and thermal diffusivity of rocks and minerals. Geothermal Service of Canada, Internal Report 81-11, 14 pp.

Judge, A.S. 1980. Thermal studies at Chalk River - August 1977 to February 1978. Geothermal Service of Canada, Internal Report 80-3, 13pp.

Lewis, T.J. and Beck, A.E. 1977. Analysis of heat flow data - detailed observations in many holes in a small area. Tectonophysics, 41, 41 - 59.

Paterson, N.R. and Watson, M.L. 1981. Ground geophysical surveys, Research Area RA-3, Report TW/GPH 81-075, 22pp + maps.

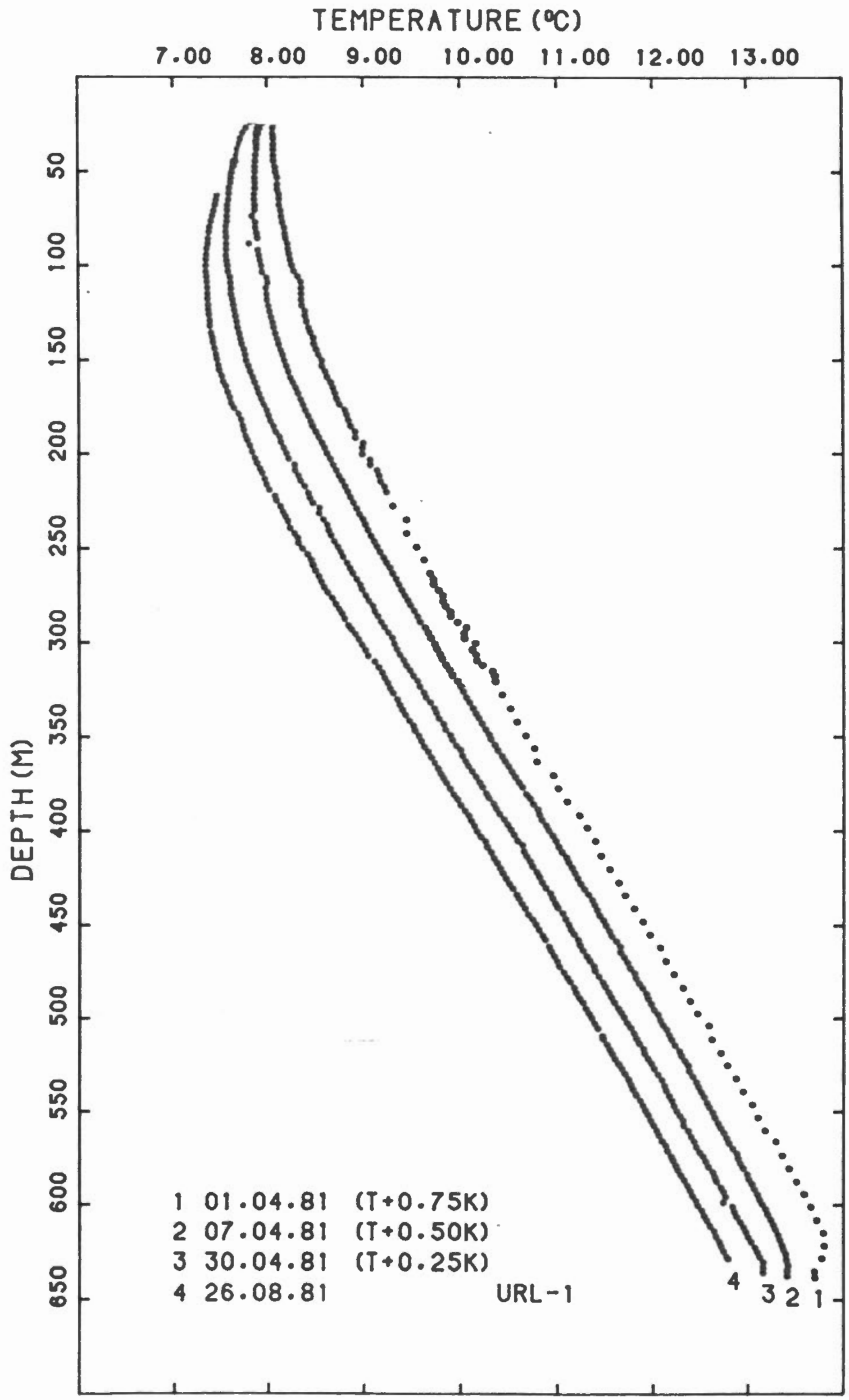

Fig. 1. Four temperature logs of URL-1. Plots are separated for clarity.

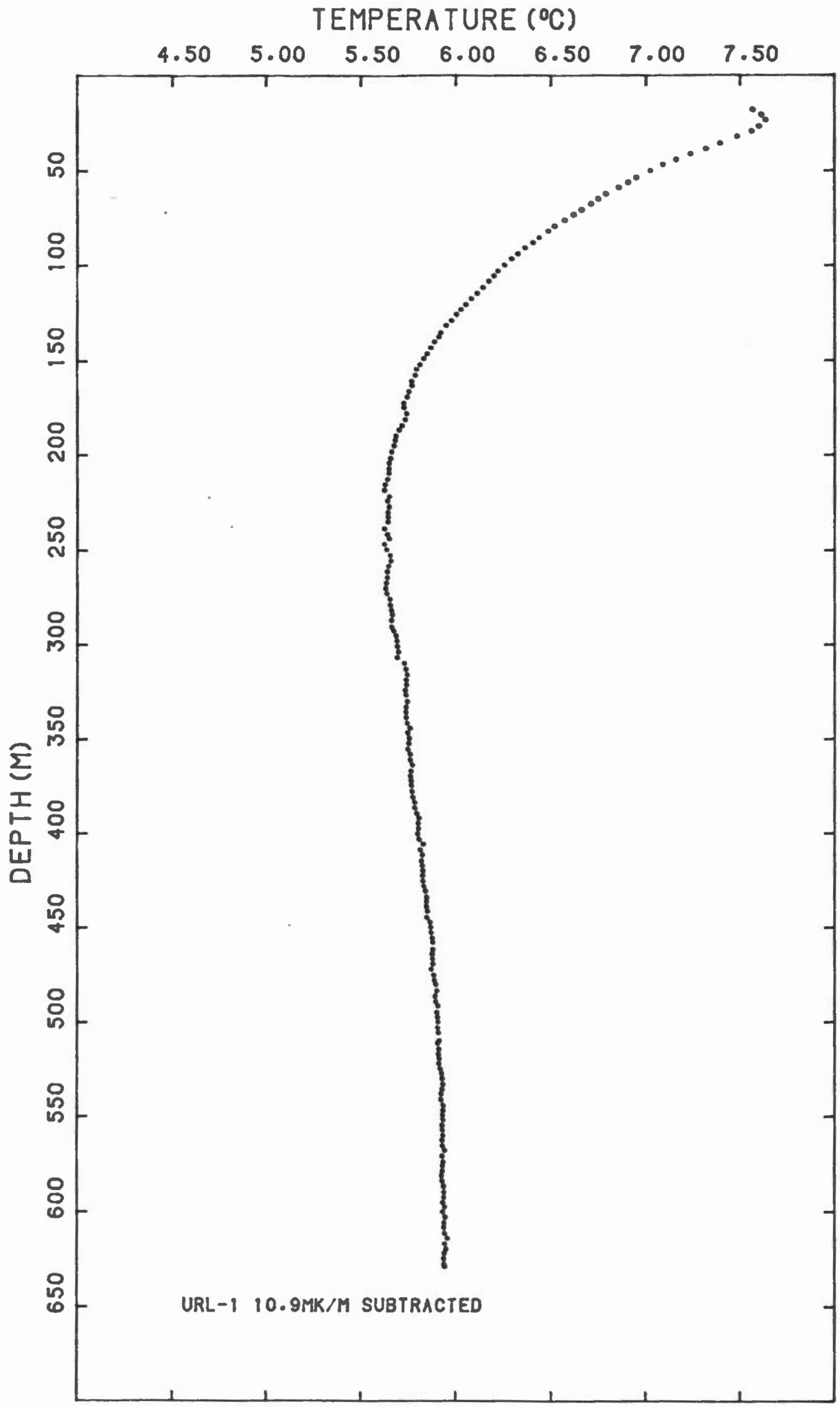

Fig. 2. Temperature log of URL-1, taken on 26.08.81, with gradient of 10.9 mKm^{-1} subtracted.

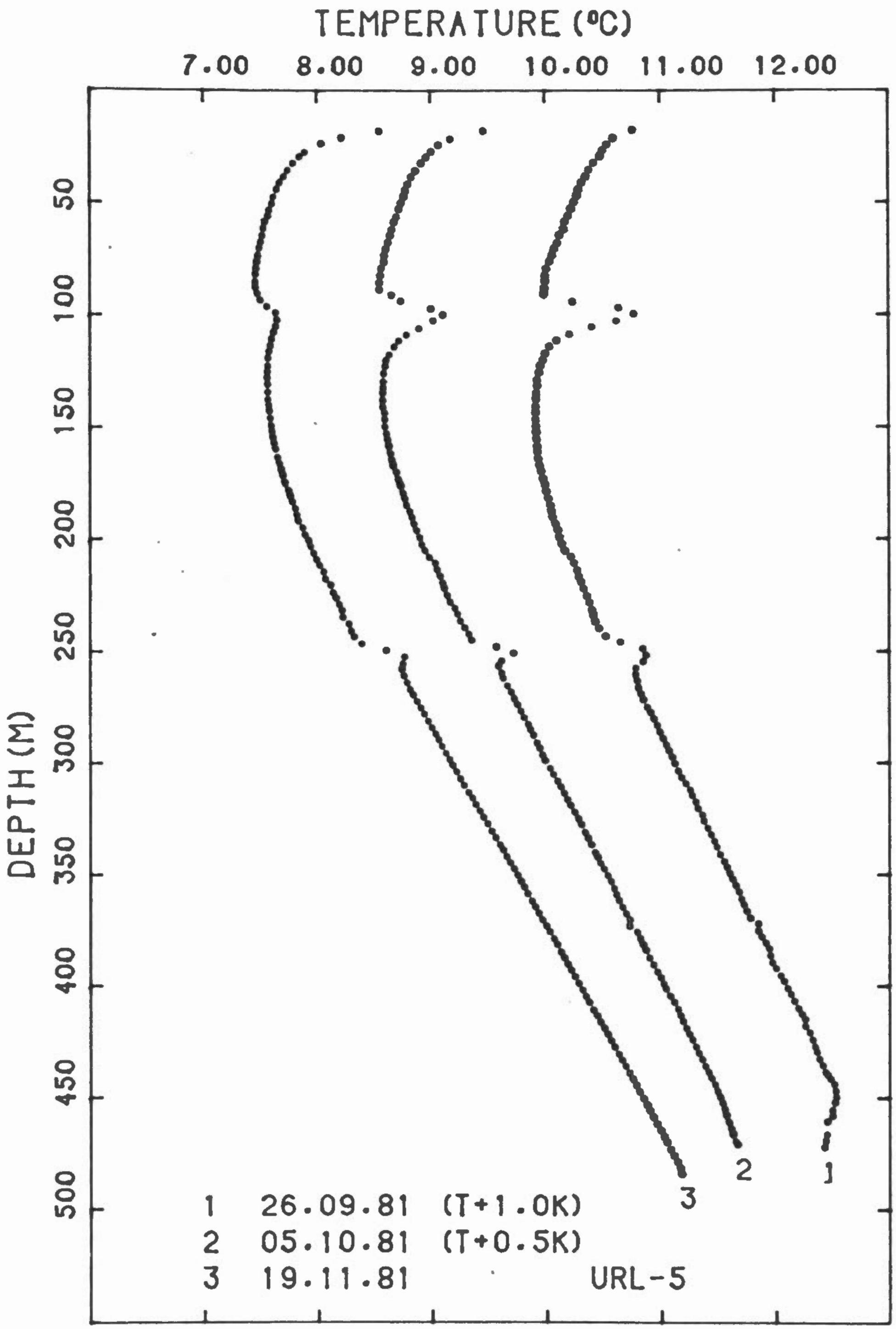

Fig. 3. Three temperature logs of URL-5

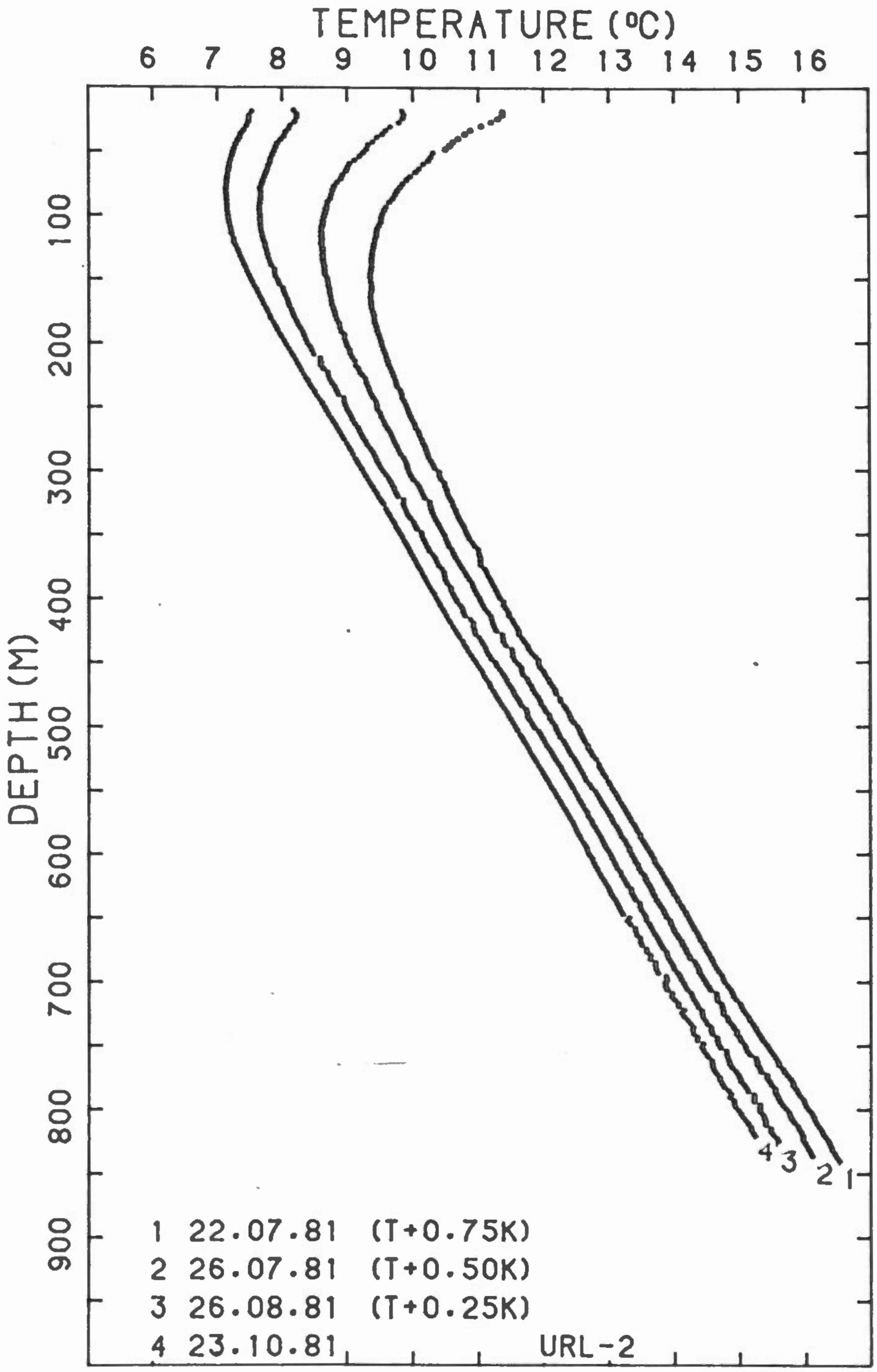

Fig. 4. Four temperature logs of URL-2.

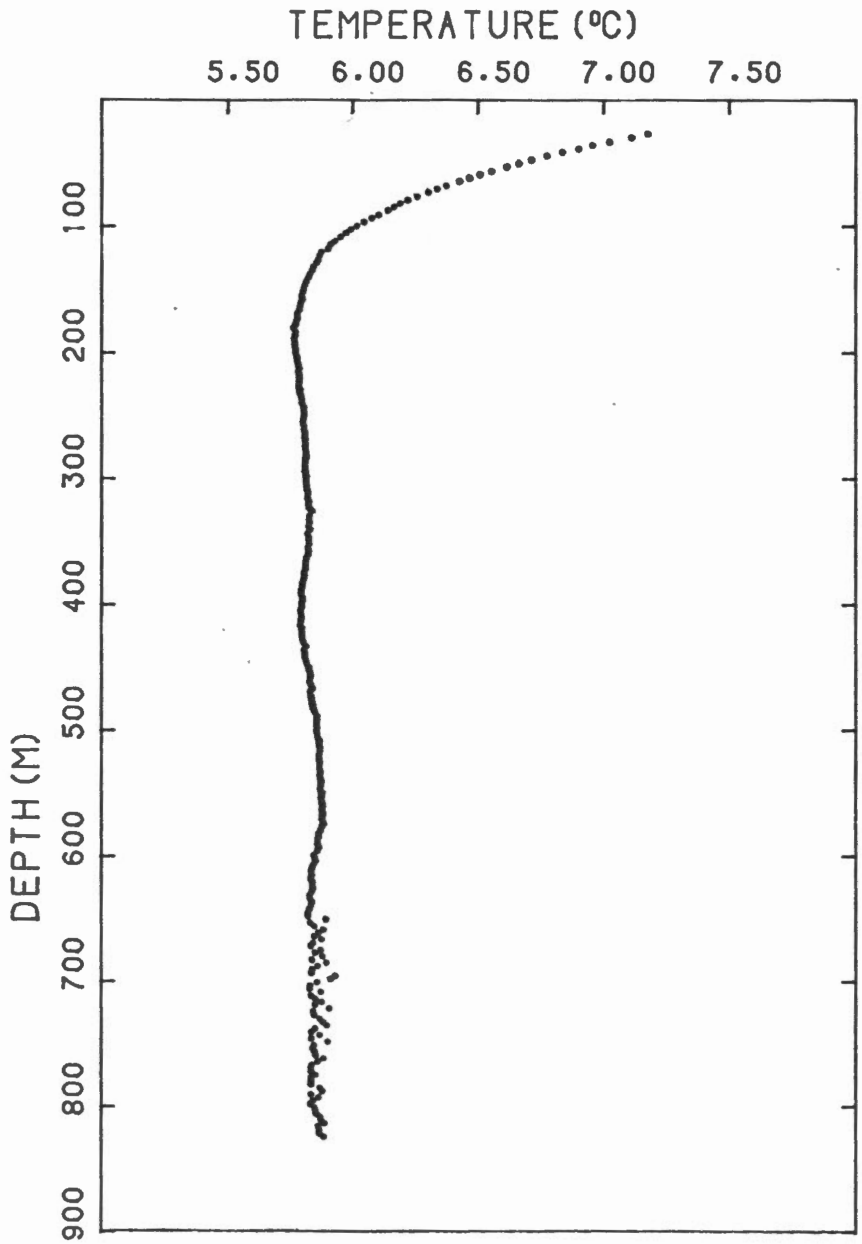

Fig. 5. Temperature log of URL-2 with gradient of 11.4 mKm^{-1} subtracted to show zones of different gradients.