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Geothermal logging of RA-4 (Atikokan)  
and URL boreholes 1979-1983

Malcolm Drury

Division of Gravity, Geothermics and Geodynamics  
Earth Physics Branch  
Energy, Mines and Resources Canada  
Ottawa

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#### Note

This report was written in 1983 and submitted in March of that year to AECL for inclusion in their Technical Record series. It contains a synthesis of the substantial amount of work undertaken in Task 303426 between 1979 and 1983. The report was withdrawn from AECL in October 1985 owing to the lack of progress in getting it published. Because it represents a substantial effort in data collection, analysis and interpretation, it is here released as an Internal Report in order that that effort can be properly documented and recognised. No subsequent geothermal logging has been possible at URL, and the hydrogeological work done there since this report was prepared may mean that some of the interpretations included in this report are no longer valid.

## Abstract

Temperature logs have been obtained since 1979 in four boreholes at RA-4, Atikokan, and in seventeen boreholes at the proposed Underground Research Laboratory site, Lac du Bonnet. The purpose was to detect and characterise fractures that could allow the movement underground of water. All logs have shown one or more of the thermal signatures of the effects of water in fractures, which suggests that water flow in fractures may be a widespread phenomenon in crystalline rocks of the Canadian Shield. Data from ATK-3 and ATK-4 suggest that fractures can become open or closed to water flow for some time after drilling ends. The large amount of data from the URL holes permits an interpretation in the form of fracture zone mapping. Three zones are postulated for the north-eastern section of the URL area: one that is ill-defined, centred approximately on 100 m depth; one that dips to the east at approximately  $18^\circ$ , and occurs at approximately 230 - 240 m at the proposed shaft location, and one that dips to the east at  $14^\circ$  and occurs at 250 - 260 m at this location. Ambiguities in interpretation of some of the logs emphasise the need for a carefully scheduled sequence of temperature logs of a hole, beginning immediately upon the end of drilling.

Geophysical and some hydrological boreholes have been geothermally logged at the Atikokan research area and the Underground Research Laboratory (URL) site as part of the geophysics activity of the Earth Physics Branch of Energy Mines and Resources Canada in the Nuclear Fuel Waste Management Programme. Geothermal logging permits the detection of water flow within boreholes and along fractures (e.g. Drury and Lewis, 1983), and it can also be used to identify passive fractures, i.e. those in which there is normally no water flow, but which accept fluid during drilling (Drury and Jessop, 1982). Observations of 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. A full discussion of the methods of measurement and the theory of the analysis has been given by Drury (1982a) and Drury et al. (1984). This report presents data from ATK and URL boreholes. For inclined holes depths are given as true vertical depth with the downhole length in parenthesis.

#### RA-4 (Atikokan)

Temperature logs have been obtained from four boreholes drilled into granite and granodiorite at Forsberg Lake near Atikokan on seven separate occasions between September 1979 and October 1982 (Drury, 1981). Holes ATK-3 and ATK-4 have been logged five times to provide a good data set for studying the return to equilibrium following drilling. The deepest hole logged, ATK-1, did not provide useful data in 1979 as an on-site hydrogeological crew had undertaken unscheduled air-lifting operations in the hole less than 24 hours before the thermal logging. The hole was subsequently logged in 1982, immediately after a long period of hydrogeological testing.

Temperature logs, RA-4

(i) ATK-1

ATK-1 is the only deep hole at RA-4 to have been geothermally logged. An initial log soon after the completion of drilling did not yield interpretable data. Subsequently the hole was unavailable for three years, until October 1982, when it was logged again. The single temperature log is shown in Fig. 1. It was obtained 1100 days after the end of drilling, and so it shows no residual thermal effects of drilling and circulation. The logging cable was of insufficient length to reach the bottom of the hole. The solid line is a plot of the data passed through a first-difference filter, which removes long period trends and enhances short period variations. For equispaced temperature measurements this is equivalent to displaying the gradient between successive points.

Prior to the thermal logging hydrological packers had been removed from the hole, and it is not possible to determine what effect this, or prior hydrological activities, might have had on the temperature profile. There are no major fracture zones indicated by the temperature log. A series of concavities in the log may indicate water flow down the hole, the water entering the hole at the upper depth of each interval, with some or all leaving at the lower depth. The depth ranges are: 112 m to 165 m (116 m to 171 m), 186 m to 218 m (194 m to 228 m) and 397 m to 442 m (419 m to 468 m). Between 112 m and 442 m the profile is generally disturbed, as indicated by the plot of filtered data. Other small temperature anomalies may indicate fractures. A single point at 572 m (612 m) may be an erroneous reading, but at 600 m (643 m) an anomaly of two points probably reflects a fracture. The temperature field below 572 m is disturbed, perhaps by the presence of fractures, perhaps by the

perturbations of previous down-hole work. This single log indicates the importance of logging a hole in which there has been a sufficient elapsed time since previous logging or pumping activities for their thermal effects to dissipate. The correlation between the presence of fractures deduced from the thermal log and those recorded in the fracture log of the core is very poor.

(ii) ATK-2

This is the shallowest of the holes, with a depth of 193 m (200 m). The first temperature log (Fig. 2) was obtained 102 days and the second 283 days after the end of drilling. The minimum measured temperature is at 67 m. The curvature in the upper 100 m of the log is commonly observed in shield boreholes, and is ascribed to climatic changes in the past century (Lewis, 1975). There is some indication that water may be entering the hole at approximately 45 m and leaving at approximately 60 m, although there are not enough data points in this range for this to be adequately resolved. Similarly, a possible zone of downward water flow, between approximately 110 m and 135 m, is inadequately resolved. However, the latter zone is indicated on both logs.

(iii) ATK-3

The first log of ATK-3 was obtained only four days after the end of drilling, and the temperature field is consequently disturbed. The third log was obtained 15 days later, and subsequent logs were taken at 230 and 397 days after the end of drilling. All logs are shown in Fig. 3. Prominent in the first four logs are positive temperature anomalies centred on depths of 27 m (28 m) and 69 m (72 m). Because both anomalies occur within the zone of temperature decrease with depth it is difficult

to calculate the temperature offsets, since the undisturbed gradient is not linear. However, estimates for the 69 m anomaly are +0.8K for the first two logs, decreasing to +0.15 K 230 days after drilling.

The anomaly at 69 m, and that at 27 m, represents a passive fracture that has filled with warmer drilling fluid during drilling. Judge (1980) reported a similar anomaly in CR-1 (Chalk River) that diminished with time. Mathematical models to describe the phenomenon have been developed; they have been discussed by Drury and Jessop (1982). The 69 m fracture is not indicated on the borehole lithology and fracture log.

Several smaller thermal anomalies are apparent. A temperature offset of 0.07 K is seen at 188 m (196 m) on the second log, and 0.05 K at the same depth on the third log. No temperature offset is seen at this depth on the first or subsequent logs. This anomaly could arise from a passive crack that has opened during drilling, in response to the stress of that activity, and has become filled with drilling fluid. In this case the fluid and rock would initially be at the same temperature, but because of the greater heat capacity of the fluid, excess heat would be passed into the crack as the fluid entered. Subsequently the anomaly would develop as the competent rock cooled while, at the intersection of fracture and hole the temperature would remain higher because of the excess heat. The development of this type of anomaly is different from that seen at 69 m, for which the heat source is fluid initially at a higher temperature than the rock. Similar small anomalies are seen at depths of 206 m (215 m), 239 m (249 m) and 286 m (299 m) on the second log. None of these correlate with anomalies on either the prior or subsequent logs. If they do represent fractures that have been induced by the drilling process, it is clear that the thermal anomalies produced by such fractures decay quickly. This suggests that the fractures are small, such that although

the initial temperature anomaly may be 0.05 - 0.1 K, only a small volume of warmer fluid is contained in the fracture and hence the quantity of excess heat is not large.

(iv) ATK-4

ATK-4 has a depth of 313 m (340 m). The hole was logged 35, 36, 50, 261 and 428 days after the end of drilling. There is very little difference between the first and second logs and only the last four logs are shown (Fig. 4). Below 200 m temperatures measured on the second log are approximately 0.04 K higher than on the first log; this is probably the result of disturbance (by some degree of mixing of the the water column) caused by the activity of logging twenty four hours earlier. A similar phenomenon is not detectable in the ATK-3 logs as its first two logs were taken during the period of rapid cooling soon after the end of drilling. A prominent thermal anomaly centred on 72 m (77 m) is seen on the first three logs. It has decayed in amplitude from approximately +0.35 K to +0.30 K between the second and third logs and has almost disappeared by the last log. A similar, though lower amplitude anomaly is centred on approximately 47 m (50 m). This has clearly decayed between the second and third logs (Fig. 4). Both large anomalies represent passive fractures. The 72 m fracture is not indicated on the lithology and fracture count log. The large anomaly in the ATK-3 logs (Fig. 3) occurs at a depth of 69 m. However, the top of the casing of ATK-3 is elevated with respect to ATK-4 by approximately 3 m. Hence, it appears that the anomalies at approximately 70 m in ATK-3 and ATK-4 represent a common, passive fracture, or fracture system. The two holes are approximately 10 m apart at that depth.

A number of short, almost isothermal sections in the first log are evident. They may represent water flow from one fracture to another within the borehole. By the time of the third log a much smoother temperature profile is observed, and water flow in the borehole appears to have ended. This may be the result of fractures closing in the time interval between the first and third logs. Alternatively the effect may arise from the decay of hydraulic potential.

#### URL (Lac du Bonnet)

A large number of holes have been drilled at the site of the proposed underground laboratory, in the granitic Lac du Bonnet batholith. This site is some 15 km north of the WNRE holes. Thermal logging of some of those holes has been discussed by Drury and Lewis (1983). Results of thermal logging of URL-1 and URL-5 have been given by Drury and Tomsons (1981) and Drury (1982b). Water flow along a dipping fracture zone intersected by both holes was postulated to explain observed changes in thermal gradient, at 312 m (325 m) in URL-1 and 252 m (261 m) in URL-5. The direction of flow, however, was deduced to be upwards at URL-1 and downwards at URL-5. There are several gradient changes in URL-1, however, that are most likely the result of conductivity variations. Further logs of URL-1 would have been helpful in resolving this question, but the hole has not subsequently been available. Results for URL-1 and URL-5, and for all other URL site holes logged, are summarised in Table 1.

#### (i) URL-2

Four successive temperature logs of URL-2 run 4, 8, 39 and 97 days after the end of drilling are discussed by Drury (1982b). The fourth log and a fifth, obtained 605 days after the end of drilling, are shown in

Fig. 5. Between the surface and 170 m (176 m) 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 90 m (92 m). No thermal anomaly appears to be associated with this fracture zone; however, the discoloured granites occur in at least the upper hundred metres in other URL holes, which perhaps indicates that this zone is hydrologically decoupled from the lower formation of generally grey granites.

Below 200 m there are five zones of different thermal gradient, which are seen in all temperature logs. Gradients in the different sections are listed in Table 2. The fourth log is replotted in Fig. 6 with temperatures reduced by the removal of a regional gradient of  $11.5 \text{ mKm}^{-1}$ , in order to show more clearly the zones of differing gradient. The breaks in gradient are not abrupt, but occur approximately at 344 m (360 m), 422 m (440 m), 570 m (600 m) and 650 m (685 m). 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 170 m (180 m) and approximately 590 m (620 m) 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 2). 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; conductivity measurements made to date do not indicate such a large variation.

Surface temperatures extrapolated from the intervals 200 - 340 m and 430 - 560 m 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 - 420 m 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 650 m and bottom hole is approximately 3% lower than that in the interval 430 - 560 m; such a change could arise from a difference in conductivity between grey and pink granites (Drury and Lewis, 1983). However, temperatures in this lowermost section are approximately 0.1 K lower than would be expected by downward extrapolation of the temperature field at 560 m, taking into account the gradient change. This fact, and the lower gradient in the section 570 - 640 m, suggests that there might be water flowing down the hole, at a rate of approximately  $1 \times 10^{-5} \text{ m}^3 \text{ s}^{-1}$ , entering in a broad zone starting at approximately 570 m (600 m). Further, the alteration of the granites suggests that water might have been circulating below 570 m (600 m) for a considerable length of time, in interconnected fractures. A full analysis of the logging results from URL-2 must await the measurement of conductivity of a large number of core samples.

(ii) URL-3

Owing to the difficulty of lowering the temperature probe past a large cavity formed by the intersection of the borehole with a fracture at approximately 70 m, URL-3 has been logged geothermally only once. The log is shown in Fig. 7. The minimum temperature in the hole occurs at approximately 100 m rather than 70 m as commonly seen in equilibrium temperature logs of holes in the area. At 70 m the effect of the fracture having been filled with warm drilling fluid is seen; the temperature has been substantially increased. A step change in the temperature profile at 150 m indicates the outflow of water that flows down the hole from an indeterminate depth. At 282 m there is a change in gradient, from  $13.7 \text{ mKm}^{-1}$  above to  $12.5 \text{ mKm}^{-1}$  below, a decrease of 9%. Such a gradient change would be produced by a flow upwards of water along a dipping fracture zone, or by a change in thermal conductivity. The conductivity of the plutonic rock is not likely to vary by 9%, and so the former explanation is preferred.

(iii) URL-6, 7, 8, 9, 10, 11

Figs. 8-13 show temperature plots of holes URL-6 to URL-11. All show thermal effects of fractures, which are listed in Table 1. The holes had been subjected to hydrogeological testing prior to the geothermal logging, so some anomalous thermal disturbances can be attributed to this. For example, the section between 61 m and 80 m in URL-10 that is almost isothermal probably arose from a zone of passive fractures. An interesting observation in URL-9 is that of two spike anomalies, characteristic of passive fractures, between 50 m and 80 m. A single spike is observed in many of the URL hole logs in this depth range.

In URL-6 there is a sharp change in gradient at 333 m in the first two logs, but this does not appear in the later two logs. This observation emphasises the need for a series of logs of each hole. Standing alone, the first log, obtained shortly after the end of drilling, could be interpreted as indicating flow up a dipping fracture encountered by the hole at 333 m. The effect probably reflects the drilling disturbance to the temperature profile.

The drilling disturbance is unusually severe in the profiles of URL-7 and URL-11, which are almost isothermal. The persistence of this isothermal profile also emphasises the need for a series of logs so that the drilling disturbance can be separated from other disturbances.

#### (iv) M-series holes

In addition to the logging of geophysical holes opportunities have also been taken to log some of the M-series hydrogeological holes. The logs are shown in Figs. 14 and 15. As these are large diameter (156 mm, in contrast to the 76 mm diameter URL and ATK holes) the possibility of convection occurring in the water column must be considered. If strong convective motion occurs, some thermal signatures of fractures may be disguised or destroyed. The phenomenon has been discussed by Hales (1937) and summarised by Drury et al. (1984). Based on the discussion by Hales (1937), and on observations of temperature stability during the logging of the holes, it is concluded that such convection was unlikely to be occurring.

Most of the M-series holes revealed some fracture-induced thermal anomaly. The interpretation for each of the holes is given in Table 1.

## DISCUSSION

The temperature data obtained from the Atikokan boreholes have justified the approach of obtaining closely-spaced discrete temperature measurements, and have shown that it is important to obtain temperature logs shortly after the end of drilling. In particular, the data from ATK-3 and ATK-4 suggest that fractures can become open or closed to water flow for some time after drilling ends. The temperature anomalies seen in the logs are generally small and do not indicate any major water flows up or down the hole. Temperature logs that are carried out with the express purpose of resolving fine detail of the temperature gradient should be obtained when the water column in the hole has not recently been disturbed by other logging activities. The apparent smoothing out of small anomalies between the first log of ATK-4 and the second log 24 hours later is most likely the result of disturbance arising from the logging process itself.

The unusually large number of boreholes logged at the URL site permits fracture mapping to be attempted. Fig. 16 shows a west-east profile across the north-eastern section of the URL site. The profile passes through the surface location of URL-5 and within a few metres of the surface locations of M1-A and URL-7. The true vertical depths of those boreholes in which fractures have been detected by thermal logging have been projected onto this profile. The fractures listed in Table 1 have been plotted on the borehole projections, and symbolically characterised to represent the different fracture types.

If it is assumed that like fractures occur in extended fracture zones, three such zones can be postulated, as shown in Fig. 16. Z1 is a zone between approximately 50 m and 150 m depth. The extent of the zone both laterally and vertically is poorly defined. The limits of the zone

shown in Fig. 16 are slightly modified from those shown by Davison et al., (1982). It is based partly on the temperature logs and partly on other data, such as rock type. Zones Z2 and Z3 are deduced and defined in Fig. 16 entirely from the temperature log data. Z2 is a zone that dips to the east at approximately 18°. Water flows into the fracture system from the boreholes and possibly from sub-vertical joints and fractures, and flows along the sub-horizontal fractures. Data are insufficient for an unambiguous determination to be made of the direction of flow: URL-1 and URL-6 data may suggest up-dip flow, but data from URL-5 strongly indicate down-dip flow. Had more logging opportunities been made available this ambiguity may well have been resolved.

If the interpretation of Z3 reported here is correct, examination of the data from URL-1, URL-5 and URL-6 suggest that the fracture zone has no dip in the north-south direction. This is contrary to the interpretation of seismic data (A.G. Green, pers. comm. 1983), which indicates a southward dip of approximately 6°.

The presence of zone Z2 has been indicated by analysis of seismic reflection data (Green and Soonawala, 1982). A third zone, Z3, is postulated on the basis of the temperature logs. This connects fractures into which water is flowing from a borehole but with no apparent up- or down-dip flow. Z3 dips to the east at approximately 14°. Davison et al. (1982) show a different configuration of Z2 and Z3, with a horizontal connection between the two over the distance between holes M1-A and URL-6. As the URL will be constructed in this part of the study area, it is important that this difference in interpretation be resolved. In fact the apparent change in flow direction along Z2 may be the result of a connection between Z2 and Z3. If this is so, the connection would be between the locations of URL-5 and URL-6, a narrower distance than that indicated by Davison et al. (1982).

The postulated fracture at 282 m in URL-3 is associated with an apparent change in thermal gradient that could be caused by flow of water up a dipping fracture zone. A fourth, deeper fracture zone may, therefore, be present at this location. A re-interpretation of the temperature data from the deeper parts of URL-1 suggests a similar gradient change at approximately 540 m in that hole. If that change is also the result of a dipping fracture, it is possible that the deep fractures in URL-3 and URL-1 are connected. Such a connection would imply a fracture zone that also dips to the east at approximately  $18^\circ$ , as does Z2. The parallelism of the zones would result from a common cause, which is highly circumstantial evidence for the existence of the deeper zone. It is suggested that future hydrogeological and seismic reflection analyses consider the possibility of the existence of a deeper fracture zone.

Other aspects of the interpretation of URL geothermal data may be summarised as follows:

1. The upper 100 m 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 312 m (325 m), at a rate of approximately  $0.6 \text{ gs}^{-1} \text{ m}^{-1}$  (Drury, 1982b).
3. In URL-5, it appears that water is flowing down this fracture zone, encountered by the hole at 252 m (260 m), at a rate of approximately  $0.3 \text{ gs}^{-1} \text{ m}^{-1}$  (Drury, 1982b).
4. There appears to be a zone of downhole water flow that coincides with altered granites in URL-2, from 570 m (600 m). Alternatively, the flow could be a general one through interconnected fracture systems. Water flow is also observed down sections of several other holes.

5. 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  $11.5 \text{ mKm}^{-1}$ . This is significantly less than that determined in borehole WN-4, where the equilibrium gradient is  $12.4 \text{ mKm}^{-1}$  (Drury and Lewis, 1983). 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, assuming that thermal conductivity of the granite is similar at both sites. There is, therefore, the possibility that there is a deep downflow of relatively cool water along a fracture 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  $50 \text{ mWm}^{-2}$ , and at Winnipeg approximately 60 km to the south-west, it is  $38 \text{ mWm}^{-2}$  (Jessop and Judge, 1971), both values being corrected for the effects of Pleistocene glaciation (Jessop, 1971). Assuming a conductivity in the URL holes of  $3.4 \text{ Wm}^{-1}\text{K}^{-1}$ , a heat flux of approximately  $47 \text{ mWm}^{-2}$ , 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. Another explanation for the difference in heat flow values at WNRE and URL is a higher radiogenic heat production in the granite at WNRE. The granite at WNRE has a high radiogenic U, Th and K content (Drury and Lewis, 1983). At present, no analyses are available for URL granites.

6. Passive fractures, or open fractures that store some drilling fluid, occur in several of the holes, for example, at 111 m in URL-1, and 100 m and 252 m in URL-5. The heat input rates for these, assuming uniform heat source strengths, are respectively  $0.25 \text{ Wm}^{-2}$ ,  $6 \text{ Wm}^{-2}$  and  $3.5 \text{ Wm}^{-2}$  (Drury, 1982b).

Finally, it is important to note that almost all holes logged geothermally at the locations discussed here and at WNRE, CRNL and East Bull Lake have shown some indication of the thermal effects of flowing water. This fact suggests that the presence of fractures that permit flow may be a widespread phenomenon in crystalline rocks of the Canadian Shield.

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\*AECL seconded staff; all others EPB staff.

Table 1

Major fractures, characterised by type, detected in URL boreholes by temperature logging. Holes with no thermal indication of fractures omitted.

<u>Hole</u>	<u>Depth (m) and type of fracture</u>				
URL-1	111 P	180 FO	312 FO, G		
URL-3	70 P	150 FO	282 G?		
URL-5	100 P	210 FO	252 FO, G		
URL-6	68 P	125 P	195 P	272 P, FO?	330 U?
URL-7	71 P	143 P?			
URL-8	52 P				
URL-9	53 P	67 P	105 P		
URL-10	68 P	200 FO			
M1-A	145 P	259 FO			
M2-A	323 FO				
M3-A	155 P	380 FO?			
M4-A	140 P	312 P?			
M5-A	331 FO				
M12-A	168 FI	180 FO			

Fracture types: P - passive; FI - entry point of down-hole flow; FO - exit point of down-hole flow; G - flow along fracture zone, indicated by change in thermal gradient; U - unknown or indefinable type. Note that more than one thermal signature may be observed for a given fracture.

Table 2

Temperature gradients in hole URL-2, log of 23.10-81,  
obtained by least squares regression

Interval(m)	Gradient (mKm <sup>-1</sup> )	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

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Earth Physics Branch  
1 Observatory Crescent  
Ottawa, Ontario  
K1A 0Y3

FIGURE CAPTIONS

- Fig. 1 Temperature plot of ATK-1 on 20.10.82. Solid line is plot of data processed by first-difference filter to enhance small anomalies of gradient.
- Fig. 2 Plots of temperature data for ATK-2 on 08.11.79 and 07.05.80. Plots are separated for clarity.
- Fig. 3 Temperature logs of ATK-3, obtained on 25.09.79, 26.09.79, 10.10.79, 09.05.80 and 23.10.80.
- Fig. 4 Temperature logs of ATK-4, obtained on 26.09.79 and subsequent dates as for ATK-3.
- Fig. 5 Temperature logs of URL-2, obtained 23.10.81 and 15.03.83.
- Fig. 6 Temperature log of URL-2 obtained on 15.03.83, with gradient of  $11.5 \text{ mKm}^{-1}$  removed to show zones of different gradients.
- Fig. 7 Temperature log of hole URL-3.
- Fig. 8 Four temperature logs of hole URL-6.
- Fig. 9 Three temperature logs of hole URL-7.
- Fig. 10 Two temperature logs of hole URL-8.
- Fig. 11 Four temperature logs of hole URL-9.
- Fig. 12 Two temperature logs of hole URL-10.
- Fig. 13 Two temperature logs of hole URL-11.
- Fig. 14 Temperature logs of M series holes.
- Fig. 15 Temperature logs of M series holes.

Fig. 16 Schematic interpretation of temperature logs in terms of fracture zone distribution. Z1 is a poorly defined zone of fractures, Z2 corresponds to a fracture zone delineated also by seismic reflection profiling, and Z3 is a postulated deeper zone that dips in the same direction, to the east, but at a shallower angle ( $14^\circ$ ) than Z2 ( $18^\circ$ ). Reference ground level is elevation of collar of URL-3. Arrows indicate postulated directions of water flow. Symbols for fractures are: single line - passive fracture; double lines - fracture into which water is flowing from the hole; triple lines - such fractures at which there is also a change in thermal gradient.

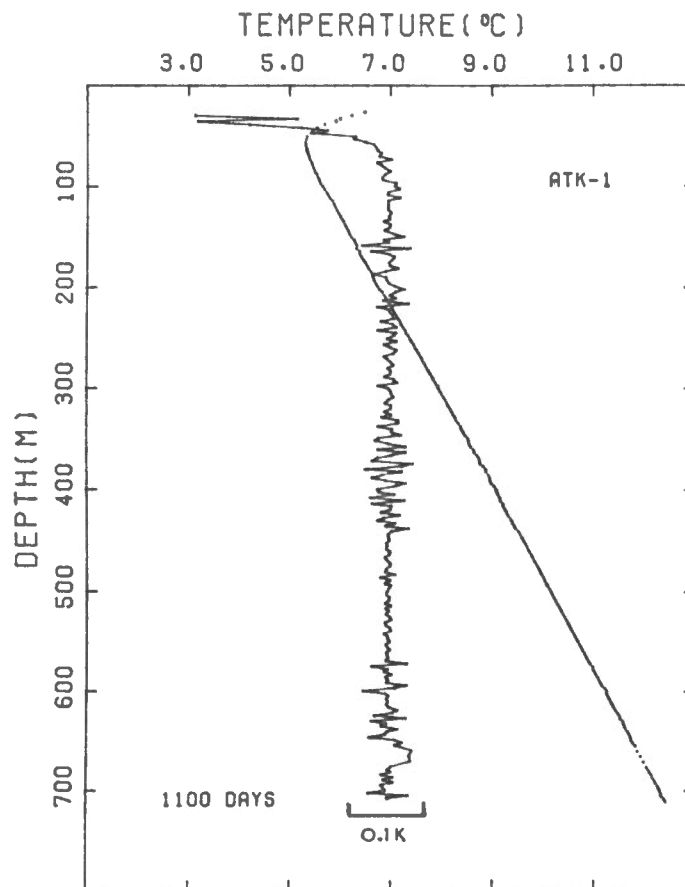


Fig. 1 Temperature plot of ATK-1 on 20.10.82. Solid line is plot of data processed by first-difference filter to enhance small anomalies of gradient.

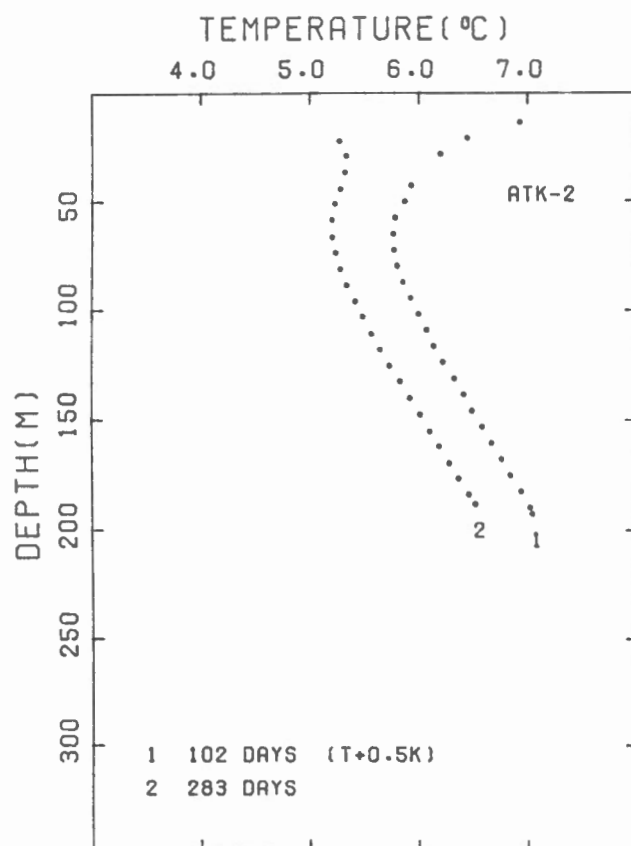


Fig. 2 Plots of temperature data for ATK-2 on 08.11.79 and 07.05.80.  
Plots are separated for clarity.

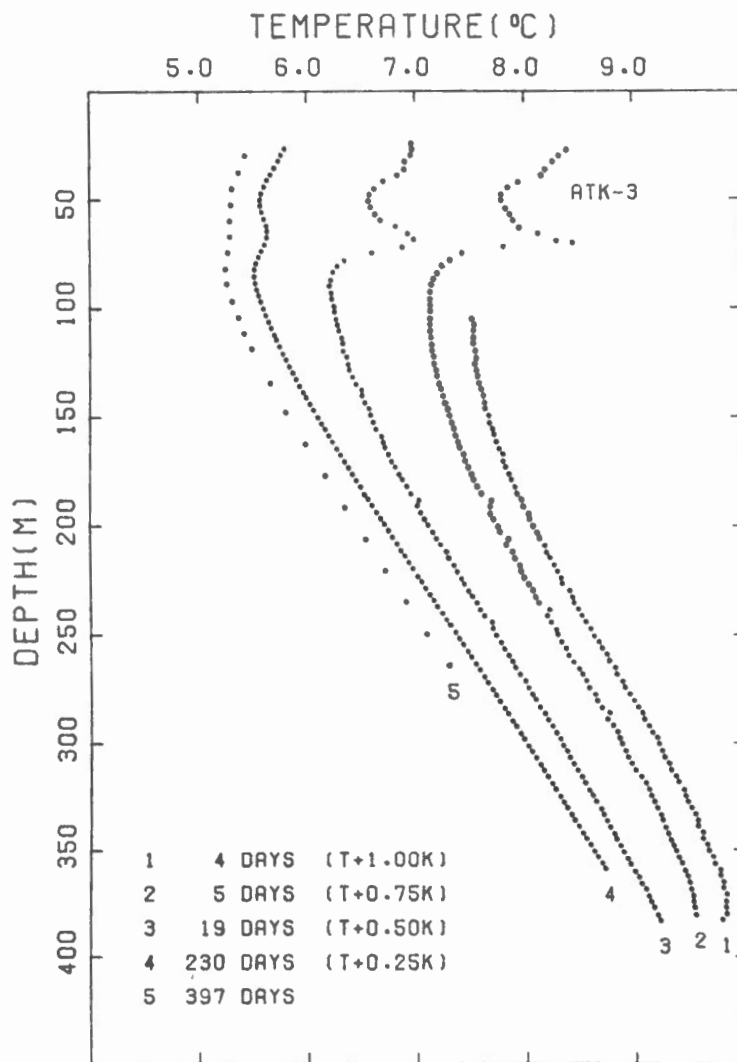


Fig. 3 Temperature logs of ATK-3, obtained on 25.09.79, 26.09.79, 10.10.79, 09.05.80 and 23.10.80.

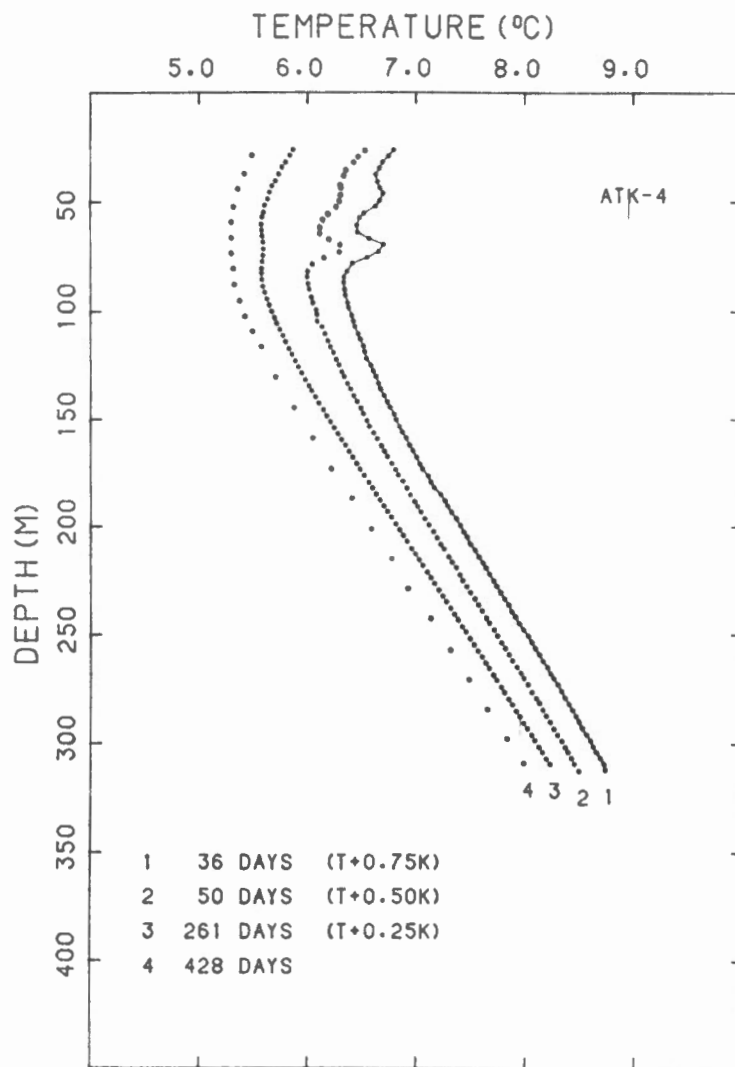


Fig. 4 Temperature logs of ATK-4, obtained on 26.09.79 and subsequent dates as for ATK-3.

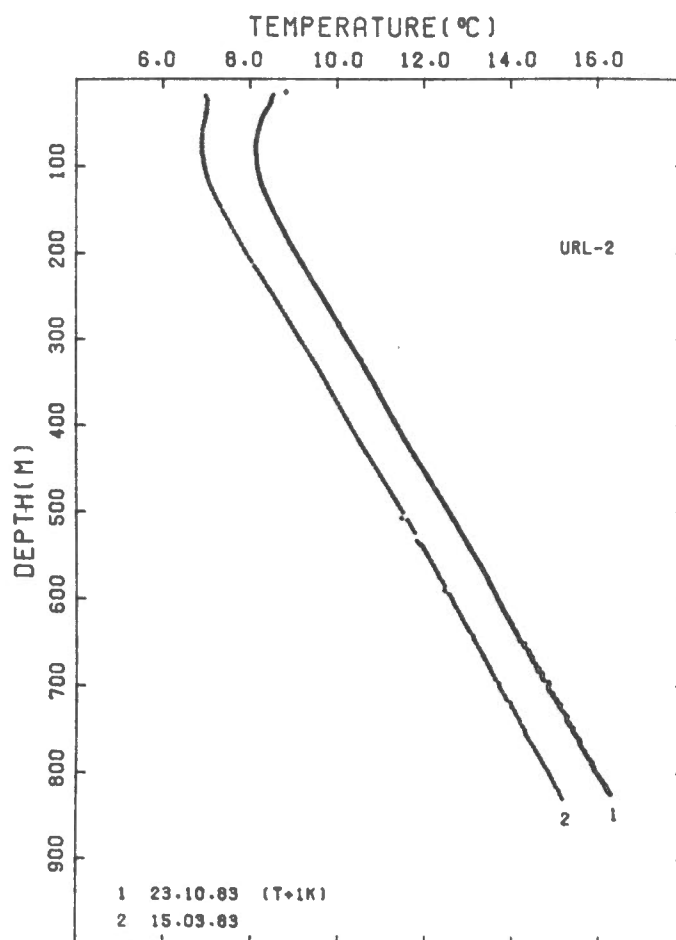


Fig. 5 Temperature logs of URL-2 obtained 23.10.81 and 15.03.83.

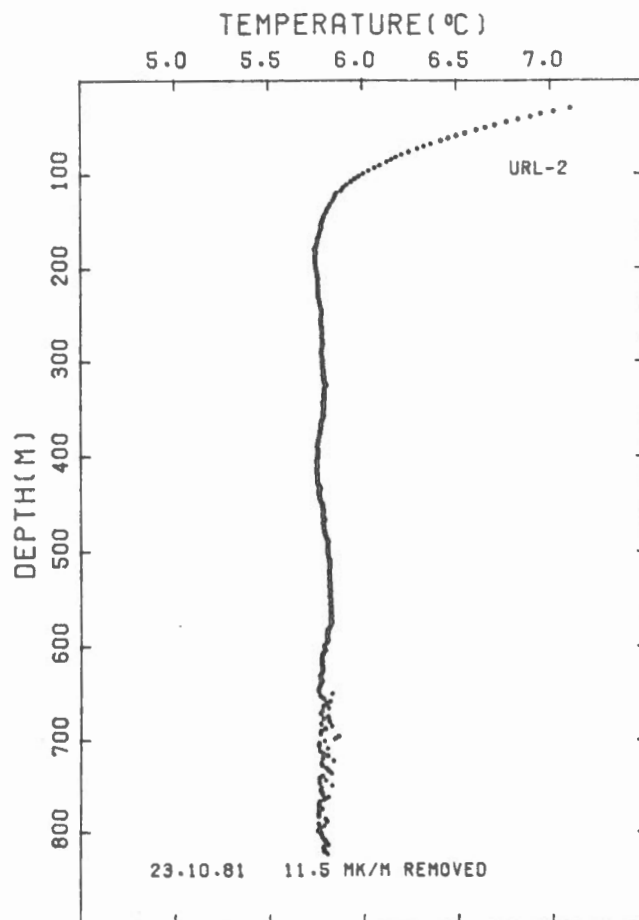


Fig. 6 Temperature log of URL-2 obtained on 15.03.83, with gradient of  $11.5 \text{ mK m}^{-1}$  removed to show zones of different gradients.

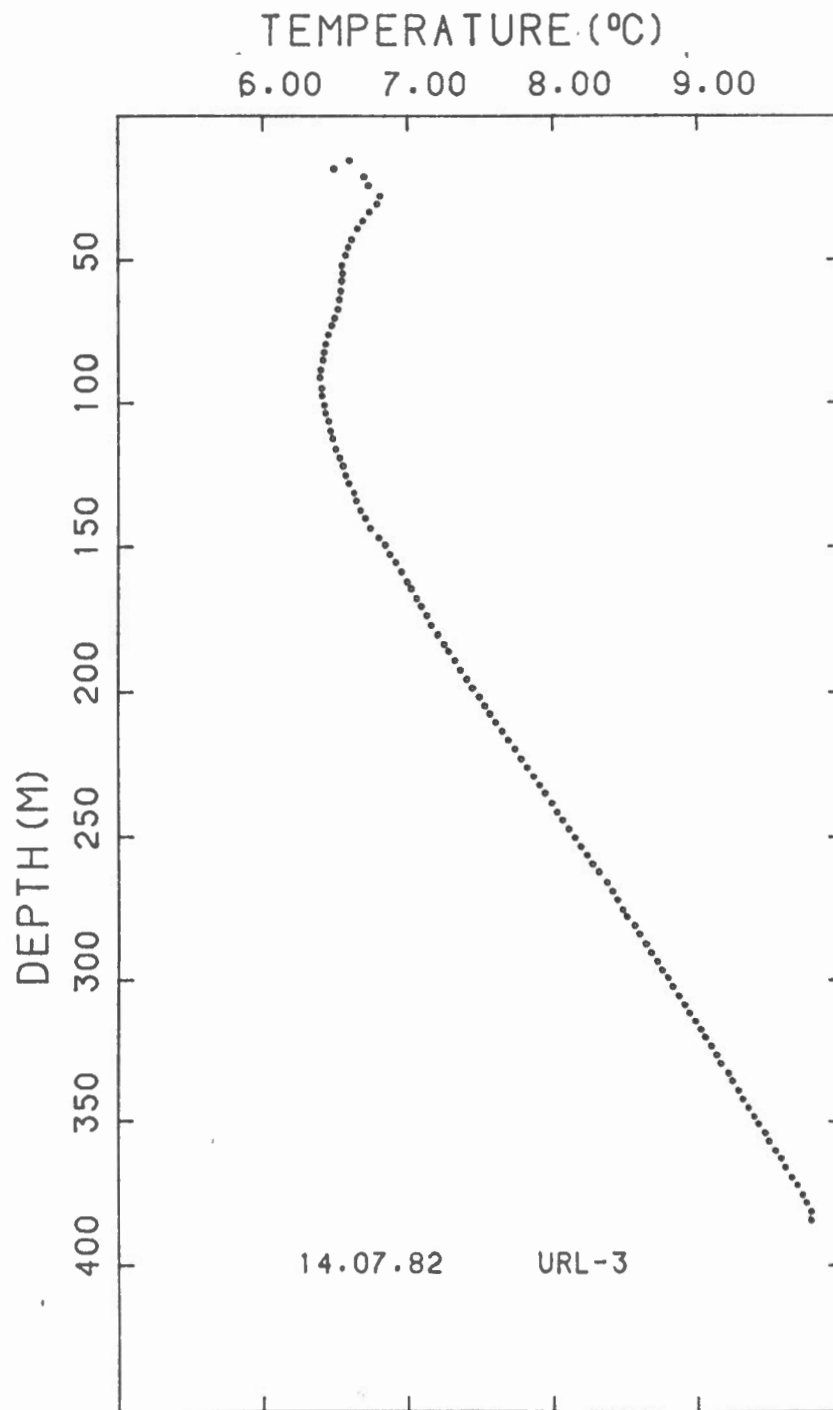


Fig. 7 Temperature log of hole URL-3.

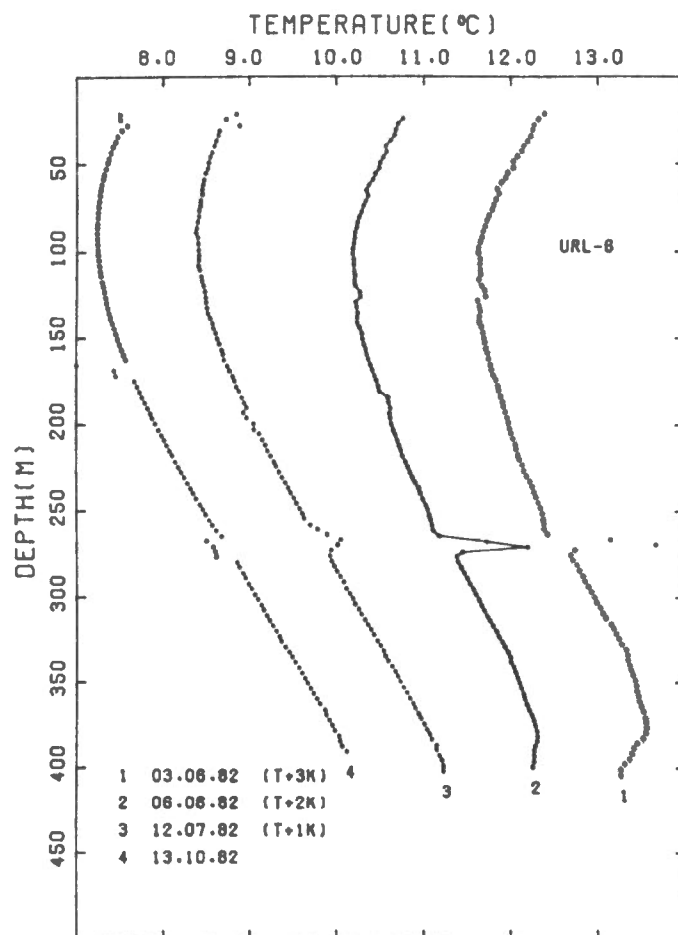


Fig. 8 Four temperature logs of hole URL-6.

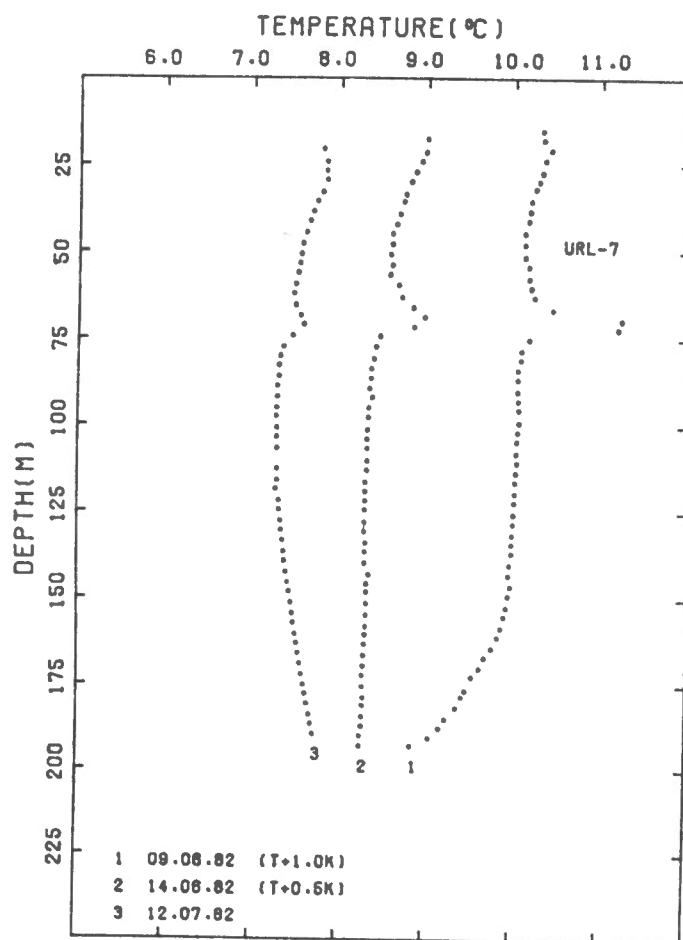


Fig. 9 Three temperature logs of hole URL-7.

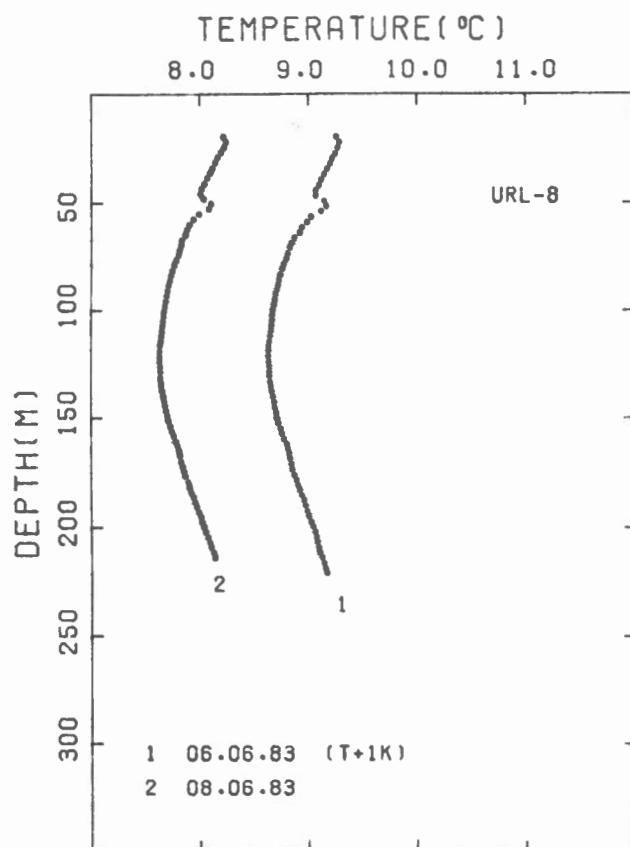


Fig. 10 Two temperature logs of hole URL-8.

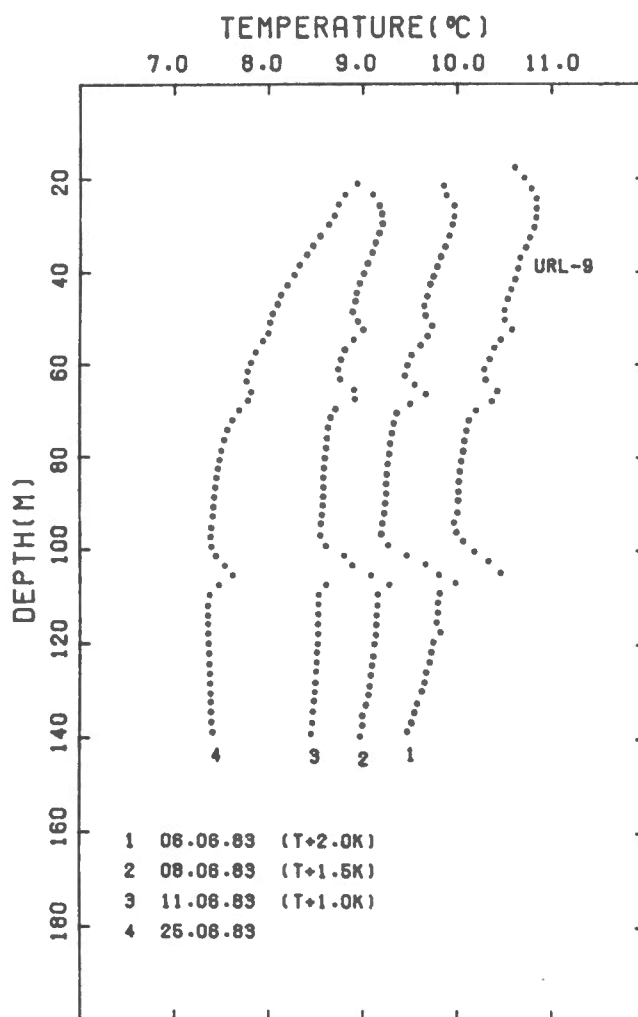


Fig. 11 Four temperature logs of hole URL-9.

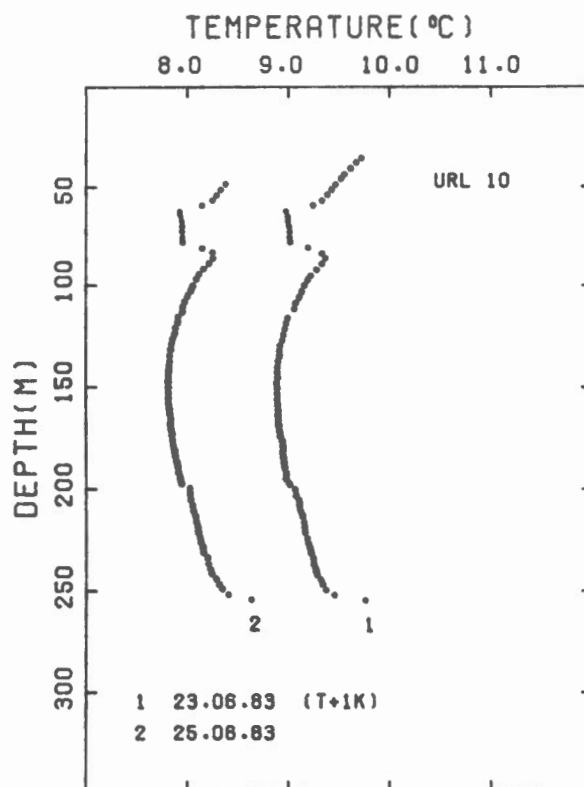


Fig. 12 Two temperature logs of hole URL-10.

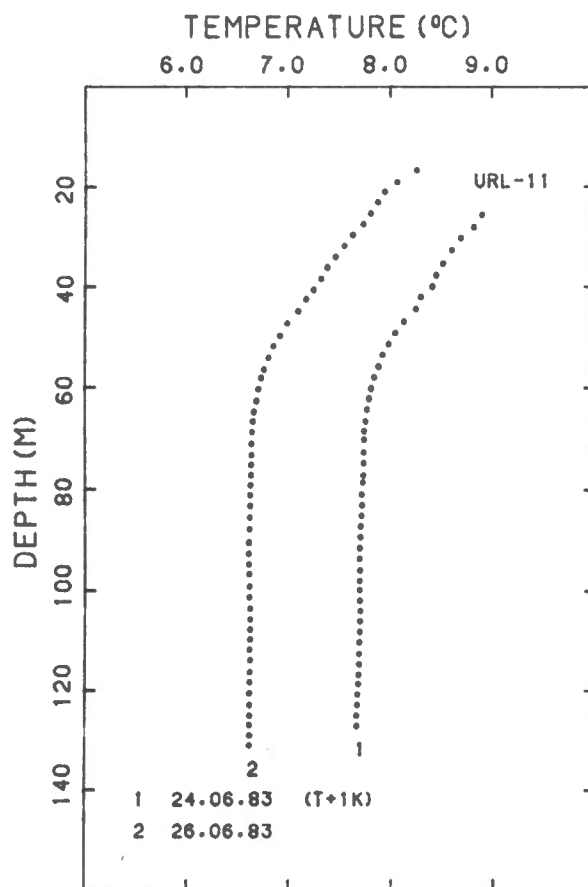


Fig. 13 Two temperature logs of hole URL-11.

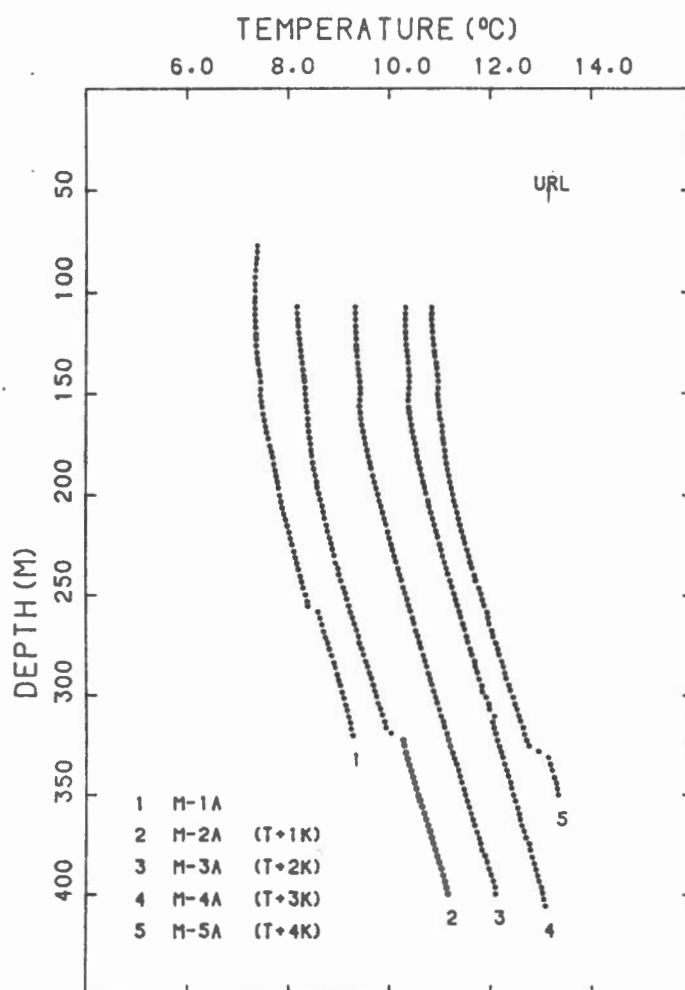


Fig. 14 Temperature logs of M series holes.

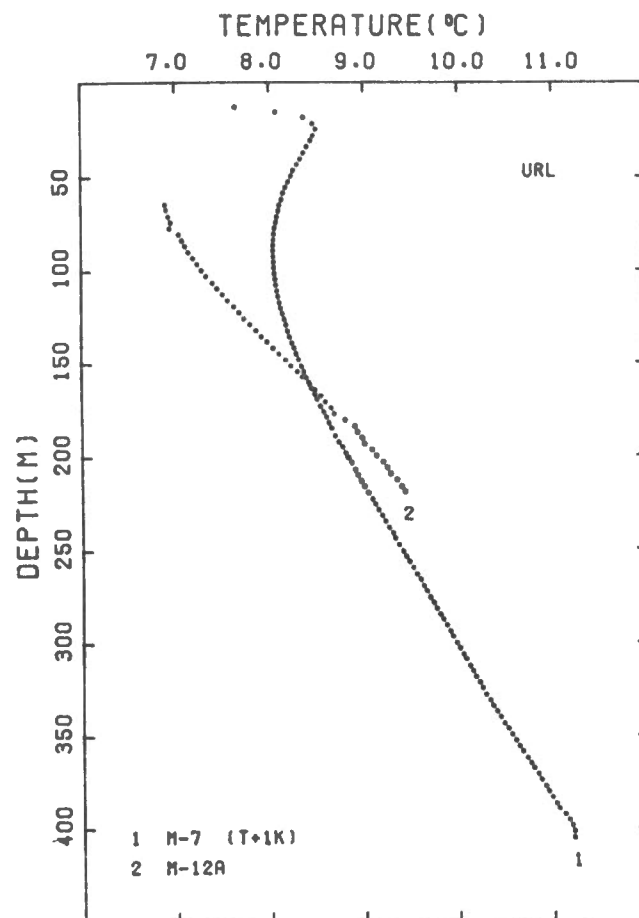


Fig. 15 Temperature logs of M series holes.

Fig. 16 Schematic interpretation of temperature logs in terms of fracture zone distribution. Z1 is a poorly defined zone of fractures, Z2 corresponds to a fracture zone delineated also by seismic reflection profiling, and Z3 is a postulated deeper zone that dips in the same direction, to the east, but at a shallower angle (14°) than Z2 (18°). Reference ground level is elevation of collar of URL-3. Arrows indicate postulated directions of water flow. Symbols for fractures are: single line - passive fracture; double lines - fracture into which water is flowing from the hole; triple lines - such fractures at which there is also a change in thermal gradient.

