CONF-8710196--1

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36

LA-UR--87-3355

DE88 001844

TITLE: TEMPERATURE LOGGING AS AN AID TO UNDERSTANDING GROUNDWATER FLOW IN BOREHOLES

AUTHOR(S): John G. Conaway, ESS-3

SUBMITTED TO: Minerals and Geotechnical Logging Society Symposium, Golden CO, October, 1987.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes.

The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy.

MASTER

Los Alamos
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

FORM NO. 836 R4
ST. NO. 2629 5/81

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

TEMPERATURE LOGGING AS AN AID TO UNDERSTANDING GROUNDWATER FLOW IN BOREHOLES

John Conaway
Los Alamos National Laboratory
Los Alamos, NM 87545

ABSTRACT

Borehole temperatures are affected by a range of physical phenomena, including drilling and engineering procedures, thermal resistivity of the rock, surface climatic changes, local heat sources and sinks, free convection of the borehole fluid, and water flows inside the borehole. As a result, temperature logs provide unique information not available from other logs. On the other hand, because the temperature log is sensitive to a variety of phenomena, one or more of these may obscure the effect being studied.

In the case where groundwater is entering the borehole at one depth and exiting at another depth (or at the surface) the temperature disturbance resulting from this flow is likely to be a prominent feature of the temperature profile of the borehole. Because of this, water flows in boreholes are often a source of noise in temperature logs, obscuring the features of interest. Recently, however, unusual groundwater behavior was noted in several boreholes at the Nevada Test Site (NTS), and temperature logs were run as part of a program to study this phenomenon. In this case the groundwater flow has been the feature of interest in the logs, and the logs have been useful as an aid in understanding the water flow in those boreholes.

INTRODUCTION

A temperature log in a thermally stable borehole through a uniform geologic formation would normally show essentially a straight line, with the temperature increasing slowly with depth at a rate corresponding to the local geothermal gradient. Changes in the slope of this line can result from many different factors, including the following:

(1) Variations in thermal resistivity of the rock with depth along the borehole[1-3].

(2) Surface climatic changes[4].

(3) Thermal effects of drilling and engineering procedures in the borehole[5-10].

(4) Local heat sources, such as radionuclides in the rock or cement setting outside casing, or heat sinks, such as groundwater movement outside the borehole[11-13].

(5) Disturbances of the borehole fluid, such as free convection or fluid flow in the borehole[14-22].

(6) Distortion of heat flow by complicated geologic structure[23].

At one time or another, temperature logs have been used to study all of the above factors, many of which are also reviewed elsewhere[24]. Clearly, a given factor could be considered to be either signal or noise depending on the goal of the temperature survey, and in any given log several of these effects may be evident. For this reason, temperature logs are not as reliable as many of the geophysical logging techniques. Still, temperature logs can be very useful under favorable conditions, and in some cases can provide unique and valuable information.

In the case where groundwater is entering the borehole at one depth and exiting at another depth (or at the surface) the temperature disturbance resulting from this flow is likely to be a prominent feature of the temperature profile of the borehole. If the goal of the survey is, say, to make heat flow estimates, then the water flow can be a serious source of noise. If water flows are the subject of the investigation, however, the "noise" becomes the signal and the problem disappears.

Unusual groundwater behavior was noted recently in some boreholes at the Nevada Test Site (NTS). While other standard geophysical logs were of little help in studying these flows, temperature logs proved to be very useful.

SOME IDEALIZED THERMAL SIGNATURES

Some simplified examples of what an ideal temperature log might look like under various circumstances will help illustrate how the thermal effects listed above can affect the log. In the illustrations presented in this section, the borehole environment is considered ideal and thermally stable in every respect except for the one effect being illustrated in each case. In practice, several of these effects are likely to be present in the same log, and interpretation may be difficult or impossible. The illustrations given here are intended as a starting point in visualizing these effects rather than as a definitive catalog. Since some thermal disturbances, such as those caused by groundwater flow in the borehole, are time-dependent, a given illustration may or may not be representative in a particular case.

In Figure 1, Curve *a* shows an ideal temperature survey through a uniform formation. There are no disturbances of any kind. The slope of the temperature log plotted against depth depends on the thermal resistivity of the rock, and Curve *b* shows a log through three different formations having three different thermal resistivities. Curve *c* shows what the effect of a warming trend on the surface of the ground might be. Curve *d* shows the effect of the exothermic reaction involved in fresh cement setting behind the casing.

In Figure 2, Curve *a* shows how a permeable zone can appear in a temperature log in a borehole after a period of circulation of liquid colder than the rock in that region. Curve *b* shows the effect of liquid entering the borehole in the middle region of the log and flowing upward. Curve *c* shows the effect of liquid entering the borehole in the middle of the log and flowing downward. Curve *d* shows the same condition as Curve *c*, but with the liquid flowing much faster.

In Figure 3, Curve *a* is ambiguous, showing either warmer liquid entering the borehole at the bottom and flowing slowly upward, exiting near the middle of the borehole, or cooler liquid entering the borehole at the top and exiting near the middle. Curve *b* shows liquid entering the borehole in the upper part of the hole and flowing downward to exit in the bottom part of the hole. Curve *c* shows what might happen if the tool hangs up on the way down the hole, and then drops free after a short period of time.

The *temperature gradient profile* of a borehole is the first derivative of temperature with depth. Features which are barely discernible in the temperature log stand out clearly in the temperature gradient profile. For example, the minor changes of slope of the temperature log resulting from changes in thermal resistivity of the formations along the borehole are obvious when plotted as temperature gradients (Figure 4). The units

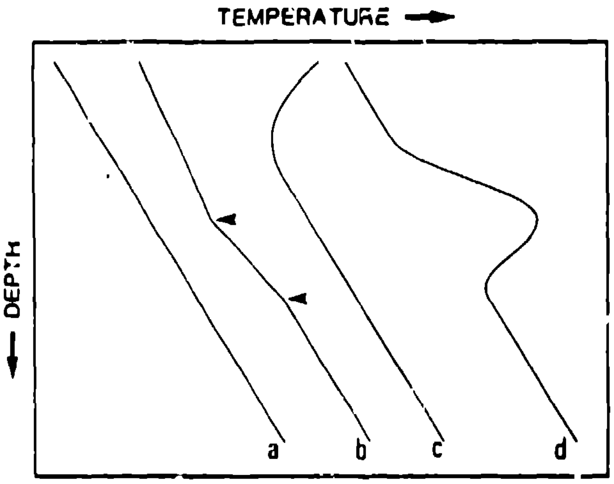

Figure 1 - *Curve a* shows a temperature survey in a thermally stable borehole through a uniform, homogeneous formation. There are no disturbances of any kind. For the ideal, steady-state situation, the slope of the line (thermal gradient) is proportional both to thermal resistivity and to the heat flow parallel to the borehole. *Curve b* shows a log through three different parallel, homogeneous formations having three different thermal resistivities. The bed boundaries are indicated by the two arrows. In the ideal case of constant, uniform heat flow parallel to the borehole and negligible influence of the borehole, the measured temperature gradient is proportional to the thermal conductivity of the rock. *Curve c* shows what the effect of a warming trend on the surface of the ground might be. Depending on the depth and temperature scale this could be seasonal (penetrating a few meters) or a long-term climatic variation (penetrating hundreds or thousands of meters into the ground). *Curve d* shows the effect of the exothermic reaction involved in fresh cement setting behind the casing. Locating the top of the cement has been a routine application of temperature logs in the petroleum industry for decades.

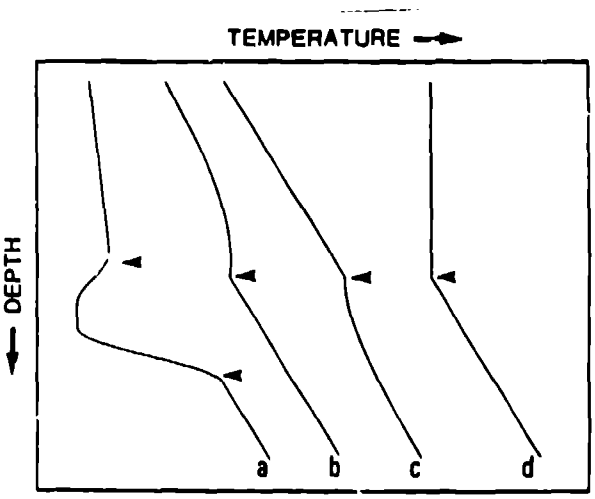

Figure 2 - *Curve a* shows how a permeable zone can appear on a temperature log in a borehole after a period of circulation of liquid colder than the rock in that region. The permeable zone is bracketed by the two arrows. The thermal gradient in the upper portion of the borehole has be changed a great deal by the circulating liquid, and the permeable zone where circulation was lost stands out as an anomalous low-temperature region. If the circulating liquid had been warmer than the rock, the temperature anomaly in the permeable zone would have been positive. *Curve b* shows the effect of liquid entering the borehole at the arrow and flowing upward. The effect of liquid flowing in the borehole can be manifested in the temperature log in many ways depending on flow rate, flow direction, properties of the rock, and number and nature of the zones of entry and exit of the liquid. Several other simple situations are illustrated in Figure 2 *c* and *d* and Figure 3 *a* and *b*. *Curve c* shows the effect of liquid entering the borehole at the arrow and flowing downward. *Curve d* shows the same condition as *Curve b*, but with the liquid flowing much faster. An actively producing gas zone can also cause similar results, and also may cause localized cooling.

shown on these axes are for purposes of illustration. The offset in the temperature log resulting from flowing water leaving the borehole becomes a prominent spike in the temperature gradient profile (Figure 5). The characteristic signature of water entering the borehole, flowing along it, and leaving the borehole at a lower level produces positive and negative excursions in the temperature gradient profile (Figure 6).

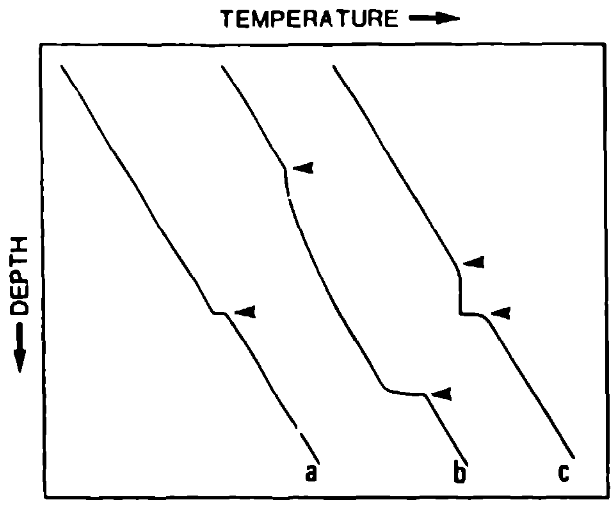

Figure 3 - *Curve a* shows liquid entering the borehole at the bottom and flowing upward, exiting at the arrow. *Curve b* shows liquid entering the borehole at the upper arrow and flowing downward to exit at the lower arrow. *Curve c* shows what might happen if the tool hangs up on the way down the hole, and then drops free after a short period of time. The tool hangs up at the upper arrow, but the shaft encoder continues to indicate increasing depth for some time as cable is payed into the hole, even though the tool has stopped. Of course, if the tool does not drop free the situation will soon become obvious on the surface. In this example, the tool drops free at the moment (apparent depth) indicated by the lower arrow.

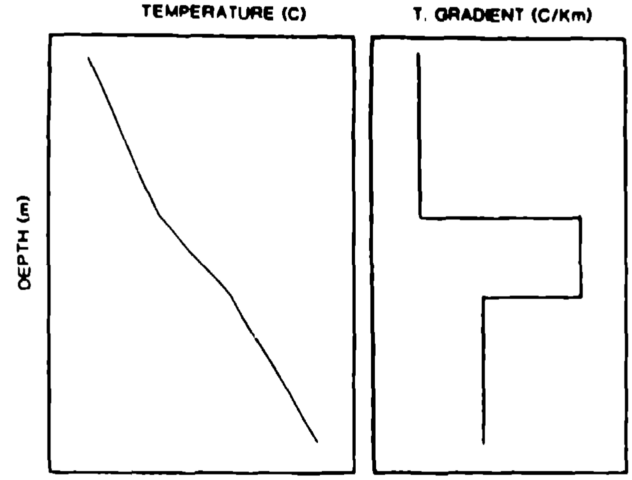

Figure 4 - The temperature log shows three distance slopes due to three geologic formations having different thermal resistivity. The temperature gradient profile, on the right, is a much more sensitive indicator of these changes in slope.

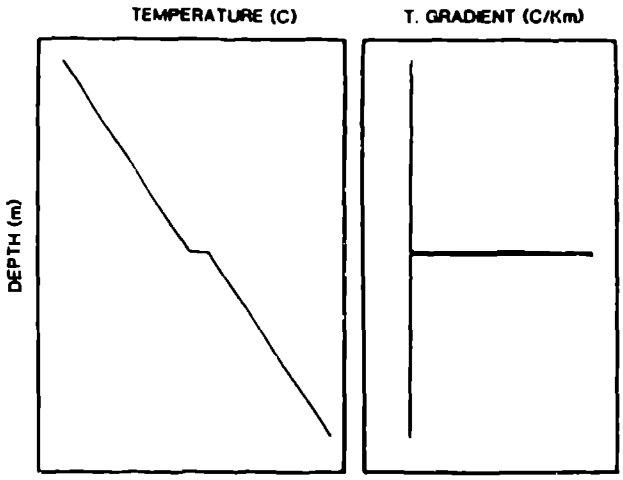

Figure 5 - The temperature log shows the characteristic offset due to flowing water leaving the borehole. In the temperature gradient profile this is manifested as a spike.

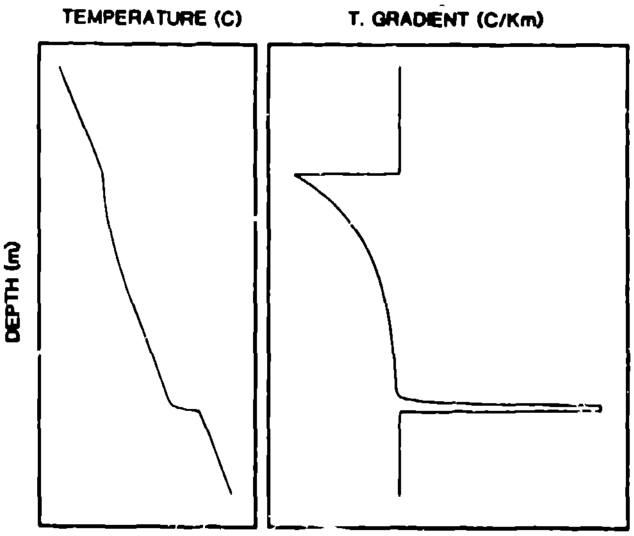

Figure 6 - The temperature log shows water entering the borehole in the upper part of the hole and flowing downward, leaving in the bottom part of the hole. In the temperature gradient profile this is manifested as a positive and negative excursion. Under certain (presumably unusual) conditions where water moves vertically along cracks or joints before entering the borehole, this curve could actually be indicating anomalously cool water entering in the lower part of the hole and flowing upward, exiting in the upper part of the hole[22].

INSTRUMENTAL CONSIDERATIONS

Accuracy is generally not a prime consideration when it comes to many applications of temperature logs. One notable exception to this is the study of vertical heat flow in the earth. For most purposes an accuracy of a few tenths Celsius is adequate. The accuracy specification for the work at the NTS is +/- 1 C. The calibration is currently performed before each log, using a bucket of water and a mercury thermometer as the standard of comparison. Although accurate enough for engineering purposes, this crude calibration has caused some problems in detailed comparisons of logs run in the same hole on different dates.

The more important specifications of a temperature logging system for the purposes described in this paper are useful precision and the thermal time constant of the sensor. The useful precision of a given system is determined by the actual output precision (the number of decimal degrees available in the recorded temperature reading) and by the thermal-equivalent electrical noise level of the logging system in decimal degrees. A useful precision of 0.001 C is a good target for precise work, and an even higher precision may be useful in some cases. This figure sometimes generates controversy in the logging community, but the only real criterion for what is useful precision should be the magnitude of the thermal signal compared with the thermal noise level in the borehole. Assuming that the sample interval in the borehole is 0.1 m, and the geothermal gradient through a given formation is 10 C/Km, the average temperature increment between readings is 0.001 C. Since thermal noise levels at least as low as 0.0001 C have been documented in a borehole under good conditions[25], it is clear that a precision of 0.001 C or better may indeed be useful in some cases[3].

The time constant of the thermal sensor is important because it degrades (smooths) the signal *before* electrical noise is added. Thus, the signal strength is reduced by the sensor time constant while the noise is not affected (except for thermal noise in the borehole). From this it is apparent that a sensor having a short time constant will give the best log, all else being equal. Time constants on the order of 1 s are achievable and this is a good target. Occasionally, the thermal sensor will pick up a glob of grease or mud on the way down the borehole and the sensor's thermal response time will be greatly increased; this can sometimes be recognized by the unusually sluggish behavior of the resulting log.

Under some conditions, accurate "stabilized" temperature data can also be extracted from the *continuous* or *dynamic* temperature log (that is, a log made with the tool constantly moving) at any desired depth by application of a simple inverse filter to remove the effect of the sensor time constant[26]. Suggested logging techniques are given in Appendix A), and a suitable filter for an exponential response has been given elsewhere[27].

QUANTITATIVE INTERPRETATION

Historically, as new logging techniques are developed they tend to be qualitative in nature. Only after a great deal of effort has been expended on development of interpretation theory do reliable quantitative results begin to emerge. In the case of temperature logs, the process of making them quantitatively useful has met with mixed success depending on the application, and in general a qualitative interpretation is the most that can be expected.

In the case of fluid flows in the borehole, attempts to derive flow rates from the temperature log tend to be based on assumptions the validity of which is generally unknown. For this reason, no effort is being expended at present to derive flow rates from the temperature logs recorded at the NTS. Some discussion of the problem of extracting quantitative information regarding flow rates and similar phenomena from temperature logs may be found elsewhere[10,21,28,29].

A CASE HISTORY

A borehole designated U4t Satellite Hole #1 (U4t-S1) was drilled at the NTS in early 1986; total depth (TD) was reached at 639.5 m on May 1, 1986. On June 4, TD was tagged at 619 m and the water level in the hole was tagged at 321.3 m, well above the supposed water table in that region. The hole was blown dry and the water level was tagged on a number of occasions, documenting a steady rise in the water in the borehole over a period of weeks.

Because of the presence of unusual amounts of water in the borehole, a study of the local hydrology was begun, including packer tests, tracer surveys, and temperature logs. Temperature logs were run by the primary logging contractor at the NTS on June 6, June 18, and July 2, 1986. These temperature logs are shown in Figure 7, Curves *a*, *b*, and *c*, respectively; Curves *d* and *e* are from borehole Ue4t, located some 200 m away from U4t-S1, and will be discussed later. The step temperature change seen in all three runs from U4t-S1 at about 320 m indicates the water level in the borehole. An additional temperature log was run in that hole on July 9 by another contractor, but the noise level of that tool is too large to permit detailed analysis of the log.

The temperature logs in U4t-S1 were run while lowering the tool into the borehole to minimize the extent to which the borehole thermal environment was disturbed by the tool. Logging speed was a slow 3 m/min. The logs were intended to be run without stopping, but run 1 was erroneously interrupted for stationary temperature measurements and some 30 m of data are missing between 565 and 595 m, and run 2 was interrupted briefly at about 420 m due to technical difficulties. As an additional difficulty, the temperature calibrations for the three runs, performed on-site with a mercury thermometer as described earlier, are different and not precisely known.

On June 6, bottom was tagged to determine TD, and an induction log was run; both of these procedures took place *before* the temperature log was run. Thus, run 1 is quite noisy due to disturbance of the water in the borehole.

Runs 2 and 3 are better logs than run 1, and some conclusions can be drawn based on them. Looking at run 2 first (Figure 7b), groundwater seems to be entering the borehole at or near the bottom. The lower 50 m of the borehole is roughly isothermal, with irregular temperature changes with depth due perhaps to mixing of inflowing water with water already in the borehole. The water appears to be flowing up the borehole and leaving the borehole at a number of levels, indicated by offsets in the temperature profile. These are presumably relatively permeable zones, including but not restricted to faults and fractures. An illustration of this water movement is shown in Figure 8.

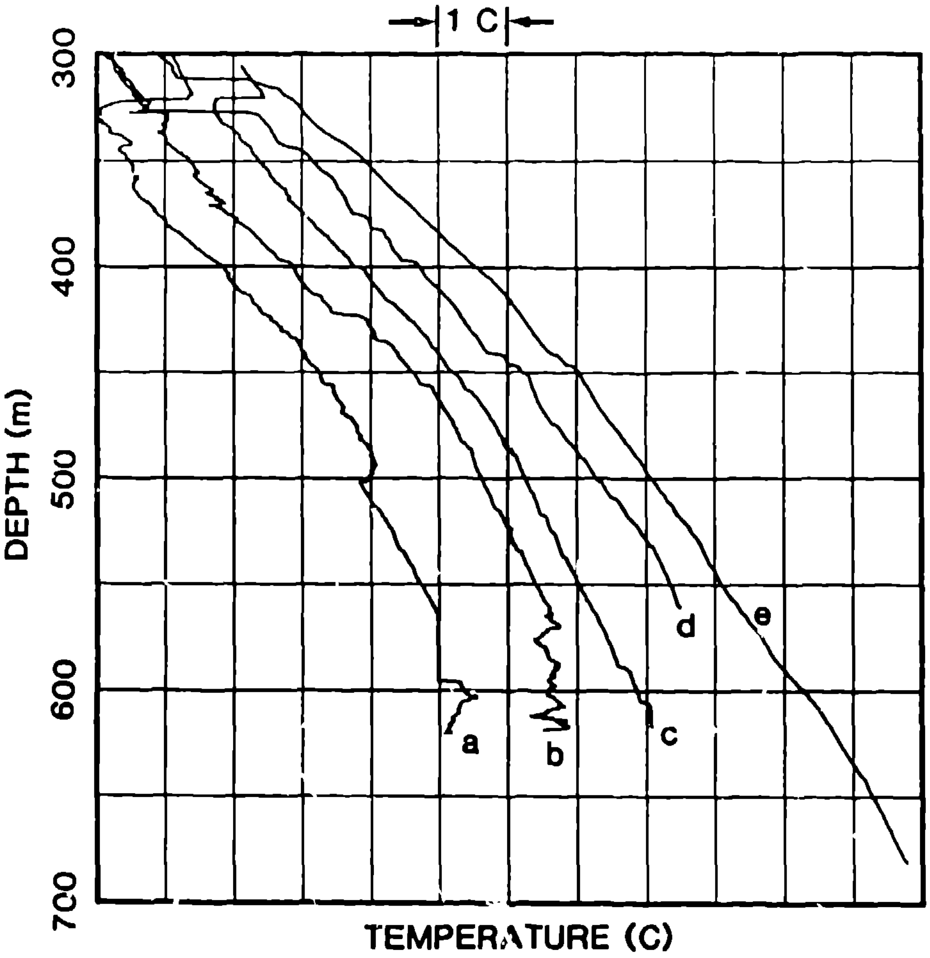

Figure 7 - Temperature logs from U4t-S1 and Ue4t. *Curves a, b,* and *c* are runs 1, 2, and 3, respectively, in U4t-S1. *Curves d* and *e* are runs 1 and 2, respectively, in Ue4t.

Run 3 shows many of the same temperature offsets as run 2 at the same depths, confirming that these features are related to fixed depths in the borehole (i.e. probably geological features) rather than noise features such as equipment problems or convection cells.

Some of the offsets seen in runs 2 and 3 have less obvious counterparts in run 1, once again indicating that these are not noise or transient disturbances. The bottom 50 m of run 1 is partially obscured due to missing data, but some sign of the possible water inflow with mixing can be seen in the bottom 20 m. That feature is no longer visible in run 3; some caving had taken place in the hole between runs 2 and 3, and the rate of water inflow may have been reduced by the extra material at the bottom of the hole.

Exploration borehole Ue4t was drilled after U4t-S1 to help understand the groundwater behavior in the area. Ue4t is located roughly 200 m south of U4t-S1. Two temperature logs were run in the hole by the prime logging contractor, on February 19 and March 13, 1987. Both logs appear to be good logs (Figure 7 Curves *d* and *e*). Similar offsets to those seen in the logs from U4t-S1 are seen in those from Ue4t, and the explanation for these is undoubtedly the same in both cases.

Figure 9 shows the portion of runs 2 and 3 in U4t-S1 between 400 and 550 m (Curves *a* and *b*, respectively), and the same depth portion of runs 1 and 2 in Ue4t (Curves *c* and *d*). This expanded view helps pick out the details, and some of the offsets indicating water leaving the borehole have been marked by arrows in this figure. Incidentally, a depth error between Curves *a* and *b* is also apparent. Temperature gradients give a still more sensitive tool for detailed interpretation. Figure 10 shows two temperature gradient profiles from U4t-S1; Curves *a* and *b* correspond to runs 2 and 3, respectively, as shown in Figure 9 (Curves *a* and *b*). These gradient profiles have been generated by numerical differentiation of the corresponding temperature logs, and have been smoothed with a cosine bell filter extending over about 1 m of depth. Curve *b* has been depth-shifted to remove the depth error mentioned above. Peaks in the temperature gradient profile (blacked in) indicate zones where the temperature increases rapidly with depth over a short depth interval. Many of the prominent peaks seem to indicate exit zones for the groundwater flowing up the hole. Similar temperature gradient profiles are given for borehole Ue4t in Figure 11; Curves *a* and *b* correspond to runs 1 and 2, as shown in Figure 9 (Curves *c* and *d*). In this case, some of the exit zones

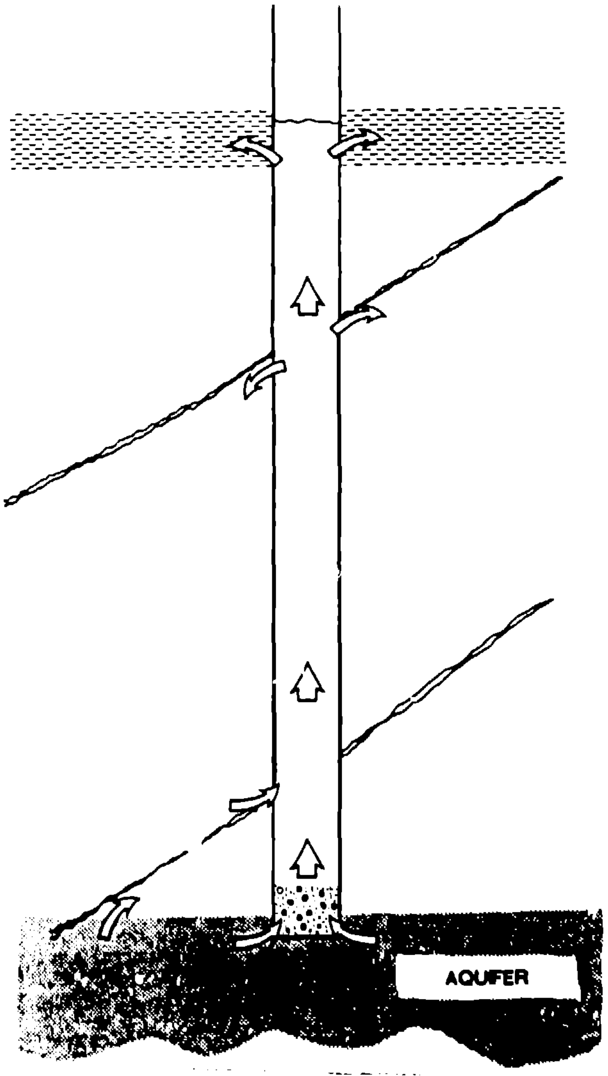

Figure 8 · Sketch of the waterflow situation which we may be seeing in U4t-S1 and Ue4t. Water from an overpressured aquifer is entering the borehole at one or more levels in the bottom, flowing upward, and leaving the borehole at many levels where the formation is permeable.

seen in Curve *a* seem to have stopped taking water by the time run 2 was made (Curve *b*). These zones may have become plugged with silt.

The suspected zones of exit of water from the borehole seen in the temperature logs and temperature gradient profiles generally correspond with electrical resistivity lows. This seems reasonable. Penetration of liquid into a dry or partially saturated formation would be expected to lower the electrical resistivity of the medium. The exit zones often correlate with hole enlargements as indicated by the caliper log, as well. This also is expected, since zones of enhanced permeability often are associated with faults, fractures, friable zones and poorly consolidated materials, all of which are less competent than normal undisturbed rock and are therefore susceptible to caving or washout.

DISCUSSION AND CONCLUSIONS

Temperature logs are influenced by many factors, including thermal resistivity of the rock, geologic structure, free convection of the borehole fluid, groundwater flows, and heat sources and sinks. Because of their sensitivity to many factors, temperature logs are not always useful in a given application. In studying groundwater flows, however, temperature logs can indicate zones of entrance and exit of the water.

The temperature logs run in Ue4t and U4t-S1 were run to test whether the logs would be useful in studying groundwater flow in this area. From the results presented in this paper, that is clearly the case. Optimum procedure was not followed in running these logs, and the interpretations given here are necessarily limited in scope. For more definitive results in studying a given hole, a study program should be set up before the hole is completed. The program would include temperature logs run using proper procedure (Appendix A) at regular intervals of time after the hole is completed. Frequent water level tags can also be useful. For more intensive study, the temperature logs can be used to augment and help plan packer and tracer surveys.

ACKNOWLEDGEMENTS

This work is supported by the United States Department of Energy.

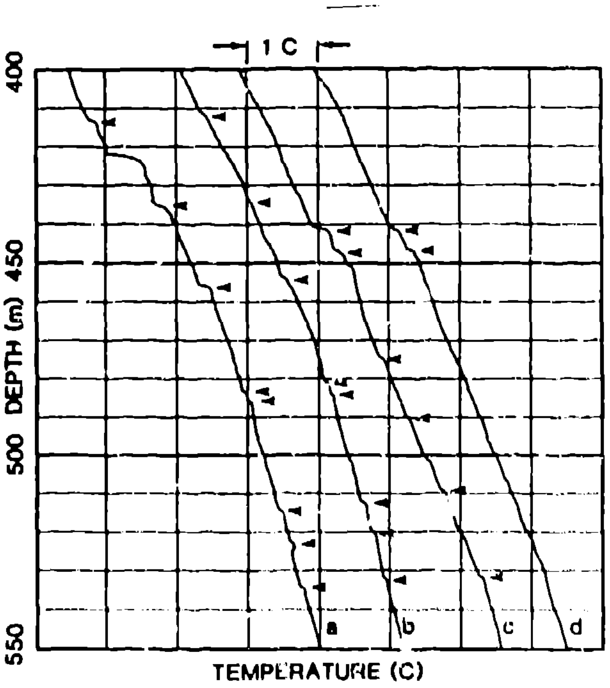

Figure 9 · A portion of the temperature logs from U4t-S1 and Ue4t. *Curves a* and *b* are runs 2 and 3, respectively, in U4t-S1. *Curves c* and *d* are runs 1 and 2, respectively, in Ue4t. Depth offsets ascribed to water leaving the borehole are indicated by arrows.

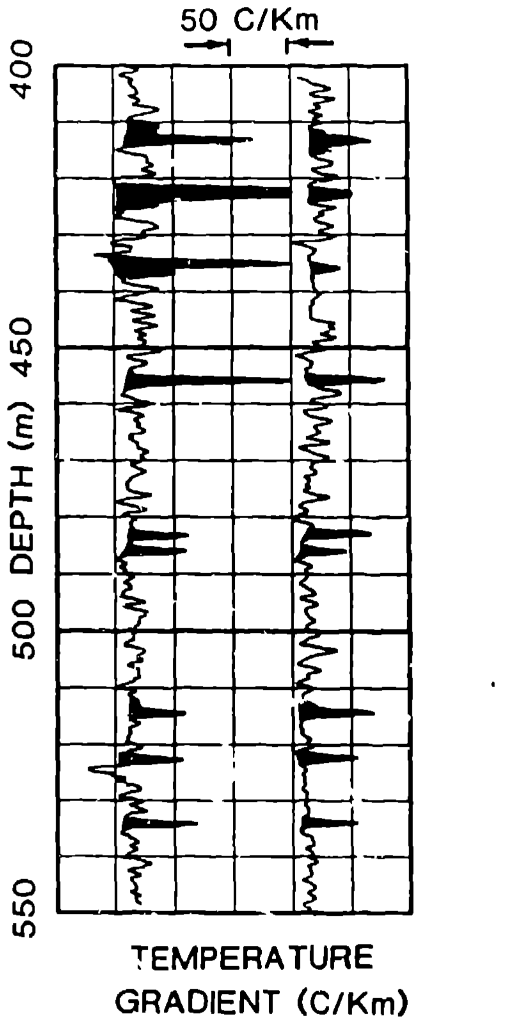

Figure 10 - A portion of the temperature gradient profiles from U4t-S1. The curve on the left is run 2, and the curve on the right is run 3. The peaks (blacked in) correspond to the temperature offsets seen in figure 9.

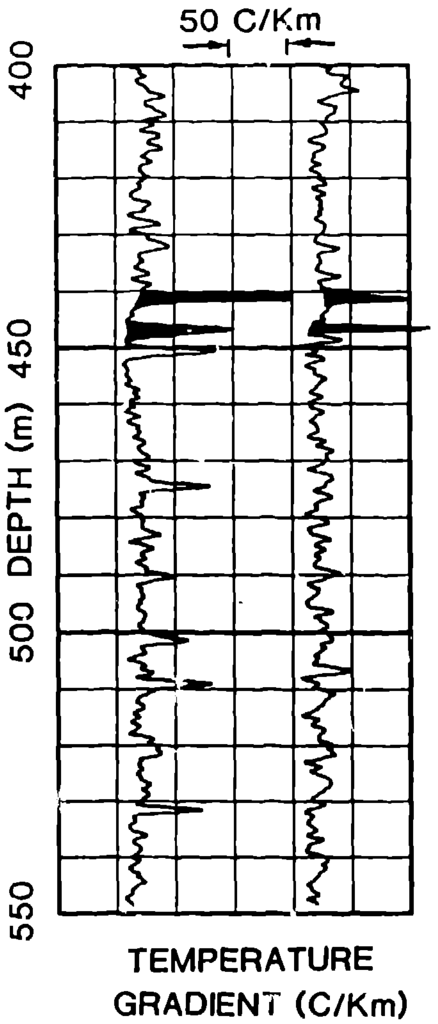

Figure 11 - A portion of the temperature gradient profiles from Ue4t. The curve on the left is run 1, and the curve on the right is run 2. The peaks (blacked in) correspond to the temperature offsets seen in figure 9.

REFERENCES

1. Roy, F. R., "Heat flow measurements in the United States," Ph.D. Thesis, Harvard University (1963).

2. Beck, A. E., "The use of thermal resistivity logs in stratigraphic correlation," *Geophysics*, 41, 300 - 309 (1976).

3. Conaway, J. G., and Beck, A. E., "Fine-scale correlation between temperature gradient logs and lithology," *Geophysics*, 42, 1401 - 1410 (1977).

4. Beck, A. E., "Climatically perturbed temperature gradients and their effect on regional and continental heat-flow means," *Tectonophysics*, 41, 17 - 39 (1977).

5. Lachenbruch, A. H., and Brewer, M. C., "Dissipation of temperature effect in drilling a well in Arctic Alaska," U. S. G. S. Bull. 1083-C, 73 - 109 (1959).

6. Smith, R. C., and Steffensen, R. J., "Computer study of factors affecting temperature profiles in water injection wells," *J. Pet. Tech.*, 22, 1447-1458, 1970.

7. Smith, R. C., and Steffensen, R. J., "Interpretation of temperature profiles in water-injection wells," J. Pet. Tech., 27, 777 784, 1975.

8. Keys, W. S., and Brown, R. F., "The use of temperature logs to trace the movement of injected water," *Ground Water*, 16, 32-48 (1978).

9. Fagley, J., Fogler, H. S., Davenport, C. B., and Millhone, R. S., "An improved simulation for interpreting temperature logs in water injection wells," *Soc. Pet. Eng. J.*, , 709-718 (1982).

10. Murphy, H. D., "Enhanced interpretation of temperature surveys taken during injection or production," *J Pet. Tech.*, 34, 1313-1326 (1982).

11. Bredehoeft, J. D., and Papadopulos, I. S., "Rates of vertical groundwater movement estimated from the Earth's thermal profile," *Water Resources Res.*, 1, 325-328 (1965).

12. Sorey, M. L., "Measurement of vertical groundwater velocity from temperature profiles in wells," *Water Resources Res.*, 7, 963-970 (1971).

13. Cook, C. E., "Radial differential temperature (RDT) logging - a new tool for detecting and treating flow behind casing," *J. Pet. Tech.*, 31, 676-682 (1979).

14. Diment, W. H., "Thermal regime of a large diameter borehole: Instability of the water column and comparison of air- and water-filled conditions," *Geophysics*, 32, 720 - 726 (1967).

15. Gretener, P. E., "On the thermal instability of large diameter wells - An observational report," *Geophysics*, 32, 727 - 738 (1967).

16. Sammel, E. A., "Convective flow and its effect on temperature logging in small-diameter wells," *Geophysics*, 33, 1004 - 1012 (1968).

17. Sass, J. H., Munroe, R. J., and Moses, T. H., "Heat flow from eastern Panama and northwestern Colombia," *Earth and Planet. Sci. Let.*, 21, 134-142 (1974).

18. Gupta, B. S., "Case Histories of temperature surveys in Kuwait," *J. Pet. Tech*, 33, 2505-2514 (1981).

19. Ibrahim, M. W., "Discussion of 'Case histories of temperature surveys in Kuwait' by B. S. Gupta, with a reply by the author," *J. Pet. Tech*, 34, 2403-2405 (1982).

20. Grant, M. A., Bixley, P. F., and Donaldson, I. G., "Internal flows in geothermal wells: their identification and effect on the wellbore temperature and pressure profiles," *Soc. Pet. Eng. J.*, 168-176 (1983).

21. Beck, A. E., and Shen, P. Y., "Temperature distribution in flowing liquid wells," *Geophysics*, 50, 1113-1118 (1985).

22. Beck, A. E., and Balling, N., "The determination of virgin rock temperatures," in *Handbook of Terrestrial Heatflow Density*, Chapter 3, R. Haenel, L. Ryback and L. Stegna, editors, Reidel Pub., Holland (in press).

23. Lee, Tien-Chang, and Henyey, T. L., "Heat-flow refraction across dissimilar media," *Geophys. J. R. Astr. Soc.*, 39, 319-333 (1974).

24. Kappelmeyer, O., and Haenel, R., "Geothermics, with Special Reference to Application," Geopublication Associates, Gebruder Borntraeger, Stuttgart (1974).

25. Bristow, Q., and Conaway, J. G., "Temperature gradient measurements in boreholes using low noise high resolution digital techniques," in *Current Research*, Part B, Geological Survey of Canada Paper 84-1b, 101 - 108 (1984).

26. Costain, J. K., "Probe response and continuous temperature measurements," *J. Geophys. Res.*, 75, 3969 - 3975 (1970).

27. Conaway, J. G., "Exact inverse filters for the deconvolution of gamma-ray logs," *Geoexploration*, 18, 1 - 14 (1980).

28. Boldizsar, T., "The distribution of temperature in flowing wells," *Am. J. Sci.*, 256, 294-298 (1958).

29. Ramey, H. J., "Wellbore heat transmissions," *J. Pet. Tech.*, 14, 427-435, 1962.

APPENDIX A

OPTIMUM LOGGING TECHNIQUES FOR HIGH-RESOLUTION TEMPERATURE LOGS

The equilibrium thermal regime in a borehole is delicate and easily disrupted. Temperature logs must be run properly to minimize the effect of the logging process on the in situ temperatures. A few observations about temperature logs and some guidelines to follow in running the logs are given in this appendix.

1. In general, smaller diameter boreholes will give better temperature logs than larger diameter boreholes. Smaller boreholes are less prone to free convection, and the disturbing effects of the drilling process on the borehole temperature regime do not last as long. Also, for a given temperature regime, the more viscous the fluid, the larger the borehole must be before free convection sets in.
2. If true formation temperatures are desired, the temperature log should generally be run as late as possible after drilling to minimize errors due to the circulation of drilling fluid. Obviously, if the fluid is pumped out and replaced or circulated after the drilling is finished the hole will require some time to reach equilibrium temperature.
3. The temperature log should be the first log run on a given day.
4. The log should be run down the hole rather than up so that the thermal sensor is entering undisturbed fluid.
5. The log should be run in a single continuous pass. The tool should not be stopped in the borehole until the entire downward run is completed.
6. Running the log slowly helps improve precision, especially if the sensor time constant is relatively long.
7. Accurate "equilibrium" temperature data can be extracted from the dynamic temperature log in some cases by application of a simple inverse filter to remove the effect of the sensor time constant. Temperature readings obtained in this manner are less susceptible to errors resulting from the thermal mass of the tool than are stationary readings.
8. For best results, more than one log should be run, especially if the logs are run shortly after drilling is completed (within a few days, weeks, or months

depending on the drilling method). This allows the analyst to discriminate more effectively between noise and desired information. The hole should be allowed to stabilize at least overnight after a log before running additional temperature logs.

9. If high-resolution temperature gradients are to be computed from a temperature log, the thermal sensor must have very high precision and low noise. A precision of .001 C with a noise level at or below that figure makes a good target when specifying temperature logging equipment.