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A SIMPLE METHOD FOR DETECTING ANOMALOUS FLUID MOTIONS IN BOREHOLES FROM CONTINUOUS TEMPERATURE LOGS

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ABSTRACT

Above a critical Rayleigh number, the fluid in a borehole convects. The aspect ratio of the convective motions is commonly between four and ten as determined by temperature-time recordings at fixed depths in cased holes. Aspect ratios greatly in excess of this range indicate anomalous fluid-flow in the hole such as might be caused by exchange of fluid among aquifers. Such high-aspect ratios can be detected from a single continuous temperature-depth log by taking the difference between the temperature gradient over a short interval and that over a longer spanning interval and dividing this difference by the gradient over the longer interval. This provides a measure of the gradient error (GE) from which an aspect ratio (AR) can be calculated. GEAR logs are presented for a large and a small diameter hole and for a large-diameter partially cased hole containing a small-diameter tubing. We attempt a preliminary assessment of the value and applicability of GEAR logs to the detection of fluid flow in and about geothermal wells.

INTRODUCTION

The criteria for the onset of convection in a vertical column of fluid heated from below was first expressed by Hales (1937). The transition from stable to turbulent conditions has been studied in laboratory experiments (e.g. Verhoeven, 1969; Olson and Roenroting, 1979). In water-filled bore holes larger than a few centimeters in radius, the convection is usually fully turbulent provided temperature increases with depth. Convection in deep water-filled holes was first observed by means of temperature-time recordings at fixed depths by Diment (1967) and Gretener (1967). More recently, such studies have been expanded to include observations in holes of a wide range in hole diameter and in holes exhibiting large ranges in geothermal gradient (Urban, et al., 1978; Urban and Diment, 1980; Diment and Urban, 1982).

Although the convective motion is turbulent in cased water-filled holes, temperature-time recordings at fixed depths reveal a quasi-periodicity about a mean value. The maximum range (R) in temperature tends to repeat within successive ten-minute intervals. Aspect ratios (AR=height/radius) of fluid motion computed from these ranges tend to fall between four and ten (Urban and Diment, 1980). AR = R/(G'a), where A is the aspect ratio, a is the radius of the hole, and G' is the thermal gradient at the depth of recording.

In open holes or in holes with perforated casings, which permit fluid flow along the hole, temperature-time recordings at fixed depths tend to be rather different, and aspect ratios tend to be higher, but our experience is very limited. Anomalous conditions might also be expected in cased holes where the annulus between the casing and hole is open and fluid is convecting or otherwise flowing within the annulus. The question is whether the same kind of information can be obtained from a single-temperature log obtained by lowering a probe at a constant rate down the hole as can be obtained by temperature-time recordings at fixed depths.

METHOD

Let us suppose that the observed temperature gradient across a short interval of depth in a hole is G and that the true or equilibrium gradient is G'.

\[ G = \frac{[T_1 - (T_2 + R)]}{AZ} = G' \pm \frac{2R}{AZ} \]

where \( T_1 \) and \( T_2 \) are the equilibrium temperatures of the top and bottom of the depth interval (AZ) and R is the range of temperature due to convective motion. The largest departure of the observed gradient from equilibrium gradient would be when the R's are largest and of opposite sign, that is 2R/AZ. It has been shown from temperature-time recordings at fixed depths that R can be approximately expressed as R = (G'aA) (Diment, 1967; Urban and Diment, 1980). It should be emphasized that we are dealing with turbulent convection, and the R derived from temperature-time recordings is simply the maximum temperature range observed over a ten-minute interval. In long recordings (hours) at the same depths, successive R's, and therefore A's, tend to have roughly the same values. We do not intend that any deeper significance be attached to R or A. It follows that:

\[ G = G' \pm \frac{(2G'aA)}{AZ} \]

and

\[ (G - G')/G' = \frac{\pm(2aA)}{AZ} = \text{Gradient Error} \]
or

\[ A = \frac{\partial z(G - G')/(2aG')}{\partial z} = \text{Aspect Ratio}. \]

In practice, we have taken \( \Delta z \) as 0.61 meters (our digitizing interval) and have supposed that \( G' \) could be represented by a spanning interval 5 times \( \Delta z \). The limitations of this approach are obvious; e.g. the gradient may not be linear over 5\( \Delta z \). However, in some applications we are not looking for small variations in GEAR (gradient error-aspect ratio) but for large ones such as may be due to large fluid motions along the hole, or along the annulus between hole and casing. In the examples which follow, we have used the absolute value of the aspect ratio because a negative value of \( A \) has no physical significance and because aspect ratio is normalized by the hole diameter. Thus, we might be able to tell whether convection is primarily within the casing or within the annulus between the hole and casing.

Instrumental noise in GEAR plots is significant because we are measuring the thermal gradient over a very short interval of depth. Thus, when the thermal gradient is low, noise contributes a larger part to the error in the GEAR logs. The problem is exacerbated by the fact that the sensitivity of thermistors used to determine temperatures decreases exponentially with increase in temperature; thus, a greater component of noise would be expected at higher temperature, especially in the deep geothermal wells considered here. The GEAR logs may be quite useful provided these limitations are understood, as will be demonstrated in the examples which follow.

**OBSERVATIONS**

GEAR logs were selected from three wells (Table 1) which permit comparison of results obtained under very different conditions. East Mesa well 31-1 is cased with pipe of uniform diameter which was cemented in place except near the bottom where the casing is slotted. Desert Peak well B23-1 has a surface string of casing cemented-in to a depth of 901 meters. The remainder of the hole is open except for a small diameter tubing extending from the surface to near the bottom. Raft River HO-9 is a shallow exploration hole in which a small diameter casing was carefully cemented into place. For each hole, we present a temperature log \((T)\) plotted at 0.61-meter intervals, a temperature-gradient log \((G)\) for 20-meter depth intervals, a GEAR log \((A)\) based on the ratio of gradient observed over an 0.61-meter interval to that over a 3.05 meter spanning interval, and an average GEAR log \((\bar{A})\) obtained by averaging aspect ratios over 30.5 meter intervals. With the exception of the temperature logs, which were machine-plotted point by point, the remainder of the logs were machine-plotted in the fashion of a histogram. This explains why the A logs are largely black where A varies rapidly. Had a greatly expanded depth scale been used, the A logs would look much different. Although values of \( \bar{A} \) may exceed several hundred, the plots terminate at 20 so that the smaller variations may be seen.

There are occasional noise spikes in all of the GEAR logs, even in those intervals which \( A \) is relatively low. We think these anomalies are largely electronic noise. However, we are cognizant of the possibility of thermo-haline convection (e.g. Turner, 1973) in drill holes and of the possibility of large solitary, convective events, which may occur in small diameter holes (Urban and Diment, 1980).

<table>
<thead>
<tr>
<th>Well</th>
<th>Number</th>
<th>Drilled by</th>
<th>State</th>
<th>County</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Depth</th>
<th>Casing depth</th>
<th>Casing</th>
<th>Tubing</th>
<th>Wellhead</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desert Peak</td>
<td>B23-1</td>
<td>Phillips</td>
<td>Nevada</td>
<td>Churchill 11</td>
<td>39°46.6'N</td>
<td>118°55.6'W</td>
<td>167 m</td>
<td>901 m</td>
<td>1647 m</td>
<td>none</td>
<td>1 atm</td>
</tr>
<tr>
<td>East Mesa</td>
<td>31-1</td>
<td>USBR</td>
<td>California</td>
<td>Imperial</td>
<td>32°48.6'N</td>
<td>115°15.7'W</td>
<td>5 atm</td>
<td>none</td>
<td>none</td>
<td>none</td>
<td>5 atm</td>
</tr>
<tr>
<td>Raft River</td>
<td>HO-9</td>
<td>USSR USGS</td>
<td>Idaho</td>
<td>Cassia</td>
<td>42°6.8'N</td>
<td>113°23.9'W</td>
<td>1 atm</td>
<td>none</td>
<td>none</td>
<td>none</td>
<td>1 atm</td>
</tr>
</tbody>
</table>

All depths are relative to ground level.
* Casing is slotted between 1647 and 1877 m.

Let us begin with East Mesa 31-1 (Fig. 1) where we have had the opportunity to make repeatable temperature logs under relatively undisturbed conditions (Urban et al., 1978; Diment and Urban, 1982), but where we have not attempted to construct GEAR logs before. In the A and \( \bar{A} \) logs (Fig. 1), it is obvious that these quantities are low and more or less what would be expected in the upper part of the hole in the sense that A and \( \bar{A} \) are well below the maximum values calculated for A from temperature-time recordings at fixed depths, the modal value of which is about A=6 (Urban and Diment, 1980). However, in the lower part of the hole, where the casing is slotted the range in A increases dramatically. We attribute this to exchange of fluids among aquifers in the slotted interval and perhaps to fluid motions in an uncemented part of annulus just above the slotted interval (Diment and Urban, 1982). Although all three temperature logs look rather noise free (Diment and Urban, 1982), the GEAR plots reveal a different picture (Fig. 2). Comparison of A logs obtained four days apart in 1978, indicated that the log obtained with the probe centralized in the hole (5/26/79) is far less noisy than the log obtained when the probe was lowered down the side of the hole (6/3/78). Moreover, the comparison of A logs obtained with centralizers in 1978 and 1982 look remarkably similar, with the exception of details in the top of the slotted interval which may reflect differences in flow patterns along the slotted interval (Diment and Urban, 1982). The reason for the differences in the A logs obtained with central-
ized and non-centralized probes is not clear. Temperature-time recordings at fixed depth with centralized and non-centralized probes show no obvious differences.

The Desert Peak well B23-1 (Fig. 3) presents a different environment. A surface string of casing was cemented-in to a depth of 901 meters, but the remainder of the hole is uncased. The temperature logs were made through a small diameter water-filled tubing. Presumably, the annulus between the tubing and the hole is also filled with water. Aspect ratios have been computed using the radius of the tubing; had they been computed using the radius of the casing, they would be about five times smaller which would make them smaller than those in East Mesa well 31-1. On the basis of this comparison, we conclude that convective motions in both the tubing and the annulus in Desert Peak well B23-1 influence the size of A and Â. Complications will be noted later.

Below the casing in the Desert Peak well, A and Â become very large where thermal gradient decreases substantially and even become negative for short intervals. We have attributed these anomalous conditions to exchange of fluids among aquifers in the uncemented part of the hole possibly including downward flow from a hot-water aquifer near the depth of the temperature maximum (Urban and Diment, 1982). Below the casing, the GEAR logs for the two different dates (Fig. 4) are rather different and reflect the continued evolution of thermal conditions in the hole. In particular, the lower part of hole has warmed up, and the thermal gradients have decreased (Urban and Diment, 1982).

Raft River HO-9 represents a class of shallow holes which have been drilled to delineate geothermal gradients for the purpose of identifying deep geothermal anomalies. Careful attention was given to the sealing of the annulus between pipe and hole with cement. Thus, temperature measurements in these holes, which were obtained long after drilling and completion, reflect equilibrium conditions. The values of A and Â are slightly larger and more variable than in East Mesa well 31-1. This would be expected because we have shown from temperature-time recordings at fixed depths in many holes that modal value of A for large-diameter holes is about six, and that the distribution of A's is roughly symmetrical about the mode. For small-diameter holes, the modal value of A is not much higher (about nine), but the distribution of A's is distinctly skewed toward higher values of A.

The differences in A's for large and small diameter holes raises a problem as to how to interpret data obtained in a small-diameter tubing, within a larger hole, cased or not, as in Desert Peak well B23-1. Provided the fluid in the annulus is capable of convecting, there would be a coupling of thermal effects across a high thermal conductivity tubing and GEAR logs would reflect a combination of these different convective regimes.

CONCLUSIONS

The development of precision, digitally recorded temperature logs, along with modest computer capability, permits manipulation of subsurface temperature data that was impossible a few years ago. Although the increased capability illustrates the imperfection in our data acquisition systems, our field techniques, and our lack of theoretical and experimental knowledge of convection in drill holes, it may also open promising avenues for expanded use of temperature logging. Acquisition of similar knowledge in unrelated fields is being vigorously pursued (e.g. Gollub and Benson, 1980). The question remains as to how this increasing knowledge can be applied to the analysis of geothermal logs. We usually deal with temperature logs obtained in a congealing mud of unknown properties that is contained within holes that are far from thermal equilibrium with respect to surrounding formations. However, when the holes are filled with water, much more information can be obtained especially if repeated logs can be made over a period of time.

We have proposed, in the form of GEAR logs, a very simple, perhaps simplistic, means of examining digitally recorded precision temperature logs. More sophisticated means will be found once the nature of turbulence is more fully understood. Nonetheless, we would venture the following conclusions based on GEAR logs and related observations: (1) Noisy logs due to instrumental imperfections can be readily identified in water-filled holes obtained long after drilling. (2) The problems encountered in mud or water-filled holes obtained shortly after drilling are quite different. The thermal effects of invasion of drilling fluid into surrounding formations may persist for a long time depending on the amount of fluid involved (e.g. Nathenson et al., 1979; Diment, 1980). Thus, the true temperature of geothermal aquifers may be underestimated. GEAR logs tend to be anomalously noisy across invaded intervals that have not returned to thermal equilibrium. (3) Fluid flow along holes can be detected under certain circumstances, but only a few situations have been examined, and it is not appropriate to generalize at this time. (4) The exsolution or dissolution of gases in water-filled holes can produce anomalous GEAR logs in shallow holes (e.g. Diment, et al., 1981). The problem may be rather common in deep geothermal wells where CO₂ is a significant component of the fluid column (e.g. Straus and Schubert, 1979). (5) GEAR logs may have the potential for discovering uncemented intervals behind casings providing the fluid in the annulus is convecting. This has not yet been proven and will not be until tested against high-quality cement bond logs. (6) GEAR logs in cased, water-filled holes may provide a sensitive display, long after drilling, of changes in water movements in aquifers penetrated by a hole. This problem may be important in the assessment of changes of flow in geothermal systems as might be occasioned by earthquake shaking or dilations due to the inflation of magma bodies at depth.
Figure 1. Temperature (T), temperature gradient (G), aspect ratio (A) and average aspect ratio ($\bar{A}$) logs observed in East Mesa well 31-1 on February 2, 1983. The casing is slotted below 1647 meters. See Table 1 and text for further details.

Figure 2. Comparison of aspect ratio (A) logs obtained in East Mesa well 31-1 on the dates indicated. The pairs of logs are placed side by side with the sign reversed to facilitate comparison. The log obtained on June 3, 1978, with the temperature-sensing probe free to swing in the hole. The probe was centered in the hole by centralizers above the probe for the remaining logs.
Figure 3 (above). Temperature ($T$), temperature gradient ($G$), aspect ratio ($A$), and average aspect ratio ($\bar{A}$) logs obtained in Desert Peak well B23-1 on October 19, 1979. The logs were made in a small diameter tubing and start at the top of the fluid column. A surface string of casing was cemented into a depth of 901 meters. See Table 1 and text for further details.

Figure 4 (left). Comparison of aspect ratio ($A$) logs obtained in Desert Peak well B23-1 on the dates indicated. They are plotted side by side with the sign of $A$ reversed on one log to facilitate comparison.
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REFERENCES


Diment, W. H., and Urban, T. C., 1982, Temperature changes with time in a deep, shut-in geothermal well near thermal equilibrium - East Mesa well 31-1, Imperial County, California: Geothermal Resources Council Transactions, v. 6, pp. 249-252.


Verhoeven, J. D., 1969, Experimental study of thermal convection in a vertical cylinder of mercury heated from below: The Physics of Fluids, v. 12, pp. 1733-1740.