GEOPHYSICS, VOL. 41, NO. 2 (APRIL 1976): P. 300–309, 5 FIGS., 3 TABLES

26

THE USE OF THERMAL RESISTIVITY LOGS IN STRATIGRAPHIC CORRELATION

A. E. BECK*

Since it has been found that the heat flow along a borehole rarely deviates more than 20 percent from the mean equilibrium value and that formation thermal resistivities may vary by as much as an order of magnitude, the profile of temperature gradient versus depth is equivalent to a log of thermal resistivity (T-log). In this work high precision temperature measurements in cased boreholes were used which yielded temperature gradients as high as 140°C/km.

Using the equivalence between thermal resistivity and temperature gradients, it has been found that the T-logs are characteristic of the formations in which they were measured with a general negative correlation between thermal resistivity and electrical resistivity, except in coal (and perhaps gas) bearing formations.

In one instance, the character of the resistivity log was used to conclude that a horizon deduced from the electrical resistivity log had been mis-picked by nearly 100 m.

INTRODUCTION

The field work on which this paper is based was originally intended simply to measure terrestrial heat flow in cased boreholes near Roma, Queensland, Australia. The Roma area forms part of the Surat Basin, which is a subbasin of the great Artesian Basin. The sedimentary formations are relatively flat lying on the regional scale and contain numerous seams of coal and carbonaceous shale up to 1 m thick (Gray, 1972) which are of minor economic interest. Many boreholes, drilled principally for gas exploration purposes, penetrate the formations and are of a suspended status. Most of these suspended wells are mud filled and, therefore, could not be used to depths greater than 100 m with the equipment used; only two water-filled holes were open to the bottom (1 km).

The usual procedure (Beck, 1965) in heat flow work is to plot temperature versus depth, obtain values of formation thermal conductivity at appropriate depths, and combine the temperature and conductivity data in one of several ways to give an equilibrium heat flow value. However in this work some unusually large changes in temperature gradient over short intervals were observed. Detailed measurements of conductivity have not been made yet, but sufficient data have been obtained to indicate that the equilibrium heat flow is close to the mean continental value o $1.5\,\mu\,\mathrm{cal\,cm^{-2}\,sec^{-1}}$ (1.5 HFU). There is no reason to suspect any significant influence from hea sources or sinks, or structure in the vicinity of the borehole, and it has been found (Beck and Judge 1969) that in the absence of obvious disturbing influences such as these, the heat flow values obtained along a borehole rarely depart by more than 20 percent of the mean value. Therefore, a log of temperature gradient versus depth is essentially the same as a log of thermal resistivity versus depth. Hereafter the log of temperature gradient (or thermal resistivity) versus depth will be referred to as the T-log.

Paper presented at the 44th Annual International SEG Meeting, November 12, 1974, Dallas, Tex. Manuscrip received by the Editor May 20, 1975; revised manuscript received July 14, 1975.

* University of Western Ontario, London, Ont.; formerly University of Queensland, Brisbane, Australia.

adients, it has been found
teristic of the formations
ured with a general nega-
thermal resistivity and
pt in coal (and perhaps

aracter of the resistivity
that a horizon deduced
ivity log had been mis-

one of several ways to
flow value. However,
lly large changes in tem-
short intervals were ob-
rements of conductivity
, but sufficient data have
te that the equilibrium
ean continental value of
FU). There is no reason
nt influence from heat
ture in the vicinity of the
found (Beck and Judge,
of obvious disturbing
the heat flow values ob-
rarely depart by more
ean value. Therefore, a
nt versus depth is essen-
thermal resistivity ver-
e log of temperature
tivity) versus depth will
g.

. Dallas, Tex. Manuscript

isbane, Australia.

Because the temperature gradients and, therefore, the thermal resistivities vary by nearly an order of magnitude, it was decided to compare T-logs with the electrical resistivity logs (E-logs).

FIELD PROCEDURES

The principal difficulty in using the existing set of thermal data is the lack of detail in the T-log. In terrestrial heat flow work, the usual practice is to lower the temperature sensor stepwise, leave the thermistor at a particular depth for 2 or 3 minutes to allow it to come to within a few thousandths of a degree centrigrade of its surrounding temperature, and then take a measurement. This is a time-consuming procedure if done for very small depth intervals, and the standard depth interval, for holes as deep as 1 km, is 10 m. For a comparison of the broad features of temperature gradients or thermal resistivity between boreholes, the coarse depth interval does not present much of a problem, but when the T-log is to be compared with an E-log, the latter containing much more detail, the averaging effect of taking large depth intervals must be considered more carefully.

To determine just how a 10-m interval would affect the appearance of a T-log, two runs were made in a mud filled borehole over a depth of nearly 200 m. On the downward run the standard 10-m interval was used and the temperature gradient data plotted as shown on curve 1 in Figure 1; nearly all curves are point-to-point plots because they were produced by a computer plotter. On the return up the borehole, 3-m intervals were used and the data plotted in three different ways. Curve 2, Figure 1, is a plot of 3-m interval gradients which shows considerably more detail than curve 1. Curve 3 is a plot of a running average taken over three intervals, i.e., each point represents a temperature gradient over approximately 10 m. Curve 4 was obtained by having a person who knew nothing about curves 1 and 3 smooth curve 2 by eye. It is quite clear that the broad features of T-log profiles are well preserved in a 10-m interval technique, although such a profile obviously lacks detail.

ELECTRICAL RESISTIVITY

Electrical resistivity profiles (E-logs) were available, having been obtained with a guarded electrode system run after the drill rods were pulled back to a depth of about 100 m. The depth interval over which a typical resistivity measurement is applicable is far less than the standard 10-m interval used for the T-log. There is, therefore, much more detail available from the E-logs than from the T-logs. To make a reasonable comparison, the E-logs must be smoothed in some manner. This was done by averaging the electrical resistivity value by eye over 3-m intervals and then computing the running average of the electrical resistivity over three intervals; that is, the smoothing procedure is similar to that described above for temperature gradients.

COMPARISON OF T-LOGS AND E-LOGS

Figure 2 shows the complete profiles in two boreholes, Euthalla No. 1 and Pleasant Hills No.

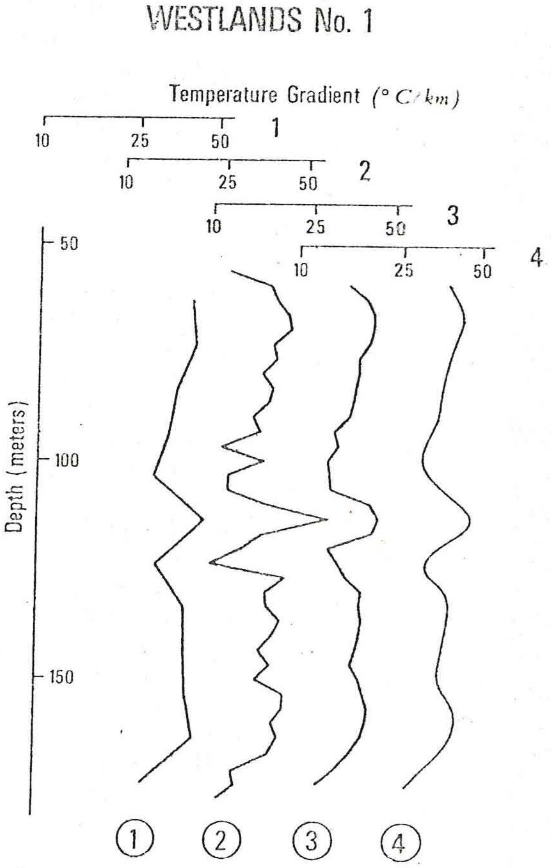

FIG. 1. Effect of treatment of temperature data on temperature gradient profile; all gradients in °C/km and on logarithmic scale. Curve 1: 10-m intervals going down; curve 2: 3-m intervals coming up; curve 3: 10-m running average of data from curve 2; curve 4: same as curve 3 but data of curve 2 smoothed by eye by person with no knowledge of curves 1–3.

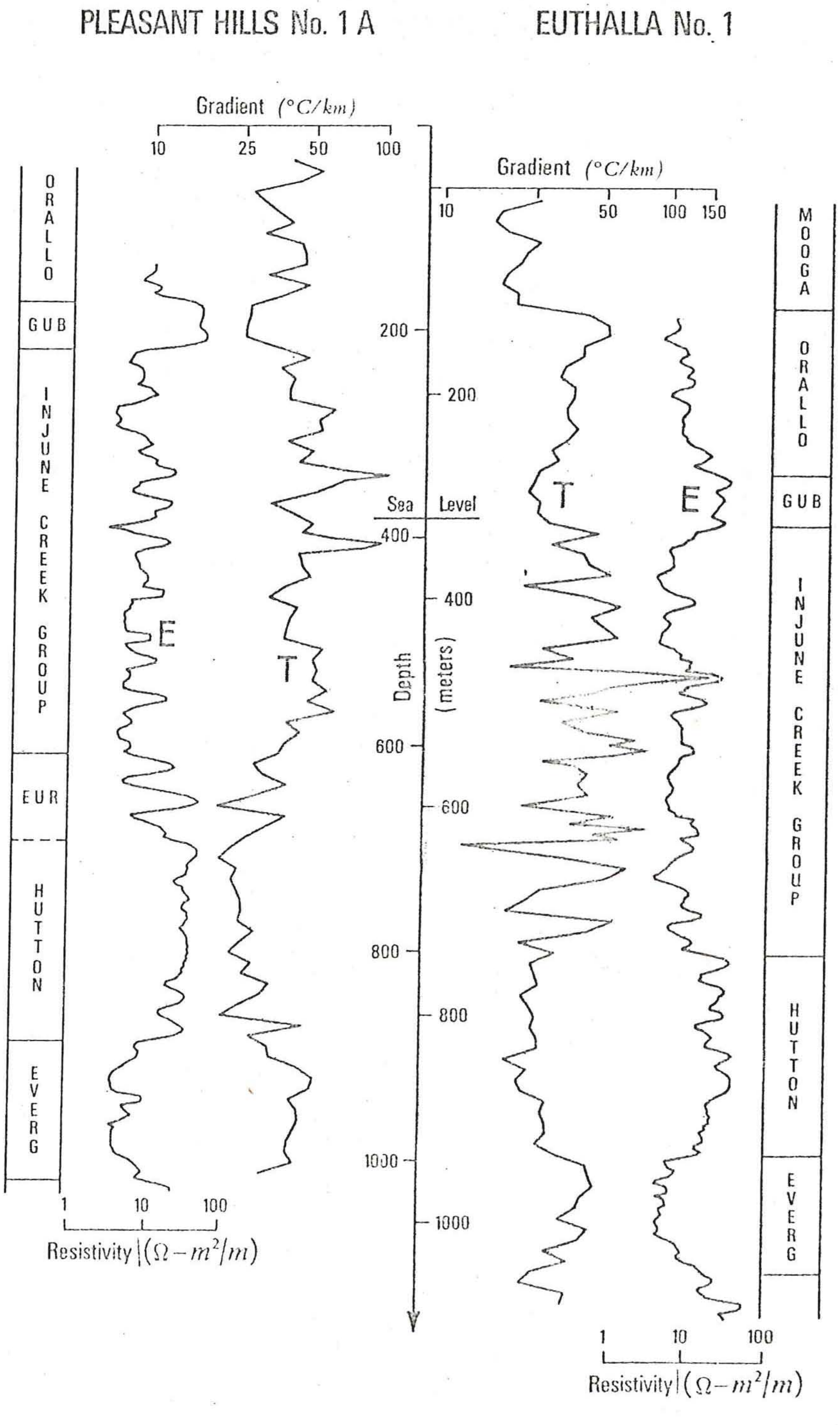

FIG. 2. T-log and E-log for two boreholes near Roma, Queensland (see Table 2 for explanation of formations.) Depth scale is linear but resistivity and gradient scales are logarithmic. Note the general correlation between thermal and electrical resistivities, except in a few local regions of very high temperature gradient attributable to coaly sections.

explanation of
ote the general
very high tem

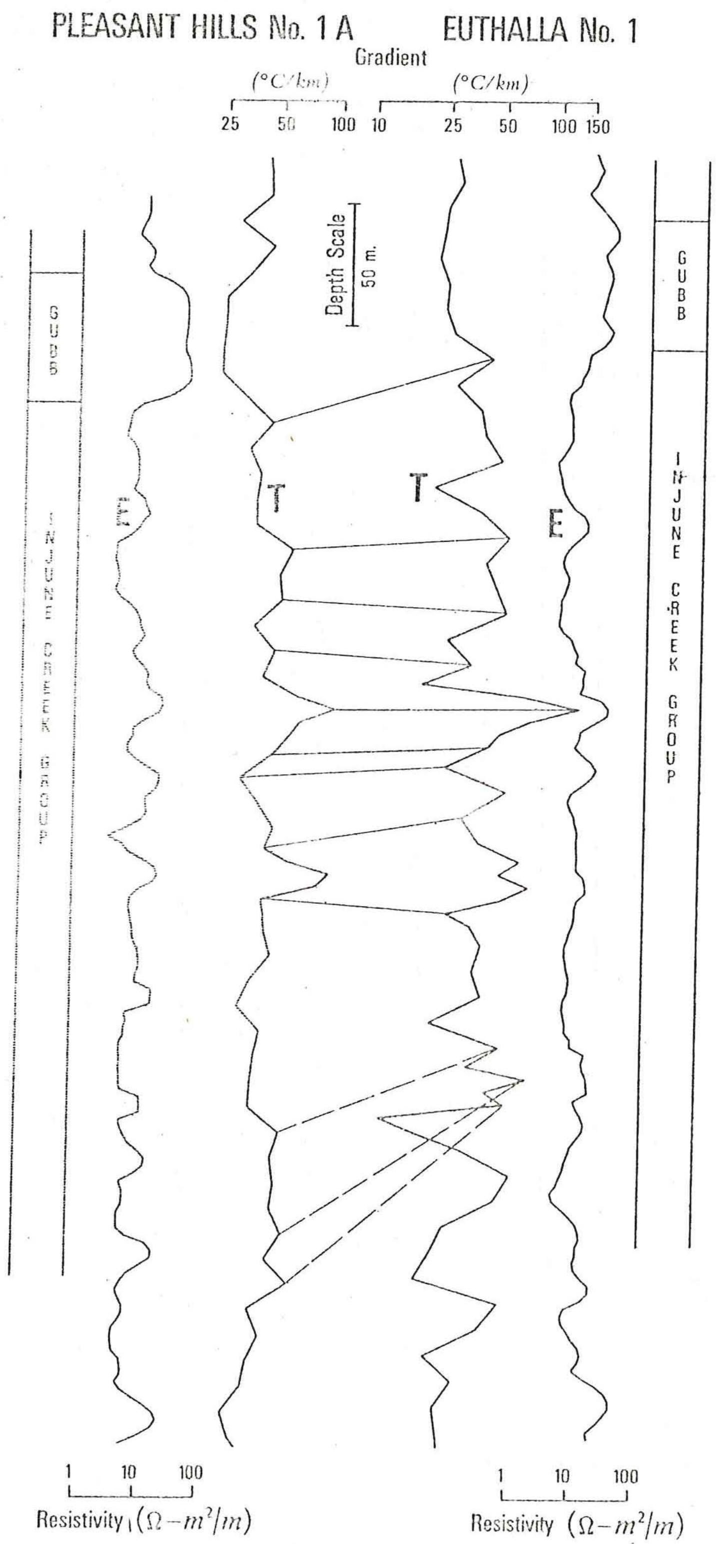

FIG. 3. Section encompassing top of Injune Creek Group from Figure 2 but using an expanded depth scale and shifting reference surface of one so as to line up major thermal resistivity peaks. Solid transverse lines join peaks due to same formation variations; dashed lines are uncertain connections.

Table 1. General data on two boreholes, diameter 16 cm.

	Euthalla 1	Pleasant Hills 1A
Latitude	26°28′22″S	26°25′10″S
Longitude	148°47′40″E	149°00′10″E
Collar	322.3 m	380.5 m
Start	6 August 1970	30 October 1972
Finish	13 August 1970	7 November 1972
Total depth	1113 m	1058 m

1A. The depth scale is linear but the temperature gradient and resistivity scales are logarithmic. The two holes are separated by a distance of approximately 25 km, and there is a difference of approximately 60 m in the collar elevations. Table 1 gives some general information about the two holes, and Table 2 gives a typical section in descriptive form. In Figure 2, depths in the boreholes have been adjusted to a common datum and mean sea level is indicated.

The generally negative correlation between thermal resistivity and electrical resistivity is immediately apparent from Figure 2, particularly for the two curves from Pleasant Hills No. 1A where the thermal resistivity variations are not as extreme as they are in the vicinity of Euthalla No. 1 hole. However, in two and possibly more sections of both boreholes the temperature gradient appears to increase simultaneously with electrical resistivity. The positive correlations occur in sections exhibiting very high temperature gradients and are, therefore, attributed to the presence of significant quantities of coal. The thermal conductivity of coal depends upon its rank but is in the vicinity of 1.0 mcal $\text{cm}^{-2}\ \text{sec}^{-1}\ {}^{\circ}\text{C}^{-1}$ (1 TCU). Possible reasons for a positive, rather than a negative, correlation between thermal and electrical resistivity in these sections will be discussed later. Part of the broad extent of some of the high values in the T-log may be attributed to the associated carbonaceous shales, siltstones and mudstones, and possibly bentonitic clays; but the T-logs are not sufficiently detailed to resolve the difference.

COMPARISON OF T-LOGS BETWEEN BOREHOLES

Figure 3 shows segments of the logs with an expanded depth scale. To facilitate comparison of curve character, the depth reference for one borehole has been shifted so as to align the shallowest major peaks in thermal resistivity. The similarity between the character of the T-logs over long sections of a borehole and through significantly varying types of formation can readily be seen. This similarity holds throughout most of the hole except in one region.

CORRECTION OF A MISPICKED HORIZON

In the Pleasant Hills No. 1A hole, the top of the Hutton sandstone was picked from the E-log at a depth of 610 m. From the character of the T-log it is believed that this horizon has been incorrectly picked and that it lies at about 690 m.

In both boreholes, the temperature gradients in the sandstone formations (Mooga, Gub beramunda, and Hutton) all lie between 20 and 25°C/km. On the other hand, it can be seen from Figure 2 that between the depths of 600 and 700 m there are long sections with gradients as high as 40°C/km. It is therefore most unlikely that the material is sandstone, because if it were, i would be necessary to postulate significant hea sources in order to explain the consequent very high heat flow in those sections with relatively high gradients. It is believed that the section from 610 to 690 m consists of the Eurombah Beds. transitional group of cross-bedded *labile* sandstones with siltstones and mudstones, which are reported as occasionally occurring between the Hutton Sandstone and the overlying Injune Creek Group. Other instances of mispicking this horizon have been reported by Gray (1972) who compared core and chip examinations with the E-logs. Fo similar reasons, it is believed that the base of the Hutton Sandstone lies about 20 m above the horizon picked on the basis of the E-log (see Figure 4)

GENERAL DISCUSSION

In some sections of the boreholes, temperature oscillations as high as ± 0.03°C were observed. A first it was thought that the thermistor containe was leaking but it was later found that the oscillation only occurred in regions of temperature gradients greater than 60°C/km. For instance, i Euthalla No. 1 at a depth of 622 m, oscillations i temperature of 0.02°C were observed in a region where the temperature gradient was 75°C/km However, when the probe was lowered 15 m int regions where the temperature gradient wa 13°C/km, no oscillations were observed, but when the probe was returned to the 622 m level the original oscillations were again observed. It therefore concluded that the oscillations are due to small convection cells.

Convection may occur in boreholes that a theoretically unstable, that is, where the crust equilibrium gradient exceeds the predicted critic roughout most of the hole

MISPICKED HORIZON

No. 1A hole, the top of the picked from the E-log at a he character of the T-log it rizon has been incorrectly at about 690 m.

the temperature gradients rmations (Mooga, Gub- on) all lie between 20 and her hand, it can be seen een the depths of 600 and ections with gradients as therefore most unlikely tone, because if it were, it ostulate significant heat lain the consequent very e sections with relatively eved that the section from of the Eurombah Beds, a cross-bedded *labile* sand- nd mudstones, which are ly occurring between the he overlying Injune Creek of mispicking this horizon ray (1972) who compared ions with the E-logs. For eved that the base of the bout 20 m above the hori- f the E-log (see Figure 4).

ISCUSSION

e boreholes, temperature 0.03°C were observed. At the thermistor container later found that the os- n regions of temperature 0°C/km. For instance, in h of 622 m, oscillations in ere observed in a region gradient was 75°C/km. e was lowered 15 m into perature gradient was were observed, but when to the 622 m level the e again observed. It is the oscillations are due

r in boreholes that are at is, where the crustal eds the predicted critical

---

Table 2. Typical section in Roma, Queensland area taken largely from Exon (1971). Two nomenclatures are indicated: that in common local use and the more recent one proposed by Exon.

Age	Earlier name (based on outcropping units)		Most recent name	Lithology
Early Cretaceous	Mooga Sandstone (part of Blythesdale Formation or Group)		Mooga Sandstone	Well bedded to cross-bedded quartzose to labile sandstone.
Early Cretaceous to Jurassic			Kumbarilla Beds	Clayey labile to quartzose sandstone; minor claystone and coal.
Middle to Late Jurassic	Orallo Formation (Fossil Wood Stage)		Orallo Formation	Fine to medium cross-bedded lithic to lithic sublabile sandstone, siltstone and mudstone, carbonaceous in part. Clay, some bentonite, minor coal. Some conglomerate near top.
	Gubberamunda Sandstone	Injune Creek Group	Gubberamunda Sandstone	Cross-bedded quartzose sandstone.
	Injune Creek Beds (Walloon coal measures)		Westbourne Formation	Grey carbonaceous micaceous siltstone grading to mudstone, very fine quartzose to sublabile sandstone.
			Springbok Sandstone	Fine to coarse labile sandstone, in part calcareous; siltstone, mudstone, minor coal.
			Birkhead Formation	Carbonaceous siltstone and mudstone, fine to medium labile sandstone, minor coal.
			Eurombah Beds	Cross-bedded, thickly bedded fine to coarse clayey labile sandstone, polymictic conglomerate, siltstone, mudstone.
Early Jurassic	These units do not outcrop		Hutton Sandstone	Quartzose sandstone.
			Evergreen Formation	Siltstone, mudstone, carbonaceous in part, minor oolitic ironstone and coal.
			Precipice Sandstone	Cross-bedded, fine to coarse clayey quartzose sandstone.

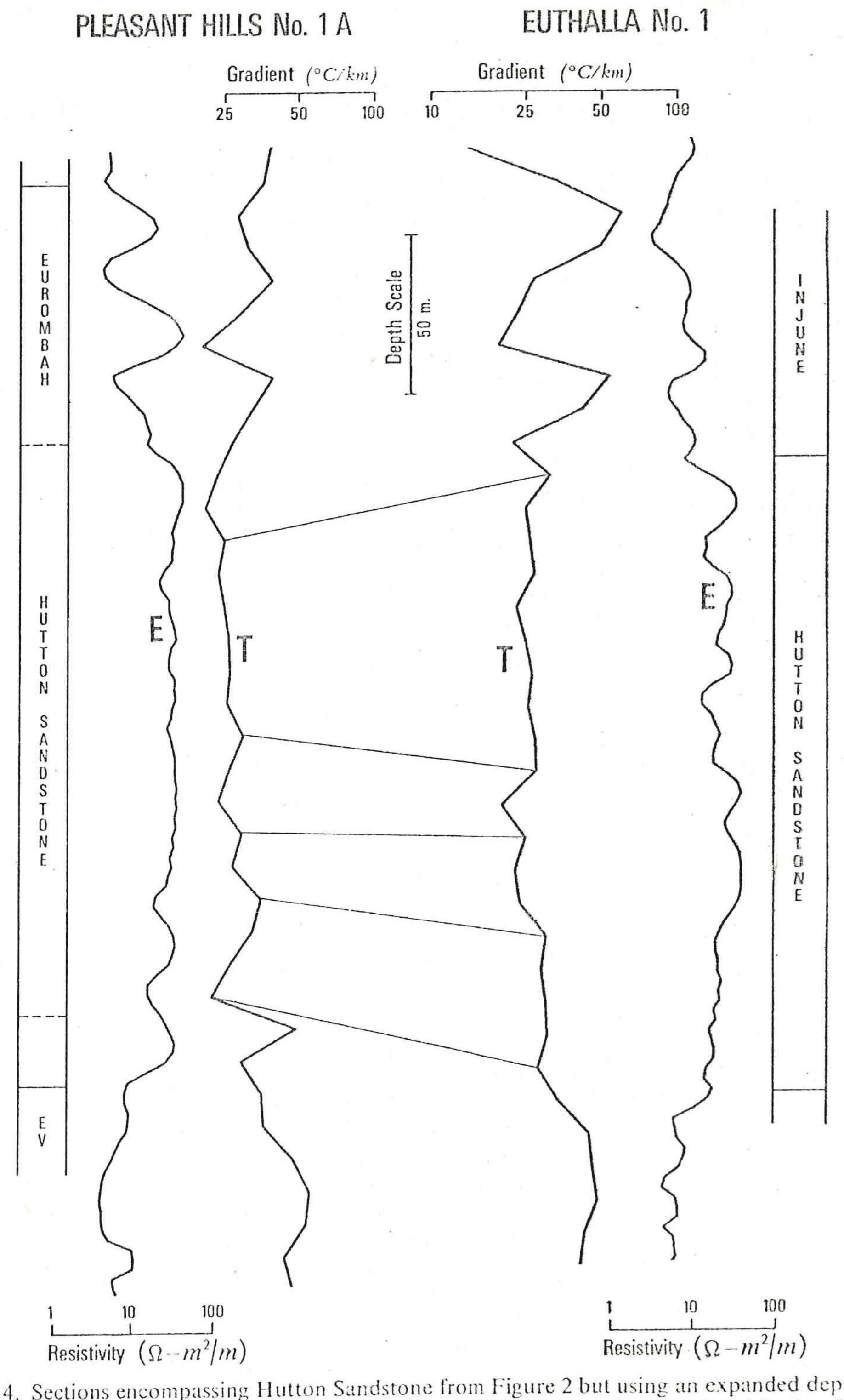

FIG. 4. Sections encompassing Hutton Sandstone from Figure 2 but using an expanded depth scal Dotted horizontal lines in sectional column of Pleasant Hills 1A indicate postulated limits of Hutto Sandstone based on gradient data; full horizontal lines indicate limits picked by E-log operator. Line between gradient peaks indicate similarity of minor variations, possibly facies changes, in the sandston

nded depth scale.
l limits of Hutton
g operator. Lines
in the sandstone.

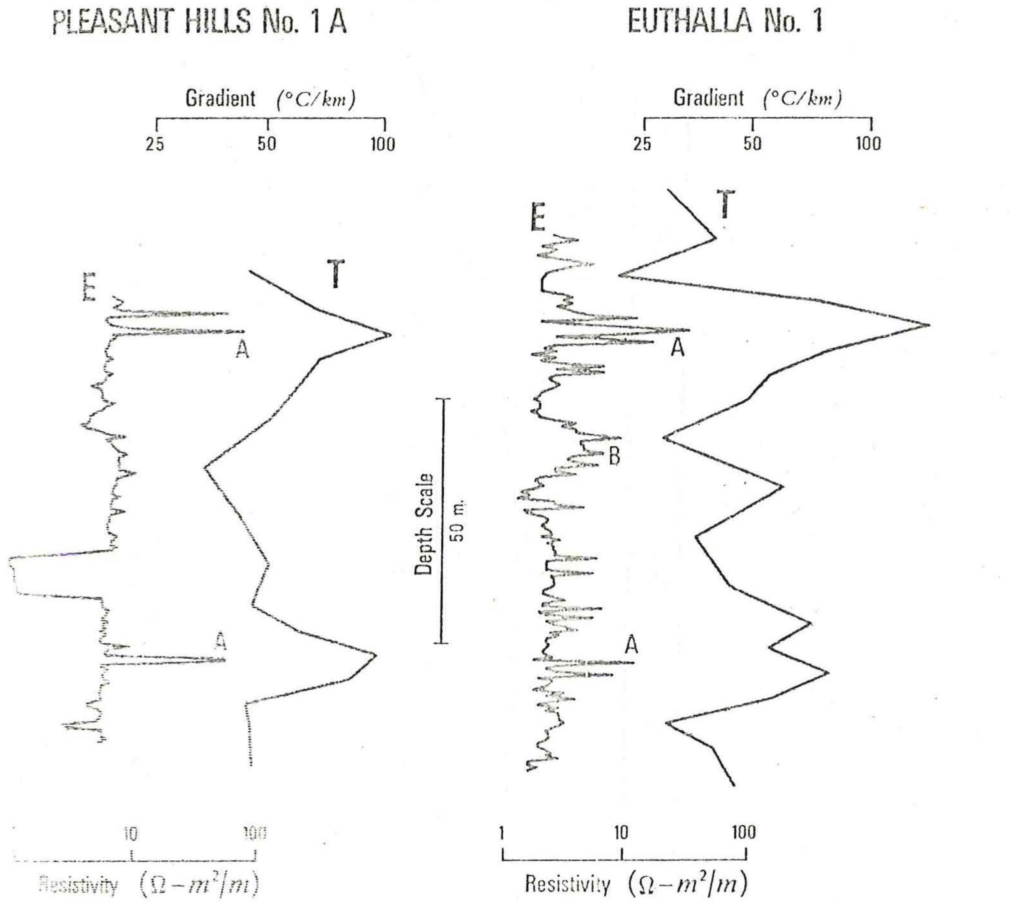

FIG. 5 Sections from same region as Figure 3 but showing more detailed electrical resistivity variations. *A* peaks due to coal formations, *B* peak due to sandstone, the differention being based on the thermal resistivity character.

gradient in a fluid filled borehole (Misener and Beck, 1960). Diment (1967) and Gretener (1967) have shown that if convection occurs it is in the form of local convection cells with a length of no more than a few borehole diameters. Therefore, although in regions of high temperature gradient the effect of small-scale convection may obscure the fine detail of thermal resistivity changes, the boreholes as a whole will remain stable and there will be little effect on the general character of the T-log.

The short distance between the above two regions of very different temperature gradient leads to a consideration of the possibility that exothermic oxidation processes initiated by the drilling of the borehole might constitute a heat source which gives the high temperature gradient. If a layered heat source occurs in a borehole, we can expect that, in the region immediately above the heat source, the temperature gradient and therefore the terrestrial heat flow will be enhanced; whereas, immediately below the heat source, the temperature gradient will be decreased, since heat from the source will be flowing counter to the natural heat flow from the earth's interior. However, not only is the wavelength of the disturbance too short for it to be caused by the initiation of a heat source at the time of drilling, but application of a worse case approach (Carslaw and Jaeger, section 3.8, 1959) shows that to explain the disturbance due to a heat source with an origin time subsequent to the time of drilling requires impossibly high source intensities.

It is interesting to compare the detailed E-log with the T-log in some segments of the borehole. For instance, Figure 5 shows a section of the

Table 3. Some typical thermal resistivies of sediments and sedimentary materials at about 25°C[1]

Material	Thermal resistivity, cm sec °C cal^{-1}
Air	15,800
Coal	800–2000
Dolostone	70–100
Ice	190
Limestone	100–170
Mud	350–600
Quartzite	55–90
Sandstone	60–250
Shale	140–330
Silica	530
Siltstone	90–170
Soils	500–1000
Water	710

[1] It must be recognized that the thermal resistivity of any particular sample is highly dependent upon its physical condition, e.g., porosity, saturating fluid, the degree of weathering, degree of consolidation, direction of heat flow if sample is anisotropic, etc.

detailed E-log alongside the T-log for both holes, in the same region as in Figure 3. It can be seen that there are many "spikes", indicating thin regions of high electrical resistivity. In some cases the spikes correlate well with peaks of the T-log but in others they do not. Since the very high thermal resistivity peaks can only reasonably be attributed to coal seams or coal-bearing strata, it is concluded that the T-log would be useful in differentiating coal-bearing formations from other formations having high electrical resistivity. The sections indicated by A in Figure 5 are those where it is postulated that coal seams occur; the high-resistivity peak indicated by B is believed to be due to a sandstone section. It is clear that without the T-log it would not be possible to differentiate sandstones from coal-bearing formations.

Since the electrical resistivity of coal increases with decreasing rank (Van Krevelen, 1961) it is interesting to speculate that the thermal resistivity behaves the same way and that the largest spikes are due to coal of low rank since the thermal resistivity of the coal also increases with decreasing rank.

The principal advantages of a T-log are that it can be used in cased boreholes and that it is free of the near-hole effects of such things as mud cake and variable zones of fluid invasion which commonly mar resistivity logs. The principal disadvantage is that with present techniques, the hole should be left standing for several days to recover thermal equilibrium. However, it is possible that with improved theoretical and logging techniques, corrections could be applied to allow for nonequilibrium of the borehole so that T-logs could be run shortly after drilling ceases.

The present work has been hampered by the fact that the data were collected with a different objective in mind and using a technique which is not suitable for detailed logging of a borehole. However, there appears to be no inherent difficulty in producing an instrument which can record either temperatures or temperature gradient continuously with the high accuracy required; work has commenced on such an instrument.

CONCLUSIONS

The potential use of temperature gradients, and therefore thermal resistivity, as a logging tool for producing characteristic profiles has been demonstrated. It has also been shown that when the thermal resistivity logs are compared with the electrical resistivity logs, ambiguities in the electrical resistivity logs can be resolved. With further development[1] the method may therefore become a useful standard logging technique since a T-log can readily be run in conjunction with any other log.

ACKNOWLEDGMENTS

This work was carried out while the author was on study leave in the Department of Physics at the University of Queensland, Brisbane, Australia. It would not have been possible without the cooperation of many people but in particular, James Kennedy of the Brisbane office and James Axford of the Roma Office of Mines Administration Pty. Ltd., and J. Anderson and W. Koppe of the Coal Branch of the Geological Survey of Queensland. The work was supported by an operating grant from the National Research Council of Canada and from the Australian Research Council.

REFERENCES

Beck, A. E., 1965, Techniques of measuring heat flow on land, *in* Terrestrial heat flow: W. H. K. Lee, Editor, AGU Monogr. 8, p. 24–57.

Beck, A. E., and Judge, A. S., 1969, Analysis of heat flow data—I. Detailed observations in a single borehole: Geophys. J., v. 18, p. 145–158.

Carslaw, H. S., and Jaeger, J. C., 1959, Conduction of heat in solids: 2nd edition, London, Oxford University Press.

---

[1] The author thanks one of the reviewers for pointing out that high-resolution continuous temperature logging facilities are available commercially and are capable of locating low grade coal seams.

nd logging techniques,
to allow for nonequi-
that T-logs could be
ises.

en hampered by the
ected with a different
a technique which is
ogging of a borehole.
be no inherent diffi-
rument which can re-
temperature gradient
h accuracy required:
ich an instrument.

IONS

erature gradients, and
, as a logging tool for
ofiles has been demon-
shown that when the
compared with the
biguities in the elec-
solved. With further
therefore become a
chnique since a T-log
nction with any other

GMENTS

t while the author was
tment of Physics at the
Brisbane, Australia. It
ble without the cooper-
t in particular, James
fice and James Axford
es Administration Pty.
W. Koppe of the Coal
Survey of Queensland.
by an operating grant
ch Council of Canada
esearch Council.

NCES

of measuring heat flow on
w: W. H. K. Lee, Editor.

S., 1969, Analysis of heat
ervations in a single bore-
145-158
C., 19[illegible], Conduction of
London, Oxford Univer-

the reviewers for pointing
nuous temperature logging
rcially and are capable of
s.

[illegible] W. H., 1967, Thermal regime of a large diameter borehole: Instability of the water column and comparison of air and water filled conditions: Geophysics, v. 32, p. 720–726.

[illegible] N. F., 1971, Roma, Queensland, 1:250,000 Geological series: Canberra, Australia, Bur. Min. Res.

[illegible] R. G., 1972, Stratigraphic drilling in the Surat and Bowen basins, 1967–70: Geol. Surv. Queensland, Rep. no. 71.

Gretener, P. E., 1967, On the thermal instability of large diameter wells—an observational report: Geophysics, v. 32, p. 727-738.

Miserner, A. D., and Beck, A. E., 1960, The measurement of heat flow over land, *in* Methods and techniques of geophysics: S. K. Runcorn, Editor, Interscience, p. 10-61.

Van Krevelen, D. W., 1961, Coal: Amsterdam, Elsevier, Scientific Publishing Co.