JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 99, NO. B6, PAGES 11,995–12,003, JUNE 10, 1994

Deconvolving Ocean Drilling Program temperature logging tool data to improve borehole temperature estimates: Chile Triple Junction

Dale S. Sawyer
Department of Geology and Geophysics, Rice University, Houston, Texas

Nathan L. Bangs
Institute for Geophysics, University of Texas at Austin

Xenia Golovchenko
Borehole Research Group, Lamont-Doherty Earth Observatory, Palisades, New York

Abstract. We present a technique for correcting borehole fluid temperature observations made by the Ocean Drilling Program (ODP) with the Lamont temperature logging tool (TLT), for the effects of the slow temperature response of one of its sensors. TLT data have been recorded in many ODP boreholes, but, perhaps partly because of tool response effects, the data have only rarely been used. It has been shown that a continuous temperature log is the convolution of a tool response function and the temperature history experienced by the tool. We use temperature data from ODP Leg 141 to estimate the tool response function of the TLT. We then use Wiener filter theory to design a deconvolution operator to remove the effect of the tool response from the recorded data. We apply the deconvolution operator to the data from Leg 141, assess the effectiveness of the deconvolution technique, and extrapolate the resulting borehole fluid temperatures to estimate the equilibrium geotherm at the two sites considered. The geothermal gradient in the accretionary wedge near the Chile Triple Junction increases with depth. This suggests that the thermal environment is not steady state, that fluid flow is transporting heat, or, most likely, both. The average heat flow in the accretionary wedge near the Chile Triple Junction is higher over the subducting Chile Ridge axis than over subducting young oceanic crust near the ridge axis.

Introduction

The Lamont temperature logging tool (TLT) is used by the Ocean Drilling Program (ODP) to measure temperatures in marine boreholes. It is a digital, internally recording, temperature and pressure sensing logging tool that attaches to the bottom of a Schlumberger logging tool string. The temperature sensor extends from the bottom of the tool into the borehole fluid and is protected by a sturdy brass cage. It is virtually cost-free to run because it is run with other logging strings and takes little or no additional time to rig up, run in the hole, or rig down. Although the TLT is run often, the data it produces are only rarely used. This is because the TLT measures temperatures in the borehole that do not represent (predrilling) formation temperatures. They differ for several reasons:

1. Drilling produces heat that is conducted into the rocks surrounding the borehole.

2. Circulation of seawater down through the drillpipe, out the bit and up the annulus around the drillpipe causes cooling or heating of different parts of the borehole during and after drilling. The seawater affects the temperatures of the rocks surrounding the borehole both by conduction of heat and by invasion into the formation.

Paper number 94JB00505.
0148-0227/94/94JB-00505$05.00

As a result, shortly after drilling and circulation are complete, the thermal environment of the borehole is different than it was prior to drilling. Unless the borehole has permanently altered the pore water flow patterns at the site, the thermal environment of the borehole will eventually return to its predrilling state, but it can take many months for a borehole to reach this equilibrium. ODP logging is almost always done in the 1-3 days following drilling, long before the temperature of the borehole fluid has reached the equilibrium temperature of the surrounding formations. For single logs, therefore, the TLT data, which at best have the ability to yield the borehole fluid temperature, are not very useful.

However, methods have been developed [e.g., *Von Herzen and Scott*, 1991] to extrapolate multiple measurements (acquired at different times after the cessation of drilling and circulation) of borehole fluid temperature versus depth to estimate the equilibrium temperature versus depth function (geotherm) at a site. The approach to using TLT data is (1) use TLT data from two or more log runs to determine the borehole fluid temperature versus depth functions at the times the logs were run, and (2) extrapolate those borehole fluid temperature versus depth functions to estimate the equilibrium borehole fluid temperature. In this sequence, most of the attention has been directed to step 2. Step 1 has often been treated as trivial; the raw data from the TLT are interpreted to directly yield the borehole fluid temperature versus depth function. *Costain* [1970], *Conaway* [1977], and *Nielsen and Balling* [1984] recognized that temperature logging

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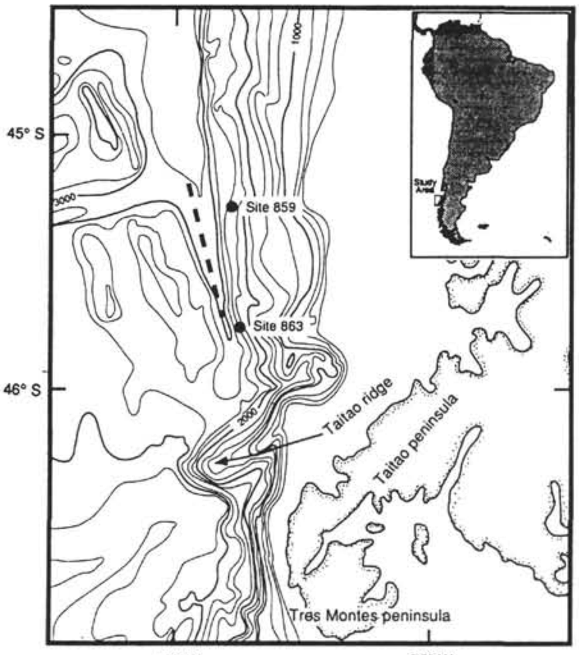

Figure 1. Location of Sites 859 and 863 drilled by ODP during Leg 141 [*Behrmann et al.*, 1992]. The bold dashed line is the axis of the Chile Ridge which is being subducted to the east under Chile. Drilling at both sites penetrated only accretionary wedge sediments.

does not directly yield borehole fluid temperature versus depth functions. However, in those studies the nature of the tool response function was not considered. We build upon their studies to show what we believe to be a very significant correction that must be applied to the raw TLT data in order to determine the borehole fluid temperature versus depth function. We will use TLT data obtained during Leg 141 in the Chile Triple Junction to illustrate the nature and significance of the correction.

ODP Leg 141 drilled a series of holes into the Chile accretionary wedge [*Behrmann et al.*, 1992]. The holes were located near the triple junction of the Chile Ridge and the Chile Trench (Figure 1). Site 859 is located north of the triple junction where young oceanic crust is being subducted, but the ridge has not yet arrived at the trench (Figure 1). Site 863 is located in the accretionary wedge almost over the trend of the recently subducted ridge (Figure 1). One of the leg objectives was to determine the ways the subducting ridge affects the overlying accretionary wedge sediments. High conductive and/or convective heat flow into the accretionary wedge sediments was thought likely to be such an effect, and as a result, thermal measurements were an important part of the leg's observational plan.

Several types of temperature measurements were made in Leg 141 holes: Water sampling and temperature probe (WSTP) measurements, advanced piston core cutting shoe temperature probe (ADARA) measurements, and TLT logs. This paper deals with the TLT data only. WSTP and ADARA data reported by *Behrmann et al.* [1992] are shown in figures and used to assess the TLT deconvolution method presented.

Leg 141 Temperature Logging Operations

TLT data were collected during two runs in each of ODP Holes 859B and 863B (Figure 1 [*Shipboard Scientific Party*, 1992a; 1992b]; Hole 859B signifies the second hole drilled at Site 859). The four TLT logging runs are designated 859-1, 859-2, 863-1, and 863-2.

The TLT tool recorded temperature and pressure at a 5-s interval throughout each log run. The pressure observations were converted to depth using an approximately linear function calibrated at between 5 and 15 points where the depths were known (the end of the drillpipe and the maximum depth of the log run). All temperature data reported here were acquired with the larger, more precise, temperature sensor on the TLT.

Runs 859-1 and 859-2 were made in Hole 859B, a 476-m below seafloor (mbsf) rotary core barrel (RCB) hole [*Behrmann et al.*, 1992]. During Run 859-1, the TLT was attached to a downhole seismometer to log temperature in conjunction with a vertical seismic profile (VSP) experiment (TLT Run 859-1). During this run we held the tool string stationary at a number of depths for intervals of 5-20 min (refered to as temperature station observations). These temperature station data were used to estimate the borehole fluid temperature using extrapolation methods (linear extrapolation to infinite time of temperature versus reciprocal time since occupying a station) similar to those used for WSTP data during Leg 141 [*Behrmann et al.*, 1992]. The TLT was then attached to the geochemical tool string (TLT Run 859-2). The tool string was lowered quickly to the bottom of the hole and then raised at the slow speed required for good data acquisition with the geochemical tools.

TLT logging runs 863-1 and 863-2 were made in Hole 863B, a

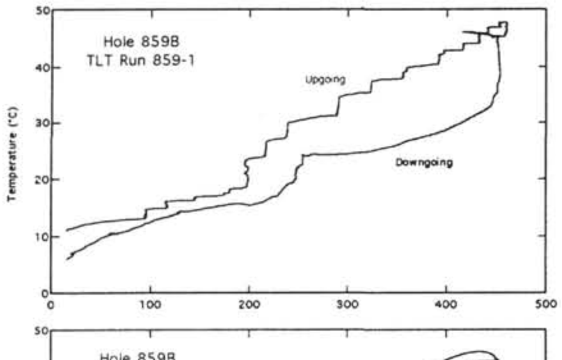

Figure 2. Observed TLT logs for two runs in Hole 859B. Systematic errors in both the upgoing and the downgoing temperature logs make them poor estimates of the borehole fluid temperature.

743-mbsf RCB hole [*Behrmann et al.,* 1992]. While preparing the hole for logging the drillpipe became stuck, with its open end at 231 mbsf. The first log run included the geophysical tool string and the TLT (TLT Run 863-1). The geochemical and formation micro-scanner (FMS) toolstrings were then run without the TLT. The final log run, with the litho-porosity tool string and the TLT (TLT Run 863-2), was successful and included six, ten-min temperature station observations. All the tool strings encountered a partial obstruction in the drill string about 100 m above the open end of the stuck pipe. They were pushed past the obstruction by pumping water down the hole. This severely affected the temperature measurements in the hole above 231 mbsf, but should not have affected the deeper part of the hole.

Unfortunately, the data obtained from the TLT do not directly yield the temperature as a function of depth in the borehole (Figure 2). This is most clearly seen in the differences between temperatures recorded on the upgoing and downgoing trips of the tool.

Methods

Costain [1970], *Conaway* [1977] and *Nielsen and Balling* [1984] showed that the temperature recorded, $T_r(t)$, by a continuous temperature logging tool like the TLT is the true temperature history experienced by the tool, $T_t(t)$, convolved with the temperature response function of the tool, $D(t)$.

$$T_r = D * T_t \tag{1}$$

where t is time.

The temperature response function of the TLT is an average of the temperatures that the tool has experienced and is unknown. An ideal experiment for estimating the tool response of the TLT in a borehole would be to instantly move a thermally equilibrated tool to another depth/temperature and let it reequilibrate (Figure 3). In this case the true temperature history experienced by the tool would be described by a step function. Then the time delayed tool response is given by the time derivative of the observed temperature [*Bracewell,* 1986].

During run 859-1, we stopped the tool string at a series of depths for periods ranging up to 20 min. While this does not form the ideal experiment described above, it comes usefully close (Figure 4a). The time derivative of the depth of the tool (Figure 4c) shows a series of near impulse functions. We take the time derivative of the recorded temperatures during this interval and smooth them with a running average filter (Figure 4d). Within the interval shown in Figure 4d there are several examples of the response function. We chose to use the one between 150 and 167 min (Figure 4d). It has the smoothest shape, the prior station was occupied for the longest time in our experiment, and the station after it was occupied for nearly as long. We ignored the positive spike at 150 min because it did not occur in any of the other examples and it seems physically unreasonable. The tool response shows a rapid rise to a peak at 60 s. The peak is followed by a slow decay dropping to 50% of the peak amplitude at 220 s. Because we only occupied this temperature station for about 1000 s, we can only estimate the first 1000 s of the tool response in this way. The response function is likely to asymptotically approach zero at large times. We approximated this by extrapolating the tail of the response to zero at 1500 s. The amplitude of the operator is normalized so that its integral, over all time, is 1.

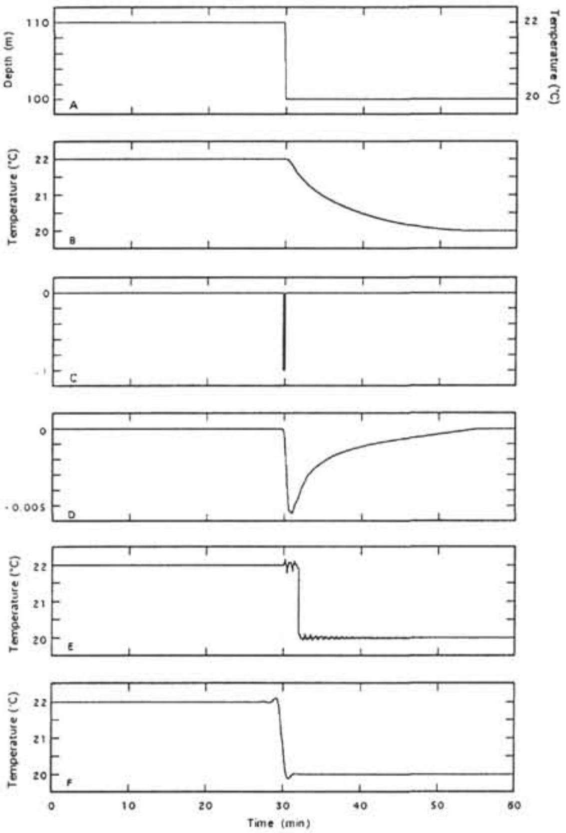

Figure 3. The ideal experiment for determining the temperature response of the TLT and the application of the deconvolution method. (a) Tool depth and true borehole fluid temperature as a function of time. (b) Expected temperature response of the TLT. (c) Time derivative of the depth (true borehole temperature) from Figure 3a. (d) Time derivative of the temperature recorded by the TLT. (e) Deconvolved temperature. (f) Deconvolved, filtered, and shifted temperature.

Designing the Temperature Deconvolution Operator

The deconvolution operator A is defined in equation (2) where δ is the impulse function.

$$A * D = \delta \tag{2}$$

When this deconvolution operator A is applied to both sides of equation (1), we see that we can theoretically obtain the true temperatures encountered by the tool from the recorded temperatures.

$$A * T_r = A * D * T_t \tag{3}$$

$$A * T_r = \delta * T_t \tag{4}$$

$$A * T_r = T_t \tag{5}$$

Costain [1970] and *Conaway* [1977] used direct inverse methods to solve this problem, while *Nielsen and Balling* [1984]

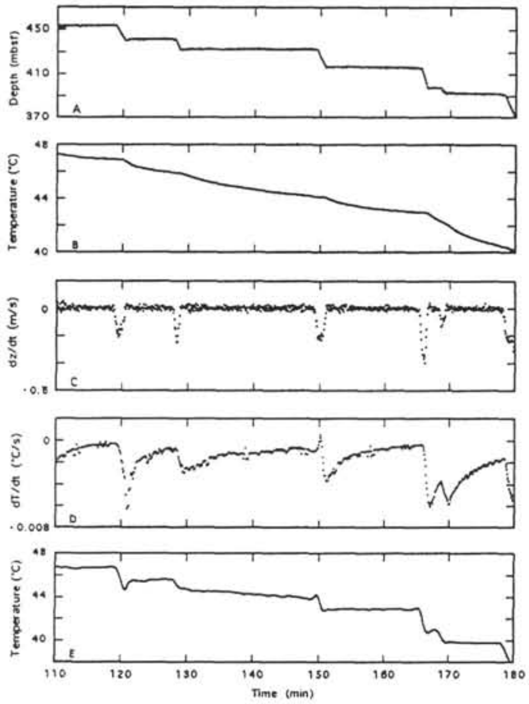

Figure 4. Obtaining the tool response from the run 859-1 data and applying the deconvolution. (a) Observed tool depth versus time. The sample interval is 5 s. (b) Observed temperature. (c) Time derivative of the tool depth. (d) Time derivative of the observed temperature. The tool response was obtained from this curve between 150 and 167 min. (e) Deconvolved, filtered, and shifted temperature profile.

use a Backus-Gilbert inversion method. In each of these studies the investigators used a theoretical response function for their temperature logging tool's sensor. The tool response function for the TLT that we obtained empirically above is a mixed phase wavelet (Figure 5). A standard technique for designing a deconvolution operator for a mixed phase wavelet is Wiener filter theory [*Yilmaz*, 1987]. A Wiener shaping filter of length n is designed using the following formulation.

$$R * A = G$$

$$\begin{bmatrix} r_0 & r_1 & \cdots & r_{n-2} & r_{n-1} \\ r_1 & r_0 & r_1 & \cdots & r_{n-2} \\ \cdots & r_1 & r_0 & r_1 & \cdots \\ r_{n-2} & \cdots & r_1 & r_0 & r_1 \\ r_{n-1} & r_{n-2} & \cdots & r_1 & r_0 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ \vdots \\ a_{n-1} \end{bmatrix} = \begin{bmatrix} g_0 \\ g_1 \\ g_2 \\ \vdots \\ g_{n-1} \end{bmatrix} \quad (6)$$

R is a Toeplitz matrix whose first row is formed of the unlagged (r_0) and first n-1 lags (r_1 to r_{n-1}) of the autocorrelation of the input wavelet; in our application the input wavelet is the tool response D. The A vector is composed of the n terms (a_0 to a_{n-1}) of the desired shaping (deconvolution) filter operator. This is the unknown in the system of equations. The G vector is composed of the unlagged (g_0) and the first n-1 lags (g_1 to g_{n-1}) of the correlation of the input wavelet (tool response D) with the desired output wavelet. We find that a 25-sample (125 s) time-delayed impulse works well for this desired output wavelet. The n by n system of linear equations is solved to find the Wiener shaping filter A. The filter designed in this way is the best (in a least squares sense) filter of length n samples for transforming the input wavelet to the desired output wavelet.

Application of the Temperature Deconvolution Operator

The deconvolution operator is convolved with the observed temperature history from a TLT run to yield an estimate of the 25-sample-delayed true temperature history of the tool (equation (5) and Figures 3 and 4). The delay is removed by advancing the data by 25 samples. To remove short-period noise amplified during the deconvolution we have applied a digital, low-pass, 0.01 Hz (100-s period), Butterworth, 3 octave/dB, filter (Figures 3 and 4). After deconvolution, shifting, and filtering, the borehole fluid geotherm is estimated by plotting the deconvolved temperatures versus depth (Figure 6).

Extrapolation of Borehole Fluid Temperatures to Equilibrium

We use the method described by *Von Herzen and Scott* [1991] to estimate the equilibrium geotherm by extrapolating temperatures from two temperature logs recorded after the cessation of drilling and fluid circulation. This method is based on an approximate solution for the radial heat conduction around a cylindrical borehole [*Bullard*, 1947].

$$T = (Q/4\pi K)\, log\left[1 + \frac{t_d}{t}\right] \quad (7)$$

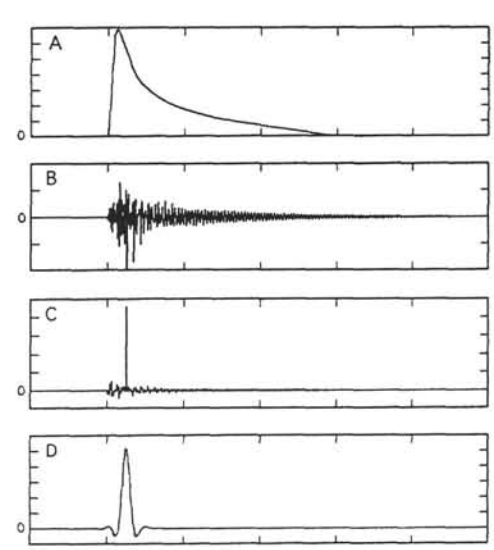

Figure 5. (a) Tool response obtained from station data from run 859-1. (b) Deconvolution operator. (c) The deconvolved tool response. (d) Deconvolved and filtered tool response. e) Deconvolved, filtered and time-shifted tool response. The amplitude of traces Figures 5a-5e are arbitrary.

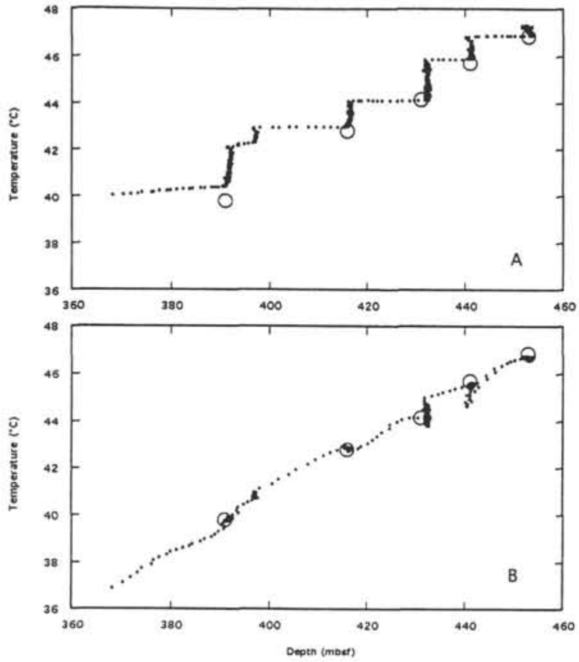

Figure 6. Comparison of temperature versus depth before and after deconvolution. Circles are extrapolated temperature station observations reported by *Shipboard Scientific Party* [1992a].

T temperature;
Q heat influx per unit length of borehole wall per unit time during drilling and circulation;
K thermal conductivity of the rock;
t_d total drilling and circulation time;
t time between measurement and cessation of drilling and circulation.

This formulation is valid when the dimensionless parameter $a^2/4\kappa t$ (κ is the thermal diffusivity and a is the borehole radius) is much smaller than 1 [*Von Herzen and Scott,* 1991]. Reasonable values for these quantities are a=0.12 m and κ=4×10^{-7} m^2 s^{-1}. The values of $a^2/4\kappa t$ in this study are 0.11 (run 859-1), 0.070 (run 859-2), 0.22 (run 863-1), and 0.074 (run 863-2).

The formulation is also based on the assumption that the heat influx due to drilling and circulation, Q, is constant [*Von Herzen and Scott,* 1991]. While this is certainly not true, the extrapolation of temperatures using equation (7) is not particularly sensitive to this assumption. In these holes, the heat influx is due mostly to the cooling effect of cold water circulation in the hole and is negative. Borehole fluid temperature logs observed at two times after the cessation of circulation can be extrapolated using equation (7).

Results

Effectiveness of the Deconvolution

We evaluate the effectiveness of the deconvolution method first with synthetic and then with observed data. The deconvolution method is applied to the synthetic data from the ideal experiment (Figures 3e and 3f). The deconvolved temperature function (including the filter and time shift) yields a reasonable approximation of the expected step function, and the tool lag has been removed. If these data are plotted as deconvolved temperature versus depth, the data would cluster tightly around two points, 110 mbsf at 22°C and 100 mbsf at 20°C. A small peak in the deconvolved temperature just prior to the step and a small trough in the deconvolved temperature just after the step are the result of the limited frequency content of the data. The deconvolution cannot correctly restore high frequency data that are not present. The filter eliminates the short period noise seen near the step in Figure 3e.

The deconvolved TLT log data (Figure 4e), like the depth history of the tool, are more steplike. The steps in the deconvolved temperature correspond well with the timing of depth changes. The deconvolved temperature is relatively constant where the tool is held at constant depth.

When these data are plotted as temperature versus depth, the usefulness of the deconvolution method becomes even clearer (Figure 6). The recorded temperature versus depth function (dots in Figure 6a) does not represent a reasonable geotherm. The true borehole fluid temperature, as indicated by the temperature station observations (open circles in Figure 6a), always lies at lower temperature than the recorded data. The curve shows multiple temperatures for a given depth. The temperature values between stations are unlikely to be real. On the other hand, the deconvolution has stacked most of the points recorded at each station observation to a point with a discrete depth and temperature (Figure 6b). These points match the extrapolated temperatures obtained for each station. Even the temperature observations that are between the stations fall along a reasonable smooth borehole fluid versus depth curve. Thus the deconvolved data are a much more reasonable estimate of borehole fluid temperature than the recorded data.

The deconvolution process improves the resolution of the borehole fluid temperature versus depth obtained from TLT data for each of the log runs discussed in this paper (Figures 7, 8, and

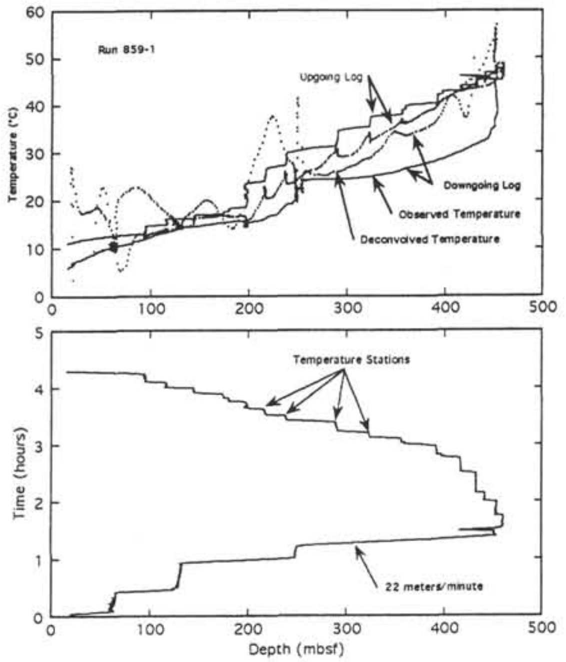

Figure 7. Log run 859-1. The bottom graph shows the depth history of the TLT tool. The top graph shows the observed (fine line) and deconvolved (solid squares) temperature log data.

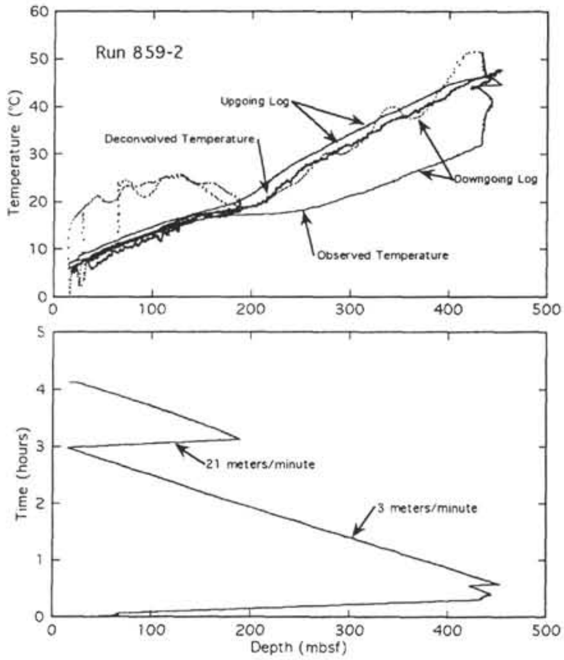

Figure 8. Log run 859-2. The bottom graph shows the depth history of the TLT tool. The approximate speed of the tool, when being raised or lowered is shown. The top graph shows the observed (fine line) and deconvolved (solid squares) temperature log data.

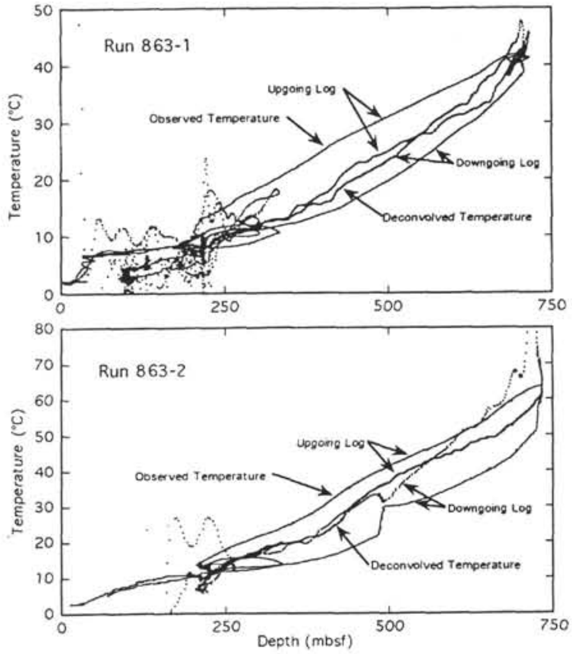

Figure 9. The observed (fine line) and deconvolved (solid squares) data from temperature log runs 863-1 (top) and 863-2 (bottom).

9), although at some depths in each log run the deconvolution did not work well. We judge the improvement due to the deconvolution in several ways. First, we expect that the deconvolution will superimpose, or at least improve the fit of, the borehole fluid temperature versus depth obtained on the downgoing and upgoing logs. Second, we expect the deconvolved temperatures to vary smoothly with depth. Third, we expect the deconvolved temperatures to be consistent with temperature station observations made during the same log run. We do not expect the deconvolved geotherm from a single TLT log run to match the WSTP (a tool which measures temperature and pressure while taking a water sample) or ADARA (a tool that measures temperatures while using piston coring) measurements. WSTP and ADARA temperature measurements are made by inserting a temperature probe into undrilled rock ahead of the formation that has been cooled by drilling fluids. Deconvolved log and station temperatures are measurements of the borehole fluid temperature, while WSTP and ADARA temperature measurements are commonly thought to represent predrilling formation temperatures.

Deconvolution improved the temperature versus depth record for run 859-1 (Figure 7) by causing the multiple temperatures recorded at each temperature station to cluster more tightly. This is the effect illustrated at larger scale in Figure 6. The downgoing and upgoing logs in the interval below 270 mbsf are much more consistent after deconvolution than before.

Deconvolution improved the temperature versus depth record for Run 859-2 (Figure 8) by bringing together the downgoing and upgoing log runs for the interval deeper than 190 mbsf. The upgoing deconvolved log is very smooth and tracks about 3°C below the recorded temperatures. The downgoing deconvolved log oscillates a bit, alternately above and below the upgoing log, but the agreement of the two is vastly better than that of the undeconvolved data. The deconvolution has improved the resolvability of the local temperature low centered at 210 mbsf (Figure 10). We pick the center of the low between 230 and 240 mbsf using the downgoing undeconvolved log, and between 190 and 200 mbsf in the upgoing undeconvolved log. Each result is skewed in the direction of tool motion because of the slow response. The shape of this feature is resolved and is positioned at the same depth in both the slow upgoing and fast downgoing deconvolved logs.

Deconvolution improved the temperature versus depth record for run 863-1 (Figure 9) by bringing together the downgoing and upgoing log runs for the portion of the hole below 250 mbsf. Prior to deconvolution, the data differed by 10°-15°C in this

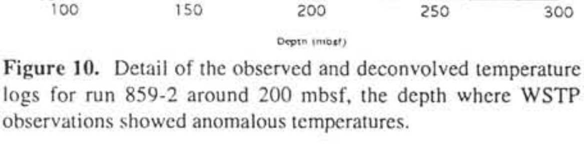

Figure 10. Detail of the observed and deconvolved temperature logs for run 859-2 around 200 mbsf, the depth where WSTP observations showed anomalous temperatures.

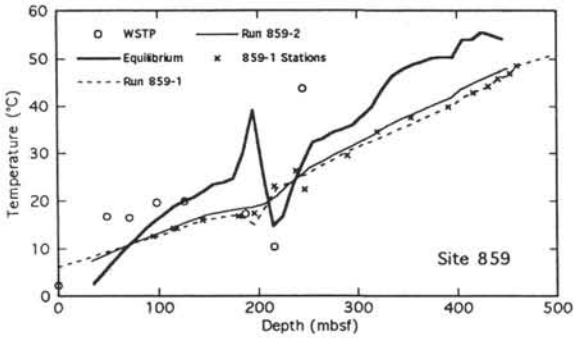

Figure 11. Interpreted borehole fluid temperature versus depth for both TLT runs in Hole 859B, extrapolated postdrilling equilibrium geotherm, and other temperature measurements at the site. The TLT borehole fluid temperature versus depth is not expected to match the WSTP results. The equilibrium geotherm is more likely to match the WSTP results.

depth range. After deconvolution the data differ by no more than 3°C over most of the range. A temperature versus depth profile obtained from either would be adequate for many scientific purposes. The hole was logged through the stuck drill pipe at 231 mbsf and due to an obstruction in the pipe, the tool string had to be pumped out into the open hole. This pumping severely disturbed the TLT measurements in the upper part of the hole, and the deconvolution was not able to resurrect these data.

Deconvolution improved the temperature versus depth record for run 863-2 (Figure 9) by bringing together the downgoing and upgoing log runs for the portion of the hole between 250 and 600 mbsf. The two curves diverge at the bottom of the hole. We speculate that this may be caused by variation of the tool response due to changing borehole fluid temperature and conductivity. The deconvolution reduced the effect of the tool stopping at 500 mbsf on the way down.

The improvement to the temperature data due to the deconvolution is greatest when the TLT is raised or lowered at a slow steady speed. The best example of this is run 859-2 (Figure 8). The tool was lowered quickly to the bottom of the hole and then, after one false start, pulled slowly and steadily nearly to the surface. The observed temperature varied quite smoothly on the upgoing log. The deconvolution reduced the temperature at most depths by 2°-3°C. The deconvolved temperature function lies closer to the upgoing (slower) temperature log than the downgoing (faster) temperature log because of the relative speed of the tool on the two passes. When the tool is moving more slowly, the effect of the slow tool response function is diminished.

When the TLT is moved very quickly, the deconvolution produces unusable results. A mild example of this is illustrated in run 859-2 (Figure 8) in the depth range 0-200 mbsf. When the tool was lowered quickly through this depth range at time zero and at 3 hours, the deconvolved temperatures deviate from the observed temperatures and the deconvolved upgoing temperatures by 10°-15°. Although we do not believe these temperatures because of this deviation, we find it curious that the two deconvolved downgoing temperature curves are similar and that they show approximately the same geotherm in this depth range as the WSTP and ADARA measurements (compare Figures 8 and 11). This suggests to us that the problem may be a change in the tool response with temperature, depth, borehole fluid thermal conductivity or some combination of these.

Interpreted Borehole Fluid Temperature Versus Depth for Each Log Run

The borehole fluid temperature versus depth for run 859-1 (Figure 11) was based on the upgoing log. The deconvolved temperatures are only well constrained at the station depths, because the tool was moved quickly from one temperature station to another, spending most of its time at the station depths. The data cluster at these depths in Figure 7.

The borehole fluid temperature versus depth for run 859-2 (Figure 11) was based on the upgoing log and the upgoing repeat log. Because the tool moved at a slow steady speed, the temperatures are roughly equally constrained at all depths.

The borehole fluid temperature versus depth for run 863-1 (Figure 12) was picked as the approximate mean of the deconvolved upgoing and downgoing log runs. The two runs were both at reasonably slow and steady speed. We picked values as shallow as 100 mbsf (because there was a cluster of points there) although the deconvolution performed poorly at depths less than about 250 mbsf as discussed earlier.

The borehole fluid temperature versus depth for run 863-2 (Figure 12) was based on the deconvolved upgoing log run. We judged that the faster downgoing log deviated too much from the upgoing log and elected to place less faith in it. The deconvolution failed for depths shallower than 190 mbsf for reasons discussed earlier.

The interpreted borehole fluid temperature versus depth functions for runs 859-1 and 863-2 match the results of the temperature stations occupied during those runs well (Figures 11 and 12). The only exception is the station at 250 mbsf in run 859-1. This station was occupied during the downgoing log trip, while the interpreted borehole fluid temperature versus depth for that run is based on the upgoing log trip. The apparent offset between the upgoing and downgoing deconvolved temperature depth functions for run 859-1 can also be seen in Figure 7. We evaluated the hypothesis that the temperature versus depth function is smooth in this depth range and that the observed change in temperature is due to the borehole heating between the time the TLT tool went down and came up. Our calculations suggest that this is not a reasonable explanation and believe that

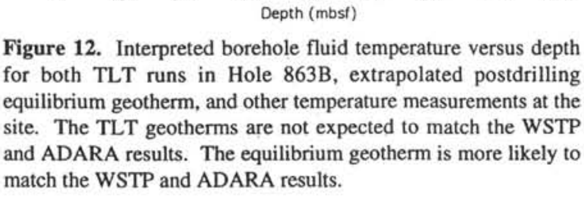

Figure 12. Interpreted borehole fluid temperature versus depth for both TLT runs in Hole 863B, extrapolated postdrilling equilibrium geotherm, and other temperature measurements at the site. The TLT geotherms are not expected to match the WSTP and ADARA results. The equilibrium geotherm is more likely to match the WSTP and ADARA results.

the temperature versus depth must be anomalous, but poorly constrained, there.

Extrapolating Log Temperatures to Equilibrium and Estimating Heat Flow

The drilling and circulation history data required to do the *Von Herzen and Scott* [1991] extrapolation for Holes 859B and 863B are summarized in Figure 13 [*Behrmann et al.*, 1992]. The extrapolation is performed for each depth using the appropriate time for beginning drilling and ending circulation. The borehole fluid temperature versus depth function from each run is assumed to have been observed at the midpoint of the time that log run was at the bottom of the hole.

The extrapolated equilibrium geotherm for Site 859 is noisy (Figure 11). Because the second log run was made shortly after the first, the extrapolation amplifies errors in the original curves. Where the two borehole fluid temperature curves cross a bit deeper than 200 mbsf, the extrapolated temperature varies wildly. The rest of the extrapolated temperature curve is smoother. The extrapolated temperatures differ significantly from the WSTP measurements reported by *Shipboard Scientific Party* [1992a] (Figure 11). The WSTP measurements are warmer than the extrapolated temperatures in the upper 140 mbsf and at 245 mbsf. They are cooler than our temperatures in between those depths. The TLT data are the only usable temperature data below 245 mbsf (*Shipboard Scientific Party* [1992a] acquired two WSTP stations below 245 mbsf, but they identified them as suspect, and we have not shown them). Both data sets show signs of thermal disturbance, perhaps by lateral water flow, in the interval 180 to 250 mbsf. The best fitting thermal gradient for the extrapolated equilibrium geotherm is 120°C/km.

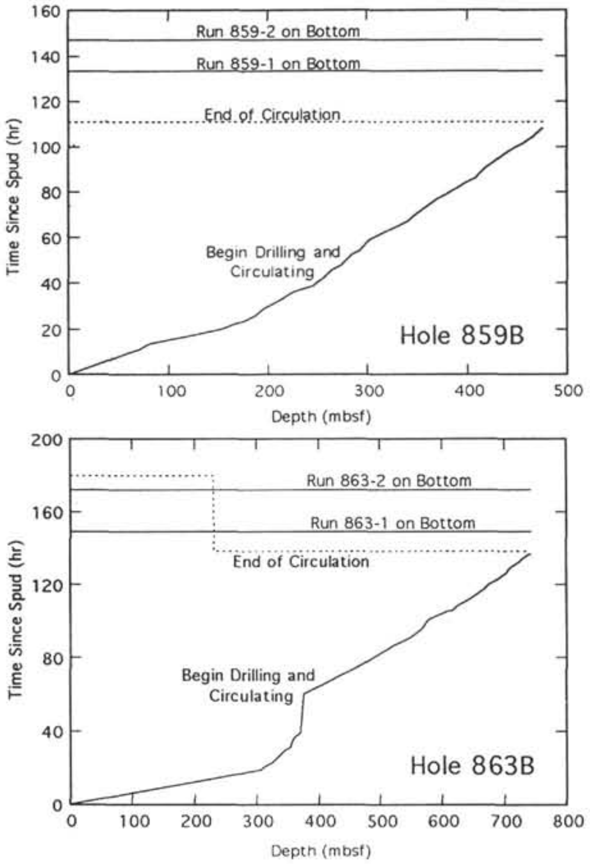

Figure 13. Drilling, circulation, and temperature logging history of Holes 859B and 863B.

Shipboard Scientific Party [1992a] reported thermal conductivity measurements at Site 859 ranging from 1.0 W/m K near the seafloor to about 1.75 W/m K at 430 mbsf. These conductivities and our extrapolated thermal gradient results indicate that the heat flow at Site 859 varies between 120 mW/m^2 at the top of the hole and 220 mW/m^2 at the bottom of the hole. The increase in the heat flow with depth observed at Site 859 cannot be explained by a conductive, steady state, one-dimensional model. It can be explained by a model in which some of the heat being conducted upwards at the bottom of the hole is advected upwards at the top of the hole, for example, by water flow. It can also be explained with non steady state models. This scenario would seem to require that a source of heat was recently emplaced below the bottom of Hole 859B and the new heat is flowing upward to establish a new equilibrium conductive gradient. The magnitude and depth of the heat source, and how recently it would have to have been emplaced, are not clear to us without numerical modeling.

The extrapolated equilibrium geotherm for Site 863 (Figure 12) is better constrained than the one for Site 859 (Figure 11), because here the two log runs were more widely separated in time (Figure 13). The results above 231 mbsf are suspect because water circulation in that part of the hole continued during logging. The results at greater depth appear reasonable. The WSTP data reported by *Shipboard Scientific Party* [1992b] (Figure 12) agree quite well with the extrapolated geotherm. A roughly linear group of WSTP measurements between 0 and 200 mbsf merge with the shallow end of our extrapolated geotherm. There is a change in the geothermal gradient from 80°C/km above 400 mbsf to 180°C/km below. A change in diagenetic history of the accretionary wedge sediments at 400 mbsf was noted by *Behrmann et al.* [1992]. The change in the geothermal gradient also shows up in the temperature data for each log run.

Shipboard Scientific Party [1992b] reported thermal conductivity measurements at Site 863 averaging 1.4 W/m K between the seafloor and 400 mbsf, and 2.1 W/m K below 400 mbsf. These conductivities and our extrapolated thermal gradient results indicate that the heat flow at Site 863 is approximately 110 mW/m^2 between the seafloor and 400 mbsf, and 380 mW/m^2 below 400 mbsf. Both the magnitude of the heat flow and its increase with depth are larger at Site 863 than at Site 859. It is not surprising that the heat flow is greater at Site 863, because it is located directly over the subducted Chile Ridge.

Discussion

We have not yet quantified the physical explanation of the tool response. Probable components are (1) the size and shape of the temperature sensor, (2) the size and shape of the metal enclosure that protects the temperature sensor, (3) the physical properties of the borehole fluid surrounding the tool, and (4) the effects of borehole fluid motion induced by the tool motion in the hole. It is possible that the tool response varies from one tool to another and probable that the tool response is a function of the absolute temperature and/or the physical properties of the borehole fluid surrounding the tool. A model of the tool response would be useful for predicting how the tool response will vary in a particular borehole. With this information, the deconvolution may be improved. Other temperature logging tools exist that have probes that equilibrate more quickly than the probe on the TLT. A significant part of our empirical tool response is probably due to items 3 and 4 above which would still affect such a tool.

Deconvolution can be used to speed up logging operations that include temperature logging. The problem of slow tool response can always be dealt with by making measurements very slowly. This can take the form of occupying many temperature stations and extrapolating the temperature at each station to equilibrium with the borehole fluid, or moving the tool steadily but very slowly, so slowly that it stays continually in equilibrium with the borehole fluid. The deconvolution method allows the TLT to be run steadily and at reasonable speed, while obtaining a continuous, equilibrium (with the borehole fluid), temperature log. The TLT works particularly well when attached to the geochemical tool string because of the slow logging speed appropriate to that tool.

The deconvolution may be applied to existing TLT data. It requires no special knowledge of circulation history or other information that are unlikely to have been recorded or preserved. It is, however, necessary to know the drilling and circulation history to extrapolate two or more deconvolved TLT logs to equilibrium as we have done.

When boreholes are reoccupied a long time after drilling, most of the problems with extrapolation of temperatures to equilibrium are eliminated. In this case a borehole fluid temperature log directly yields the equilibrium geotherm. Deconvolution may be useful for reinterpreting some existing data of this type.

Conclusions

More reasonable borehole fluid temperature estimates can be obtained from TLT data if the effects of the tool response function are removed. The TLT tool response function may be empirically determined using temperature data acquired by holding the tool stationary at a series of two or more depths in a borehole. The temperature recorded by the TLT tool is approximately the convolution of a tool response function with the true temperatures experienced by the tool. An effective deconvolution operator for the empirically determined TLT tool response may be designed using Wiener filter theory. The deconvolution technique may be usefully applied to previously recorded TLT data. If an empirical tool response function can be determined, the technique should be applicable to data from other temperature logging tools.

The geothermal gradient and heat flow in the accretionary wedge near the Chile Triple Junction increases with depth. This suggests that the thermal environment is not steady state, that fluid is advecting heat, or both. The geothermal gradient and heat flow in the accretionary wedge near the Chile Triple Junction are higher over the subducting Chile Ridge axis than over subducting young oceanic crust near the ridge axis.

Acknowledgments. We thank Captain Ed Oonk, Ken Horne, Dave Huey, Bill Mills, and their crews for making the acquisition of these data possible on board the D/V *JOIDES Resolution*. This work was an outgrowth of many stimulating discussions with Steve Lewis, Jan Behrmann, Kevin Brown, and the rest of the Leg 141 shipboard scientific party. We appreciate the useful comments provided by three anonymous referees. This work was supported by grants TAMRF PO#20598 (D.S.S.), USSSP14120676 (D.S.S.), and USSSP14120672 (N.L.B.). This is UTIG contribution number 1055.

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N. L. Bangs, Institute for Geophysics, University of Texas at Austin, 8701 N. Mopac Blvd., Austin, TX 78759. (nathan@utig.ig.utexas.edu)

X. Golovchenko, Borehole Research Group, Lamont-Doherty Earth Observatory, Palisades, NY 10964.

D. S. Sawyer, Department of Geology and Geophysics, Rice University, P.O. Box 1892, Houston, TX 77251. (email: dale@rice.edu)

(Received April 30, 1993; revised December 3, 1993;
accepted February 15, 1994.)