HOW HOT IS IT?
(A COMPARISON OF ADVANCED TECHNOLOGY TEMPERATURE LOGGING SYSTEMS)

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ABSTRACT

Temperature is a basic input for many branches of geology and geophysics, but obtaining detailed, precise temperature logs has faced problems in cost, reliability and limiting temperatures.

Field tests were conducted in the summer of 1995 on four "state of the art" temperature logging systems. Over a one month period each of the systems were used to log a 1050 meter deep hole. In addition, two of the tools were used to log a geothermal exploration well in Nevada to extend the temperature range of the tests.

The four systems used are of three major types and cover the range of currently available technology. They are; 1) a conventional "electric-line" system, 2) two separate pressure and temperature sensing "memory tool" computer systems, and 3) a Distributed optical fibre Temperature Sensing (DTS) system.

The tools produced temperature versus depth and temperature gradient versus depth logs that were coincident within the "noise" level. The multiple independent logs demonstrate that most of the "noise" seen in gradient logs is due to convection cells in the borehole and to meter scale lithology changes outside the hole. Internal system noise was shown to be relatively small. The computer and electric-line tools have about an order of magnitude better precision and resolution than the DTS, but the DTS has the advantage of being able to measure temperature instantaneously throughout the hole, and would be well suited for monitoring dynamic systems. These systems had various strong points, but all provided accurate, detailed, cost effective measurements in the field.

INTRODUCTION

Temperature is a basic physical property of matter (like mass, volume etc.). As such, crustal temperatures are inputs in many fields of geology and geophysics. The accuracy, ease and cost of making downhole temperature measurements has changed considerably in the last 30-40 years. Until the 1960's, temperatures were usually obtained by maximum reading thermometers or clock driven (Amarada or Kuster) recorders. The accuracy and resolution, in terms of depth and temperature, were limited. In addition their use in un-equilibrated holes, soon after drilling was stopped, further degraded their scientific value (Blackwell and Spafford, 1987).

The development of electric-line tools, which have an electrical connection to the surface, provided much better accuracy and precision in both temperature and depth. With these tools, it was now possible to make an essentially continuous temperature versus depth log relatively quickly and inexpensively, with a precision of $\pm 0.001°C$ (Roy et al., 1968, Sass et al., 1968, Blackwell and Spafford, 1987). The main limiting factor became cable temperature limits of $\approx 150\text{-}300°C$ and to some degree the cost of long (>1km) cables.

Computer tools were developed starting in the late 1980's. These are self-contained, battery powered, computer and sensor packages that are lowered into the hole on a solid wire (slick-line). The sensor and computer can be housed in a Dewar flask assembly for higher temperature environments. This allows operation at temperatures on the order of 400°C for about half a day. Other advantages are that the slick-line itself is a fraction of the cost of electric-line, and it can be packed-off for pressure build-up tests. Since slick-line reels are present at most drilling sites, only the tool itself needs to be sent to the site, thus reducing the overhead costs of making logs.

The newest type of tool is the Distributed optical fibre Temperature Sensing (DTS) system. This tool is based on the Raman effect backscattered laser light in an optical fibre. By measuring the intensity of backscattered light versus time, temperature can be determined for the entire length of the fibre at one time (Hurtig et al., 1994). The DTS tool, in its present form is suitable for borehole

logging to depths of 4 - 10 km depending on hardware configuration. The GFZ device used in this study is configured for logging to depths up to 4 km, but was used with a 1 km cable. Another type of optical fibre tool, based on the Brillouin backscatter effect has been tested on loops as long as 32km (Bao et al., 1993a&b). Currently these systems have about an order of magnitude less accuracy in temperature and depth than computer or electric-line tools, but this difference could eventually disappear. Laboratory experiments have shown that an optical fibre imbedded in a steel tube could work at up to 550°C (Schrötter and Holenberg, pers. comm.), however the manufacturer states that optical fibre should work at up to 750°C depending on the coating used. The biggest advantage of the DTS system, is that once the cable is in the hole, temperature along the length of the cable can be measured repeatedly, instantaneously, and without physically disturbing the borehole, making it a very good tool for studying transient events.

This report will review the results of field tests conducted in the summer of 1995 on four temperature tools from the last three types discussed above. One electric-line, two computer and one DTS tools were used to log a 1050m deep hole in Saline County, Kansas, USA. The two computer tools were also used to log a geothermal well in Nevada. Finally, an equipment test was run on the electric-line tool in a well just outside of Parsons, Kansas.

SITES

The first hole was located ≈1/2 km north of Salina, Kansas in the Great Plains province of the USA (Figure 1). Called Smokyhill, it is located at 38°-52.3' N and 97°-34.5' W or SWSWSW sec. 32, T13S-R2W. The well was drilled in 1980 to a depth of 1050m in the Ordovician Arbuckle dolomite by the USGS as a disposal test hole. The hole is lined with 27.3cm diameter steel casing to 85m and 19.4cm casing to 1020m. Cement fills the annulus between the hole and casing. The water table is at 38m. The well has been undisturbed since testing in 1981, thus it is at thermal equilibrium. As part of the Great Plains province, the area has been quiet tectonically since the Cretaceous. The most recent possibly significant thermal disturbance was the post-glacial (Wisconsonian) warming. The climate change effect should extend down to ≈1.6 km based on a conduction length $l=(4\kappa t)^{1/2}$ (where t=20,000yrs or $6.3x10^{11}$s, $\kappa=10^{-6}m^2/s$). This thermal disturbance is not relevant to the study at hand though, since all instruments should see the same effect. Heat flow measurements confirm that the region has a background heatflow of 50-60 mW/m^2, indicative of tectonically "quiet" areas (Blackwell and Steele, 1989). The hole was first logged in 1981 (Blackwell and Steele, 1989) The section consists of nearly horizontal strata of Paleozoic shales, sandstones and limestones. These materials have a fairly broad range of thermal conductivities (1-5W/m°K) (Blackwell and Steele, 1989). This variation results in a lot of "character" in the temperature-depth and gradient-depth logs. A second well near Parsons, Kansas was used to quantify the internal noise level of the SMU electric-line tool.
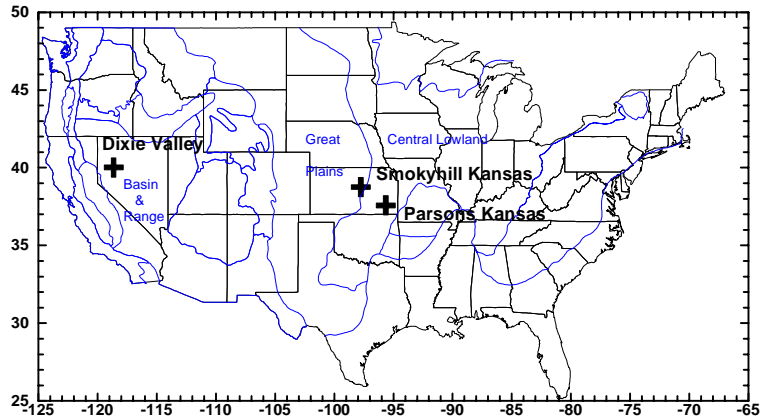

Figure 1. Map of the contiguous United States showing selected physiographic provinces and the well sites used in this study.

The third well is located in the basin and range province of western North America. Dixie Valley 82-5 was drilled as a geothermal observation well in 1985 and is located in the Dixie Valley production area (Benoit, 1991). As with the Kansas sites, the details of the thermal regime are not important as long as the well is unchanged on the time scale of several days between logging runs. The well is cased and grouted to the depths logged.

TOOLS

SMU electric-line tool. This tool is an updated version of the one described in Blackwell and Spafford (1987). It uses an Analog Devices 590 integrated circuit which outputs a current proportional to temperature. it has a limiting resolution of ≈0.001°C , precision of ≈0.1°C and a (programmed) sample interval of 0.1m. The signal is passed to the surface through a 4000m, single conductor cable and displayed and recorded on a PC. It has been used at temperatures up to 175°C but is only rated for 150°C. The entire assembly occupies ≈2m^3 of space inside of a full-sized van, making it very easy to get to a site and set up. The primary disadvantages are the fairly low temperature limit and the need to maintain extremely high electrical insulation values for the system (≈10^9 Ω). Normal logging speed in a liquid filled hole is ≈3m/minute for all the tools in this report. For typical probe response times of 3-7s, logging at 3-5m/min. does not require deconvolution to obtain the actual water temperature of the recorded point.

SMU computer tool. This tool is a self-contained computer and sensor that are connected to the surface by slick-line. The computer is based on a mil-spec CMOS

80286 and has 1 Meg of RAM. It measures external temperature and pressure and internal temperature at programmable intervals as small as 1 second.   The electronics are housed in a stainless steel Dewar flask assembly. The tool measures 45mm by 3m and weighs ≈25Kg. At SMU it is used with a 7600m slick-line cable on a hydraulic reel.   The reel, hydraulic drive and gasoline engine are mounted on a double axle trailer that weighs ≈1700kg. Precision and accuracy are about the same as for the electric-line tool. This tool is rated for operation at 400°C for 10 hours. The tool and support equipment are commercially available

In operation the tool is first connected on the surface to a PC, the sampling sequence programmed into the tool, and the clocks in the tool computer and the surface PC synchronized. The tool is then lowered into the hole on the slick-line.   Depth versus time is recorded by the surface PC. Once the tool is brought out of the hole it is

reconnected to the Surface PC which downloads the temperature and pressure versus time measurements from the tool. Time is then used to correlate the measurements with depth for the final output.

This tool is very portable, like the electric-line, and can be worked, with some difficulty, by one person. Also, since slick-line is used at almost all working drill sites, only the tool and a surface computer need be taken to some locations.   The main drawback is the need to replace the lithium batteries, at about $150.00 per set of batteries, after about 20 hours of use. Replacing batteries involves some soldering and should be done in a relatively clean environment. Also, metal O-rings must be changed out after every use at temperatures over about 200°C.

	SMU electric-line tool	SMU computer tool	Sandia computer tool	GFZ DTS
Limiting precision	0.1°C	0.1°C	0.1°C	0.3°C
Limiting resolution	0.001°C	0.001°C	0.001°C	0.1°C
Minimum sample interval	0.1m	1.0s	20s	0.25 - 1.0m
Temperature Limit	150°C	400° for 10hrs	425° for 8 hrs	750°C
Maximum # of samples per run	unlimited	64,000	3,000	unlimited
Size and weight of sensor	25mm x 1.3m 2kg	45mm x 3.0m 20kg	50mm x 1.9m 18kg	7mmx1km 35kg
Approximate cost of tool	$5000	$45,000	$30,000	$100,000

Table 1. Summary of statistics for tools used in this study.

Sandia computer tool.   This tool is similar in performance to the SMU computer tool and is in the testing stage at this time. The tool development is part of an ongoing DOE program to develop less expensive ways of producing computer tools and then transferring the technology to industry. The minimum sampling interval is not as small (10 seconds) and memory not as large as the SMU tool (96K), but these are being improved. The minimum sampling interval of 20 seconds results in a depth interval of about 1m at typical logging speeds of 3m/minute. The tool measures 50mm in diameter and is just under 2m long. and weighs 18Kg (Lysne and Henfling, 1994).   In use the tool demonstrated the inherent flexibility of slick-line tools. For the tests, Sandia Labs did not bring their own slick-line logging truck, but used the SMU line and attached their depth encoder to the SMU reel. Also of note, the Sandia tool uses simple, readily available, drop-in lithium batteries (i.e. no soldering).

The next generation of pressure temperature tool (from Sandia) is expected in early 1996. Improvements will include; ≈1 second sample intervals, greater memory, better response time, and programming for the tool to "react" to the logging situation. For example, at a large change in temperature gradient, the tool would decrease the sample interval.   Conversely, if pressure remains constant (implying the tool is stationary) the sample interval would be increased.

GeoForschungsZentrum (GFZ) DTS tool.   This tool consists of a laser unit about 40x30x30cm, a portable PC, and an optic fibre cable 1km in length.   The cable (sensor) is installed in the borehole prior to the first temperature measurement, thus allowing a simultaneous temperature recording over the entire borehole depth (cable length). The technique was first applied to down-hole logging in the early 1990's (Hurtig et al., 1994). A

preliminary comparison with the SMU electric-line tool was made in 1994 (Förster et al., 1996).

Temperature measurements are based on the Raman back-scattering effect. A laser is pulsed through a fibre optic cable. Part of the light that is scattered and returned to the surface has an amplitude that is dependent on the temperature of the material. Since the light is scattered throughout its travel, the temperature can be measured throughout the cable almost instantaneously. Currently this tool has a resolution of ≈0.1°C, precision of ≈0.3°C and a sample interval of 1.0m. Sakaguchi and Matsushima (1995) report on the use of an optical fibre for temperature measurement and imply a precision of 1-3°C in field use, however this system is somewhat different. The precision and resolution will see improvement in the near future as the equipment is refined. For more detail and references on DTS, see Förster et al., (1995) and Sakaguchi and Matsushima (1995). With further efforts in optic fibre coatings and cable construction, temperature measurements up to 750°C should be possible.

RESULTS

The results of the logs are summarized in Figure 2. At this scale, all the logs are virtually identical. Differences in depth and temperature resolution are not apparent. Some slight calibration errors in both slope and intercept are barely detectable. The slight differences between tools suggests that all need to be run through a common calibration oven.

The gradient of temperature with depth yields more detail on how the tools respond to changes in lithology (Figure 2). Gradient logs are normally filtered in some way to reduce the noise. The variations in sample interval and resolution though, prevented using the same filters on all logs. A seven point median followed by a seven point running average filter was used on the two SMU tools. No filter was used on the Sandia and DTS tools, because the coarseness of the sample interval already makes the gradient logs fairly smooth, and the depth resolution would be further degraded with an averaging filter, which tends to spread out sharp features. The gradients are generally coincident within the "noise" level. The primary difference is the large number of spikes in the Sandia log. These are due to the system "dropouts". Also evident on the different logs are some small (>3m) offsets in response, probably due to several factors such as cable stretch, reference depth errors and different probe time response constants.

The leftmost temperature log, at the top of Figure 2, is for the DTS tool. Notice that, above the water table, the DTS shows the annual effect very well while the other tools do not. Since the DTS is stationary in the hole while logging, it has time to equilibrate in air, conventional tools at normal logging speeds do not have time to equilibrate in air, and are thus of limited use above the water table.
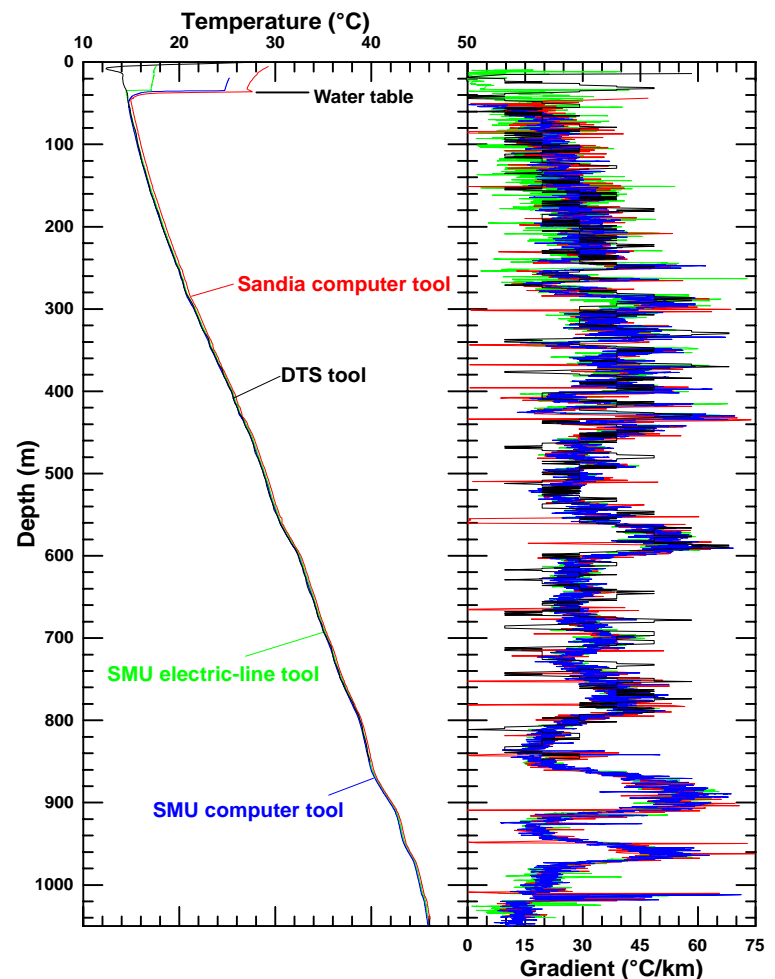

Figure 2. Temperature versus depth and temperature gradient versus depth logs for Smokyhill, Kansas. At this scale, the temperature-depth logs are nearly identical, and the gradient logs are coincident to "within the noise".

The temperature and gradient logs obviously respond to the lithology and can discriminate units at scales down to ≈3m. The lithologic resolution and discrimination of a temperature log for this hole has been discussed in Blackwell and Steele, (1989). Figure 3 shows how well the temperature gradient log corresponds to the more commonly available gamma ray and sonic logs and to the lithology of the hole.
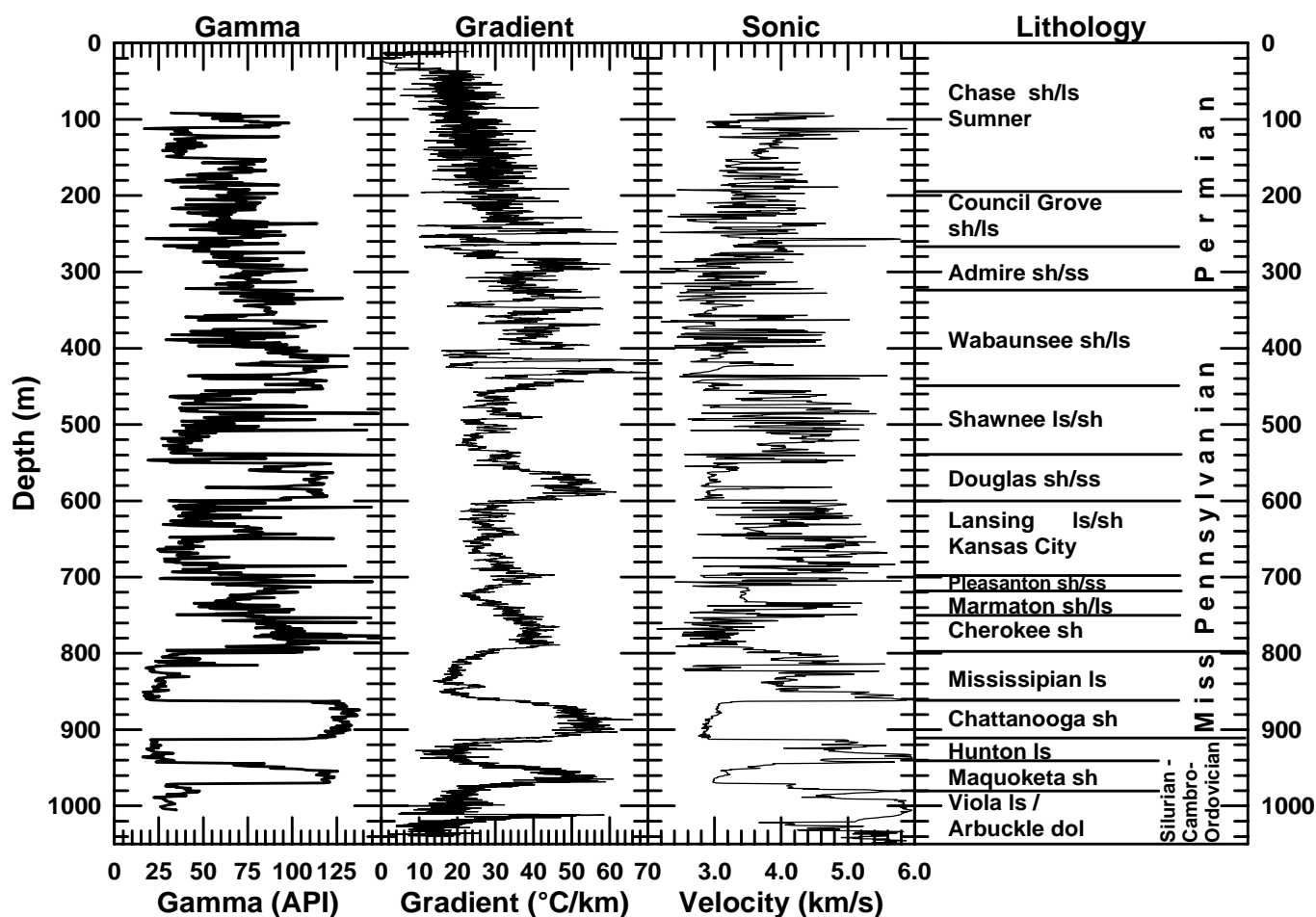
Figure 3. Gamma ray, temperature gradient, sonic, and lithology logs for Smokyhill Kansas. Lithology after Förster et al., (1995) and Blackwell and Steele, (1989). The temperature gradient log correlates with the lithology as well as the more commonly availible gamma ray and sonic velocity logs.

Looking at a small section of the logs, from 650-850m, where there are pronounced changes in lithology and thermal conductivity (Figure 4), shows that the tools still all track together within the "noise". At this scale the differences in depth and temperature resolution are apparent and are amplified in the gradient logs. The offset between the SMU electric and computer tools is constant, but the Sandia tool comes relatively 0.1°C closer to the other two in high gradient sections. This could be due to a longer probe response time for the Sandia tool, a depth offset in the data or a difference in logging speed. Note also that the Sandia tool "dropouts" at 714, 752, 780, and 843m, are evident in the temperature-depth curve. The coarser resolution of the DTS tool is evident in both logs, especially the gradient log, where the DTS signal is the least detailed.

Excluding the large noise spikes in the Sandia tool, the gradient logs correlate very well down to about a three meter scale. The correlation appears to be fairly good down to about 1-2m, but this interval is also at or below the limiting resolution of the Sandia and GFZ tools, so no firm conclusions can be drawn with respect to comparisons. Comparing just the two SMU tools, there appears to be good correlation of the response, down to ≈1m intervals when compensation is made for the apparent ≈1m depth error between the two logs. From this it is obvious that the tools are recording real

variations in temperature due to hole and or rock conditions, and that tool noise and general fluid motion noise, excluding in-hole convection cells, are not significant at scales of at least 5m and up.

Another interesting result is the nature of the "noise" in the thermal signal. The thermal noise has always been evident in high precision temperature logs, but so far the primary attention it has received is filtering to get rid of it. Urban et al. (1978) and Blackwell and Spafford (1987) speculated that it comes from a combination of the tool, fluid movement and hole characteristics such as roughness, size, etc. In this case, where four separate tools were run on different days over a one month period, it should be possible to differentiate some of these effects.

Blackwell et al. (1982) demonstrated that hole size variations can induce a very strong temperature signal (possibly by creating convection cells). In this case though, since the hole is open only at the bottom, and the annulus was filled with cement, there should be no size changes other than a casing change at 85m. The papers of Gretner (1967), Diment (1967), Sammel (1968), and Urban et al. (1978) all indicate that convection cells should exist in most holes with positive geothermal gradients. These cells are predicted to produce temperature fluctuations on the order of .01-.05°C for the

gradients seen in the Smokyhill well. These fluctuations would have a 10-50°C/km effect on unfiltered gradients at 1m intervals. Though it is difficult to quantify, the fluctuations in the Sandia tool and the DTS tool appear to be in the 10-30°C/km range. For the higher resolution SMU tools, filtering can probably reduce this convection cell effect on gradients to the 1-10°C/km range. Fluctuations in the 1-10°C/km range are seen in the SMU gradient logs. The predicted size of the convection cells range from hole diameter (19.5cm) up to ≈2m (Sammel, 1968) for Smokyhill well conditions. Alternatively, using the relation: $A=R/G'a$ (Diment and Urban, 1983), where A is the cell aspect ratio (height / radius), R is the maximum temperature fluctuation range, G' is the geothermal gradient and a is the radius of the well we get an aspect ratio of 2-50 for this well, implying convection cells heights in the 0.2-5m range. The 0.2m end of cell sizes is near the limiting resolution of the SMU tools, but convection cells in the 1m and up range should be easily detectable. Looking at the expanded gradient plot (Figure 4), there appear to be some regular variations at this scale.
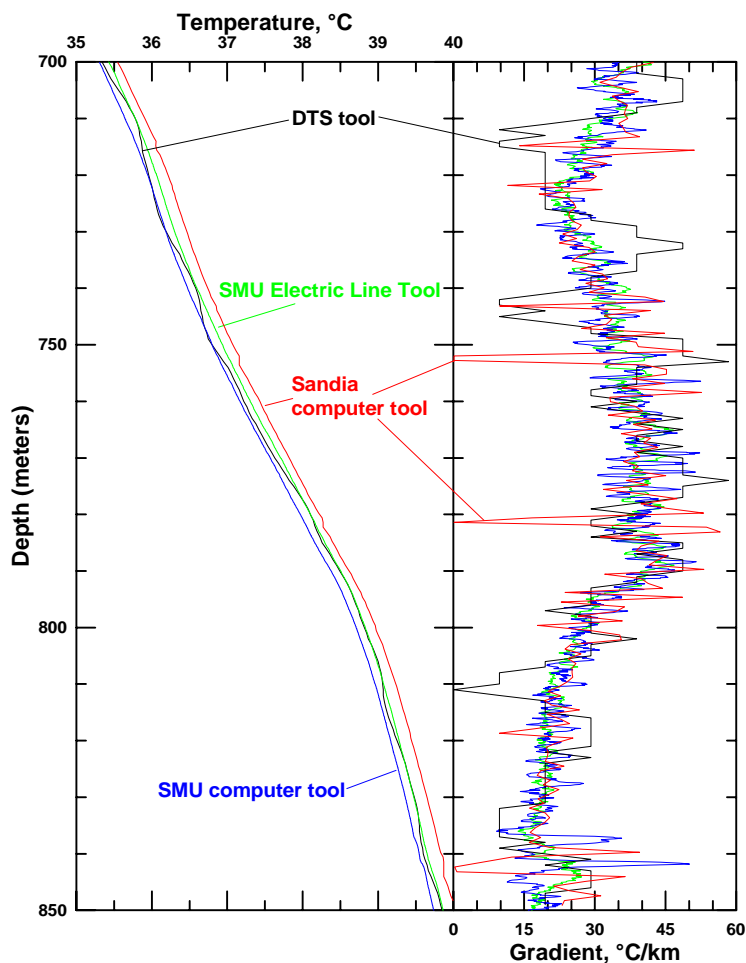

Figure 4. Detail of Smokyhill log from 700-850m. At this scale, some small variations between tools are evident in the temperature logs, and the coarser resolution of the DTS tool is evident in the gradient log.

Figure 5 shows a 20m portion of the two SMU tool's gradient versus depth logs, which were normalized by subtracting a 50 point, moving window average of the gradient log from each point. Oscillations in the 1-4m

height range are present. These log sections look very much like those of Gretner (1967), Diment (1967), Sammel (1968), and Urban et al. (1978), with the exception that depth is substituted for time. Pfister and Rybach (1995) see the same variations with depth and attribute them entirely to convection cells. A Fourier transform of the SMU gradient data (Figure 10) shows the dominant signals to be in the 0.1-0.01hz (≈10-1 m) range. Some of the 1-10m frequency must be due to lithology too (this is point discussed below), thus it cannot be definitely attributable to convection cells, but it is likely that they are present in the 1-10m height range. More work is needed on differentiating between convection cells and lithology in temperature logs.
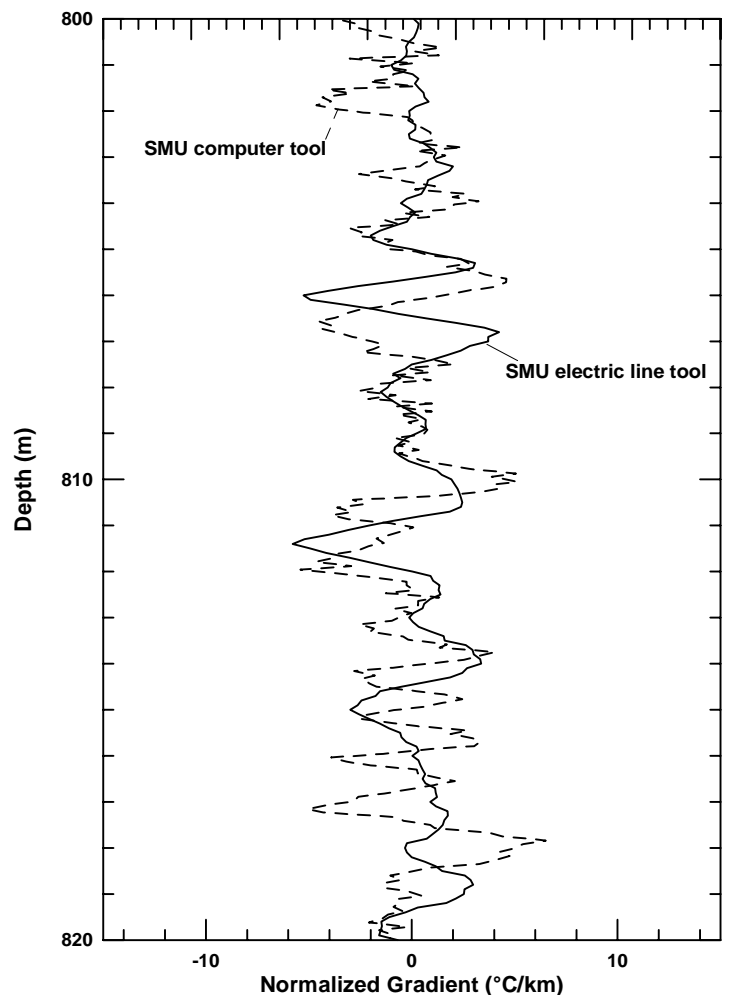

Figure 5. A 20 meter section of the SMU electric-line and computer tool's "normalized" temperature gradient versus depth logs.

The "noise" appears to decrease below 250 meters as compared to above 250 meters in all but the DTS log (Figure 1.). The lack of noise in the DTS log is due to the coarseness of the gradient log (≈3m depth and ≈30°C/km gradient resolution). There is no known hole condition or casing change at this point. The gradients are lower in the "noisier" section than the "quiet" section, making the "noise" change unlikely to be due to a change in convection in the water column. There is a change in lithology at this point though, from alternating limestones and shales of the Council Grove to the more consistent shale, with minor sands, of the Admire. Thus it appears

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that what at first glance is a noise problem, especially if only a single log were available, is probably tool response to thin bedded lithologies.

To get a better idea of the noise sources for the SMU electric-line tool, a test was conducted in another well near Parsons Kansas. The hole was first logged using normal procedures. The sensor head was then packed with insulation and wrapped with tape in order to increase the response time constant of the probe. The "packed" probe has a response time about 40 times as long as the "normal" configuration. For the gradient log of the "packed" probe, the dominant high frequency signal should be the internal, instrument noise. Comparing the two gradient logs (Figure 6) it is obvious the instrument noise is very small compared to the other sources present (it is in the 0-2°C/km range on a filtered log). The level of instrument noise should be about the same or smaller in the computer tools.
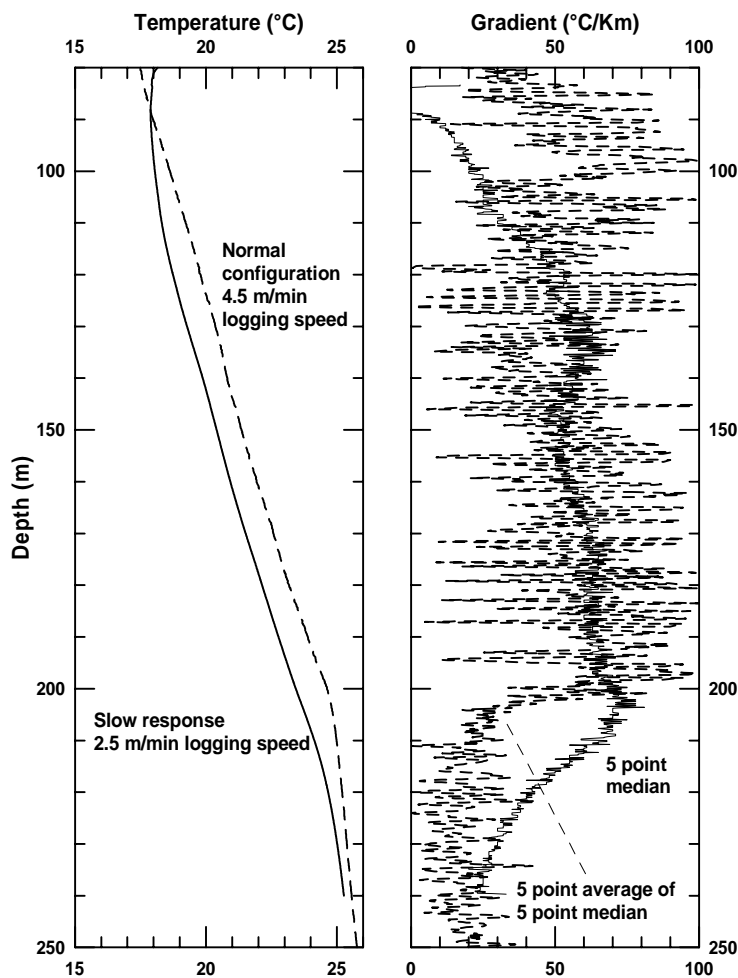

Figure 6. Temperature versus depth and temperature gradient versus depth logs for Parsons Kansas. In the gradient log, the smoother line is from the damped system, and shows that internal, system noise is small compared to other sources of noise.

A final set of logs were made in a geothermal well at Dixie Valley Nevada to compare the two computer tools in a higher temperature environment. The two logs were coincident up to the maximum 195 °C temperature reached

CONCLUSIONS

All the tools performed acceptably well. They are relatively portable, accurate, and need only one or two people to operate. All the tools can be used to make temperature versus depth logs, discriminate lithology, identify fluid flow etc. The computer and electric-line tools have about an order of magnitude greater precision and resolution than the DTS, but this difference will likely decrease in the future. Also, the Sandia tool will have an improved depth resolution and memory in the near future. The DTS has the advantage of being able to measure temperature continuously throughout the hole, and would be well suited for monitoring dynamic systems such as production or non-equilibrium wells.

The often ignored "noise" in a thermal well log was shown to be due mostly to actual variations in lithology and borehole convection cells. The internal tool noise is relatively small for electric-line and computer tools, thus for these tools borehole effects, such as convection cells, are the limit on field precision. Convection cells in boreholes still need more study in order to better quanify their effects. The DTS system would be ideal for this if it could be improved by roughly an order of magnitude in accuracy and precision. More sophisticated filtering methods are being developed to maximize the information obtained from a temperature log. Deconvolution algorithms are being developed in order to log at higher speeds without loss of information. Finally, a readily accessible calibration oven is needed for use by the geothermal community.

ACKNOWLEDGMENTS

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