PROCEEDINGS, Thirty-Seventh Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 30 - February 1, 2012
SGP-TR-194

TOWARDS A SHALLOW HEAT FLOW PROBE FOR MAPPING THERMAL ANOMALIES

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ABSTRACT

Conductive heat flow is arguably the only measurable surface expression of the thermal state of the crust at any given location. However, the geothermal component of heat flow (average ~0.06 W/m^2) is effectively masked by solar irradiation (average daily peak ~300 W/m^2) at shallow levels. Heat flow measurements must therefore be made in boreholes at least 100 m deep, below the level of influence of the seasonal surface temperature cycle. Such boreholes are drilled at considerable cost, or pre-existing boreholes are accessed opportunistically. Hot Dry Rocks (HDR) is developing and trialing a tool to detect variations in geothermal heat flow from measurements made within the top 1.5 m of the earth. The strategy is to record time-series data and use frequency-domain filtering to reveal regional variations in the geothermal (DC) signal underlying the time-varying solar signal. The goal is to detect variations on the order of 0.01 W/m^2. This represents several orders of magnitude greater sensitivity than existing shallow temperature probes. The technical challenges revolve around achieving the necessary precision, accuracy, durability, reliability, thermal bulk (or lack of!), cost, usability and power efficiency for the probe; as well as designing appropriate field procedures, data processing algorithms and interpretation strategies. To date, HDR has designed, manufactured and calibrated a set of 12 prototype tools, and deployed six of these in a remote part of South Australia for extended field trials. Initial results have been encouraging. HDR hopes that the shallow heat flow probe will eventually become a useful geophysical tool for mapping the extent and magnitude of a thermal anomaly prior to expensive drilling. HDR has applied for patent protection for the probe.

INTRODUCTION

The vision

Hot Dry Rocks Pty Ltd (HDR: Australia) is developing a tool and a methodology to reliably, accurately and precisely measure conductive heat flow in the top few meters of the earth's crust. Such a tool and methodology would remove a current substantial barrier to regional heat flow mapping—namely the current requirement for fully cored boreholes to depths greater than 100 m.

The main barrier to measuring geothermal heat flow at shallow levels is the thermal disturbance of the diurnal and season temperature cycles at the surface of the earth. At any given moment and location, the heat flow in the top few meters of the earth is dominated by the periodic ebb and flow of solar energy diffusing in and out of the ground. HDR aims to precisely and accurately measure a time series of shallow heat flow and

extract the geothermal conductive heat flow signal from within the solar dominated signal.
HDR's ultimate objective is to develop a new geophysical survey system to generate 'heat anomaly' maps. Such maps would delineate the extent and magnitude of anomalous sub-surface heat sources in the same way that existing geophysical techniques currently delineate anomalous subsurface density (gravity), magnetic susceptibility (magnetics), electrical properties (MT, TEM etc; Figure 1), sonic velocity (seismic tomography) and other geophysical properties.

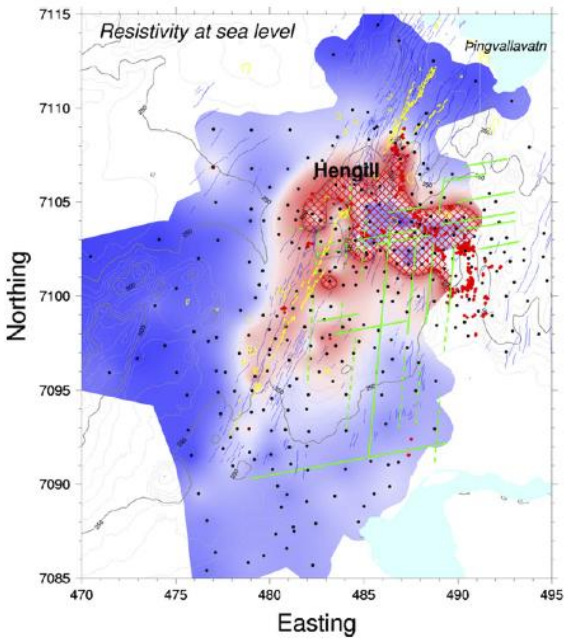

Figure 1: A resistivity depth slice map from Árnason et al. (2010), as an illustration of how a heat anomaly map might eventually look.

The value

Regional heat flow surveying would provide an additional layer of geophysical data valuable for exploration for geothermal energy, accumulations of radioactive material (eg IOCG deposits), ground water flow paths and other phenomena that influence the magnitude and direction of heat flow in the crust. The auxiliary data generated by a heat flow probe would also be of value for agricultural studies and geotechnical surveys prior to laying underground power cables.
At present, regional heat flow surveying is prohibitively expensive due to the requirement for relatively deep boreholes. However, tools that penetrate just a meter or two into the surface of the earth could be deployed over wide areas at just a fraction of the cost of obtaining a single reliable heat flow measurement at present.

The concept

Where the assumption of pure conduction holds in the top meter of the Earth, changes in temperature at the Earth's surface diffuse into the ground in a manner that can be characterized by (Carslaw and Jaeger, 1959, p58):

Equation 1: $T_\theta = T_0 \times \mathrm{erfc}[z/(2\sqrt{(\kappa t)})]$

where T_θ is the departure from the original equilibrium temperature at time (t) and depth (z), and 'erfc()' is the 'complimentary error function.' The temperature at any depth, z, is then the natural equilibrium temperature plus the sum of the diffusion effects of all historical changes in surface temperature.
Changes in surface temperature due to weather are dominated by two periodic cycles; the 24-hour diurnal cycle and the 365-day annual cycle. Simplistically, the observed temperature gradient in the top meter of the ground, G_0, is the sum of three individual components:

Equation 2: $G_0 = G_g + G_d + G_a$

where G_g is the equilibrium geothermal gradient, G_d is the variable gradient due to the diurnal cycle, and G_a is the variable gradient due to the annual cycle.
Vertical conductive heat flow is the product of thermal gradient and vertical thermal conductivity. Vertical thermal conductivity

should remain relatively constant at any given location, and could be measured just once or twice at each location per survey. The thermal gradient, however, is grossly disturbed by the surface temperature cycles.

The conceptual basis to HDR's shallow heat flow probe is to record precise time-series of shallow temperatures simultaneously at a number of locations across a region for a period of weeks to months. G_d could then be effectively filtered from each individual record.

If we assume that the annual surface temperature signal is broadly constant across a survey area, then lateral variations in observed gradient would be due only to variations in the underlying equilibrium heat flow and the thermal diffusivity of the ground. The thermal diffusivity could be measured at each survey point and corrections applied, allowing us to derive maps of the variation in heat flow across a survey area. Our probes would provide relative, rather than absolute, values of heat flow, revealing thermal anomalies.

PREVIOUS SHALLOW THERMAL PROBES

Previous work relevant to the development of a terrestrial heat flow probe can be divided into two broad categories; techniques designed to obtain terrestrial heat flow (or temperature gradients) and techniques developed to obtain heat flow on astronomical bodies (e.g. the moon, comets, planets etc). A brief summary of the published work to date is provided below.

Terrestrial heat flow probes

Heat flow probes of various forms have been routinely used to determine heat flow in the deep ocean since the 1950's. The first probes were Bullard and Ewing-type probes, essentially thermistor-lined probes with no *in situ* thermal conductivity measuring capabilities (Bullard, 1954; Gerard *et al*., 1962). Samples of the ocean floor were required for thermal conductivity analyses at the surface. The oceanic heat flow probe evolved in the early 1970's to the Lister probe, which included an *in situ* thermal conductivity sensor in the form of a line-source heater (Hyndman *et al*., 1978).

Christoffel and Calhaem (1969) designed a heat flow probe intended for use in soft sediments. The six-foot long, cylindrical, steel probe incorporated four thermistors, which measured both absolute and relative thermal gradients, as well as a line-source thermal conductivity sensor in the form of a coil of heating wire wrapped around the probe. However they only reported testing the probe in the relatively shallow water of the Wellington Harbour (NZ) and did not report any experiments conducted on land.

Sass *et al*. (1981) constructed a probe to determine heat flow in boreholes while drilling was still progressing. The probe consisted of a two-meter long steel tube, with three thermistors for measuring temperature, and a coiled-heater-wire thermal conductivity sensor (line-source of heat). The methodology involved ceasing drilling temporarily to obtain heat flow 'on the fly'. The probe was lowered down the drill stem and 'injected' about 1.65 m into the formation at the bottom of the hole using hydraulics. Temperature and thermal conductivity measurements were then taken and the entire process was complete after about one hour. Several such measurements throughout the drilling resulted in a final heat flow value closely comparable to that obtained by high-resolution temperature logging (completed months after drilling so that the hole was thermally equilibrated) and thermal conductivity measurements on core.

Shallow temperature surveys are occasionally utilized during exploration for conventional geothermal systems (i.e. relatively high temperature, convecting systems). Such settings are generally associated with particularly high heat flow and high temperature gradients, which make anomalies

relatively easy to detect. Most of these surveys require inserting thermistor probes 1–2 m into the ground, and allowing the temperatures to equilibrate. Some authors have devised methods of correcting for near-surface effects such as the annual solar cycle (e.g. Olmsted and Ingebritsen, 1986).

Experimenters in Norway investigated the thermal structure and seasonal heat transfer patterns in permafrost using a shallow thermistor-lined probe (Putkonen, 1998). From a full annual cycle of temperature data in the top meter of permafrost, collected at intervals between once per hour and once per day, they determined that thermal conduction was the dominant heat transfer mechanism in that environment.

Coolbaugh *et al*. (2007) described a recent shallow temperature surveying methodology to detect 'blind' geothermal systems (i.e. those systems that do not have surface features such as hot springs and geysers) by rapid measurement of ground temperature at a depth of two meters. They constructed 2.2 m long, hollow, thin, cylindrical steel probes within which they placed several platinum resistance (RTD) thermometers. A hammer-drill, run by a generator, was used to drive the probes into the ground. The entire system could be transported on the back of a 2-person ATV. Two base stations were set up to monitor the drift of the temperature gradient throughout the survey, due mostly to the annual solar cycle. They used these base stations to 'correct' the other stations by adding to each measurement the average temperature drop of the two base stations between the time the survey commenced and the time of the particular measurement. They found that both base stations declined at a steady rate of ~0.05°C/day for the 9 days that their survey ran. Their method successfully delineated the Desert Queen geothermal aquifer (60 m deep, 90°C thermal aquifer) and also identified a previously unknown continuation of the aquifer.

The authors mentioned above admitted that their correction is not a complete correction for the drift in temperature gradient, as the magnitude and depth to which it penetrates depends on the thermal diffusivity of the soil. They later reported attempts to apply corrections for this effect, and for variations in surface albedo (Coolbaugh *et al*., 2010). The technique appears useful for detecting thermal anomalies on the order of ±0.5°C at two meters depth.

Astronomical heat flow probes

Heat flow from astronomical bodies (planets, moons, comets, etc) is of interest to researchers for a number of reasons, arguably the most important of which is to constrain models of planetary evolution and composition (i.e. the amount of radioactive elements) (Hagermann, 2005). A number of heat flow measurements have been made on the lunar surface and measurements are planned in the near future for other astronomical bodies (e.g. Mars). The Apollo 13 mission was the first to contain a heat flow probe as part of its payload but was unsuccessful in deploying the probe. The later Apollo 15 mission was the first successful attempt at measuring heat flow.

The Apollo 15 and 17 heat flow probes were essentially identical and consisted of one-meter probes split into two 50 cm sections, each with two differential thermocouples. Thermal conductivity sensors were line-source heaters (coils of heater wire) within the probe. The 'LUNAR-A penetrator', a much bulkier and self-propelled probe, consisted of similar temperature and thermal conductivity sensors. That probe was launched from orbit and penetrated about one meter into the surface. The MUPUS probe, intended to measure heat flow on a comet, is a thin cylindrical carbon-fibre probe about 40 cm long, with a bulky head containing electronics.

Most of the astronomical heat flow probes contain thermocouples or platinum resistance

thermometers (RTD's) for measuring temperature, and coiled-heater wire to generate a line-heat source for thermal conductivity measurements. Banaszkiewicz *et al*. (2007), however, designed modular thermal conductivity sensors (~2 cm length) of coiled-heater wire, which generate a point source of heat for thermal conductivity measurements.

DESIGN CRITERIA FOR A SHALLOW HEAT FLOW PROBE

Conductive heat flow is the product of thermal gradient and thermal conductivity. Mean global conductive heat flow on continents in on the order of 65 mW/m^2 (Pollack *et al*., 1993), and mean thermal gradient is about 0.025°C/m. Heat flow anomalies of interest for geothermal or IOCG exploration arguably start at about 25% above the mean. It follows that the mean ground temperature at a depth of one meter above a thermal anomaly of interest might be just 0.006°C higher than 'average'. To detect such a subtle thermal signature will require a probe and methodology about two orders of magnitude more sensitive than those described by Coolbaugh *et al*. (2010). Achieving this is not without its challenges.

A probe to detect departures from 'average' terrestrial conductive heat flow in the top few meters of the earth must meet stringent design criteria. To be of practical value, it must be able to delineate heat flow variations on the order of ±10 mW/m^2. To delineate vertical heat flow variations of this magnitude, it must be able to sense small variations in the mean temperature gradient and quantify the mean vertical thermal conductivity to a high precision over a short depth interval. Vertical thermal conductivity measurements should be accurate to better than ~5%. Thermal gradient measurements must resolve temperature to better than ±0.005°C accuracy at a depth of one meter.

Any such probe must make good thermal contact with the ground, must be electronically insensitive to variations in surface temperature and moisture, must be calibrated within tight specifications, must be relatively thermally neutral with the ground, and must hold sensors steady at precise depths. The following list includes these and other design criteria:

- Strong enough to withstand repeated insertion and removal from the ground,
- Temperature sensors accurate to ±0.005°C and precise to ±0.001°C,
- Operating temperature range 0–50°C,
- Minimal drift in sensor response with time,
- Vertical thermal conductivity measured *in situ* to better than ±5% accuracy,
- Low thermal bulk for rapid equilibration,
- Thermal conductance similar to ground so as to not disturb natural thermal state,
- Depth accurate to ±10 mm,
- Data logged directly to memory,
- Environment and abrasion resistant,
- Power source and memory for up to 12 months data collection,
- Data collection once every 15 minutes,
- Reliable, repeatable, portable, safe tool insertion and removal,
- Cheap enough for mass production.

To date, no existing probe has achieved the precision and accuracy required to map variations in surface heat flow at the precision required to delineate subsurface heat sources associated with conductive geothermal systems or concentrations of uranium.

PROGRESS TO DATE

Probe design and construction

At the time of writing, HDR had designed and manufactured a set of 12 precision heat flow probes. The casing of each probe was 16 mm OD / 12 mm ID seamless stainless steel, with

a masonry drill bit welded to the tip and an 'SDS Max' drill attachment at the top (Figure 2). Total length of each probe was about 160 cm, with 120 cm of hollow internal space.

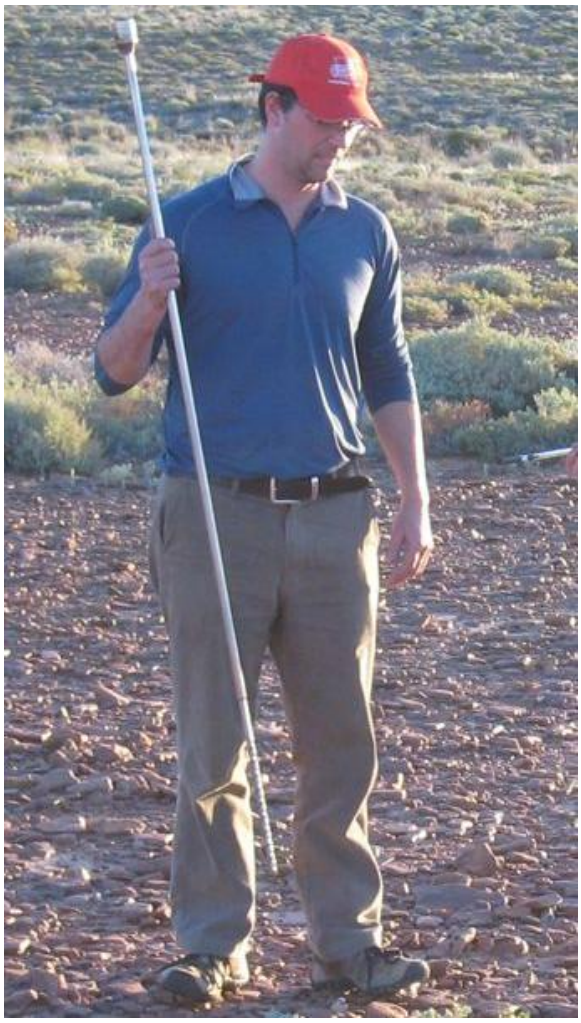

Figure 2: Professor David Giles of the University of Adelaide holding one of the probe casings prior to insertion. Note the SDS Max drill head and masonry bit.

A sensor string containing six calibrated thermistors spaced at 20 cm intervals from 10 cm to 110 cm depth was inserted into each casing after it was drilled into the ground and filled with paraffin oil (Figure 3). The thermistors were individually calibrated to 0.001°C precision in HDR's laboratory prior to their integration onto the sensor assemblies.

Figure 3: The author inserting a string of thermistors into one of the probe casings fully inserted in the ground.

Data were automatically logged and stored in local solid-state memory housed in boxes connected to each probe by one meter of cable (Figure 4). The electrical resistance of each thermistor (six per probe) was read and stored at 15-minute intervals from initialization until readings were manually terminated prior to data recovery. The data logging and storage boxes held air temperature sensors, on-board battery power and memory sufficient for at least 12 months of autonomous operation.

PROBE DEPLOYMENT

HDR carried out a joint field excursion with the University of Adelaide in late July (winter) 2011 to deploy the first six test probes under field conditions. Two locations were chosen near the town of Roxby Downs, approx-

imately seven hours drive north of Adelaide, South Australia. We deployed three probes in each of two locations, separated by a distance of about 50 km. The locations were chosen for their expected relative heat flow contrast, relative ease of road access, and seclusion from the unwanted attention of passers by. At each location, the three probes were inserted up to 10 meters from each other.

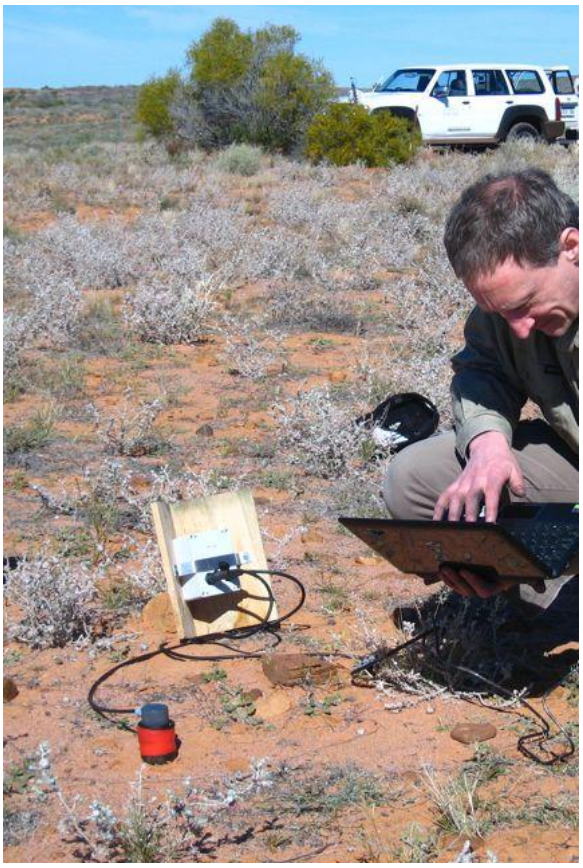

Figure 4: The author initializing one of the probes for data collection. Note the compact data storage and logging box.

The probe casings were driven into the ground using a hand-operated 1,200-watt SDS Max electric hammer drill powered by a 2,000-watt diesel generator. While eventually successful, experience taught that a more powerful drill and generator combination might be required in future (Figure 5).

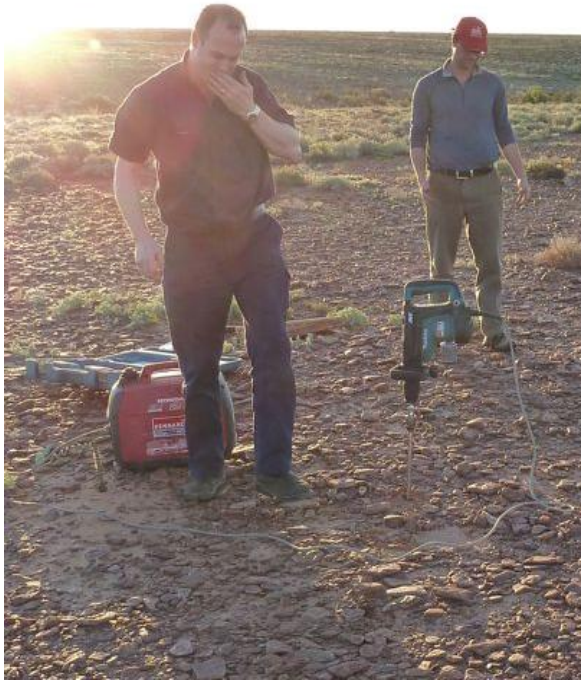

Figure 5: Chris Pierson (Flawless Fabrications) and Prof Giles contemplating a partially inserted probe casing that tested the power limits of the drill and generator.

For extended remote field deployment, each logging box was housed off the ground under a rudimentary wooden sun-shelter, to simultaneously protect the electronic components from direct sunlight and surface water run-off (Figure 6).

Nader Shahin, an Honours student from the University of Adelaide, revisited the sites in early September 2011 (early spring) and attempted to retrieve about six weeks of data from the probes. Data from five of the probes were corrupted when downloaded. HDR later traced the problem to interference in the downloading data stream by the laptop's virus protection software. No data corruption was observed when the virus protection software was disabled. However, the first six weeks of data were lost. Nader reinitialized the five probes and left them to record more data.

Figure 6: Installed and initialized unit.

Figure 7: Data cable chewed off at its junction with the probe.

Nader could not download the sixth probe in the field due to the severing of its data cable, apparently by some hungry or curious creature (Figure 7)—the logger needed attachment to the probe to complete the power circuit during download. Nader returned the data logger to HDR and we subsequently recovered 11.5 days of clean data and narrowed the time of the faunal attack to between 23:48 on 8 August and 00:03 on 9 August.

On 26 October 2011 (mid-spring), Anson Antriasian (HDR) and Professor David Giles (University of Adelaide) revisited the five remaining probes and successfully recovered seven weeks of data from each. They reinitialized the probes and left them to continue recording. Eleven weeks have since elapsed at the time of writing. We intend to recover the probes in early March 2012, to effectively provide six months of continuous data.

RECOVERED DATA

Processing

Raw data recovered from the probes were in the format of time-stamped sequences of bits related to the electrical resistances across the thermistor sensors in the probes. These bit sequences first had to be converted into temperature values using the calibration relationships HDR previously derived for the sensors.

Each probe thus produced seven series of temperature data at 15-minute intervals, representing air temperature within the logging box and the temperature of each of the six underground thermistor sensors (depths 10, 30, 50, 70, 90 and 110 cm). In total, the five probes generated almost 165,000 individual temperature records over the seven-week period.

Observations

At face value, the data recorded by each probe followed expected patterns of behavior. The recorded temperature at 10 cm depth in the soil mimicked the fluctuations in air temperature, with a peak–trough magnitude on the order of 10°C. The periodic signal decayed at deeper levels. A snapshot of the changing one-meter temperature profile over a single 24-hour period (Figure 8) illustrates the decay in amplitude of the diurnal temperature signal as it diffused into the ground.

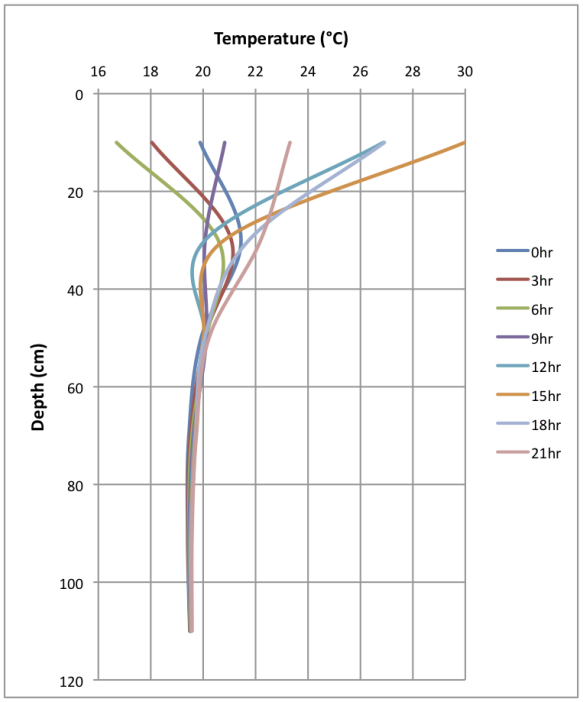

Figure 8: A single 24-hour record of temperature over one-meter depth interval. By 50 cm depth, the amplitude of the thermal pulse had decayed to just a few percent of its surface value.

The full record from one of the probes is illustrated in Figure 9. The beginning date of the record was 5 September 2011. Each 24-hour period is clearly delineated by a characteristic peak and trough in air temperature as the sun made its regular passage through the sky (note that the magnitude of the 'Air' record might not truly represent open air temperature as the sensor was housed within the airtight logging box.)

Looking closer at the third week of belowground data (Figure 10), we observe that the shape of the periodic temperature signal is more 'saw-tooth' than sinusoidal, with the ground tending to heat relatively quickly and cool relatively slowly each day. We also observe that the temperature signal diffuses into the ground with a phase offset and decreasing magnitude with depth. The daily temperature fluctuation is clearly discernable at the scale of the graph down to at least 70 cm depth (Figure 11), although at that depth its amplitude has decayed to about 0.05°C. Even at 110 cm depth, however, the second derivative of the temperature curve with respect to time still reveals the daily periodic cycle (Figure 12).

The mean ground temperature was slowly increasing over the recording period, as expected in spring. For example, Figure 11 indicates a gradual rise of about 0.9°C at one meter depth over the third week of recording.

The marked departure from the regular diurnal temperature cycle at the start of the fifth week (Figure 9) corresponded to the heaviest (of six) rain event during the recording period, with 4.6 mm reported by the Bureau of Meteorology at nearby Andamooka on 4 October. The next heaviest fall of 2.8 mm on 30 September had no apparent impact on ground temperature.

As a final observation of the stability and precision of the thermistor sensors, Figure 13 illustrates the data from the 110 cm deep sensor over a three-day period at the start of the second week. This was a period of relatively stable temperature at that depth, making it possible to display the data on a very compact vertical scale. The data on Figure 13 demonstrate that the stability and precision of the thermistor sensors are both better than ±0.001°C at about 20°C.

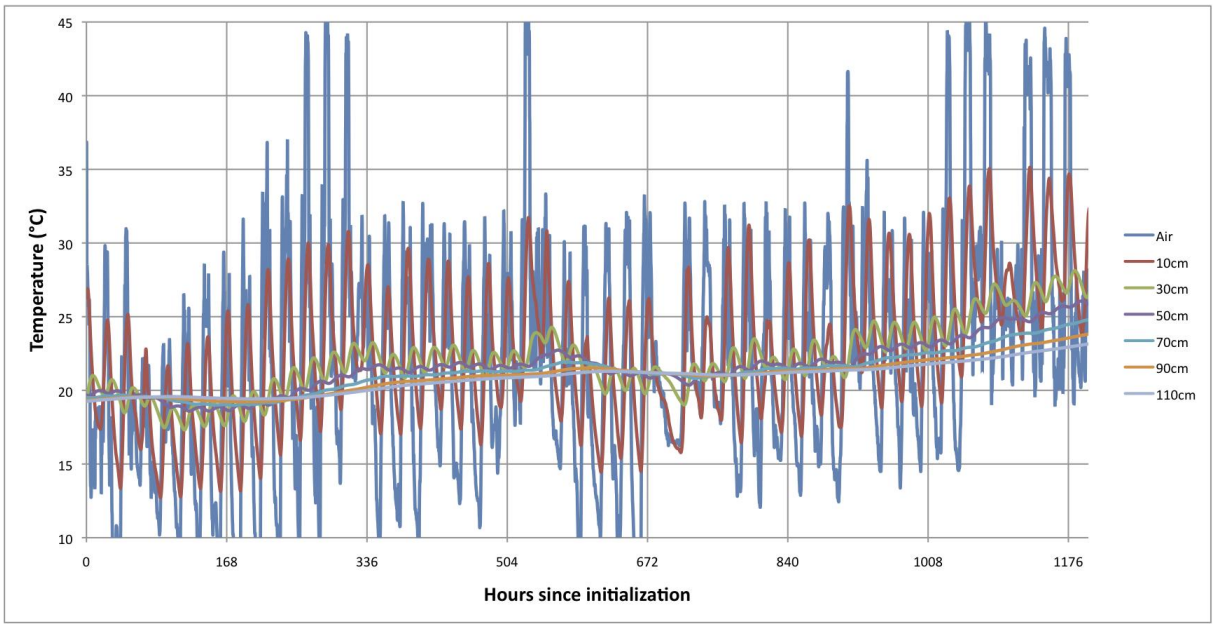

Figure 9: Full record from one probe, showing almost 50 days of temperature from seven sensors as indicated on the legend. Vertical grid lines mark weeks since initialization.

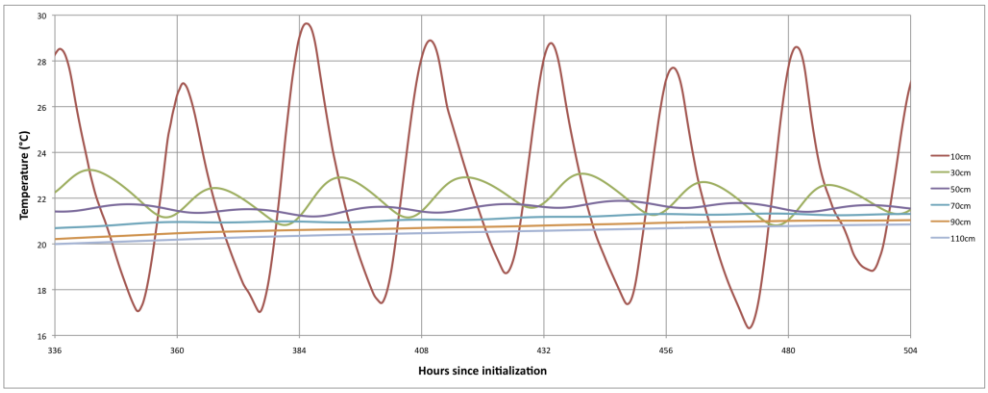

Figure 10: Expanded view of the third week of data from the seven belowground sensors, as indicated by the legend. Vertical grid lines denote 24-hour periods.

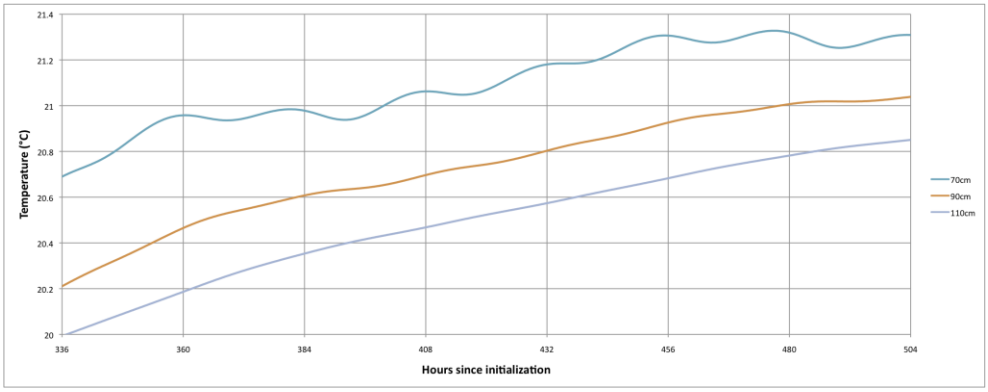

Figure 11: Expanded vertical scale for the 70 cm, 90 cm and 110 cm sensors, as indicated by the legend. Vertical grid lines denote 24-hour periods.

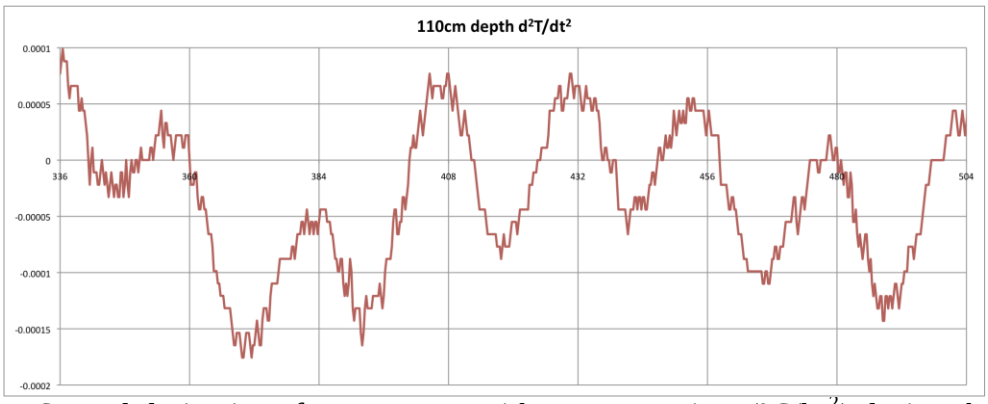

Figure 12: Second derivative of temperature with respect to time (°C/hr^2) during the third week of data collection at a depth of 110 cm. Second derivative minima correspond to local maxima in the temperature cycle. Vertical grid lines denote 24-hour periods.

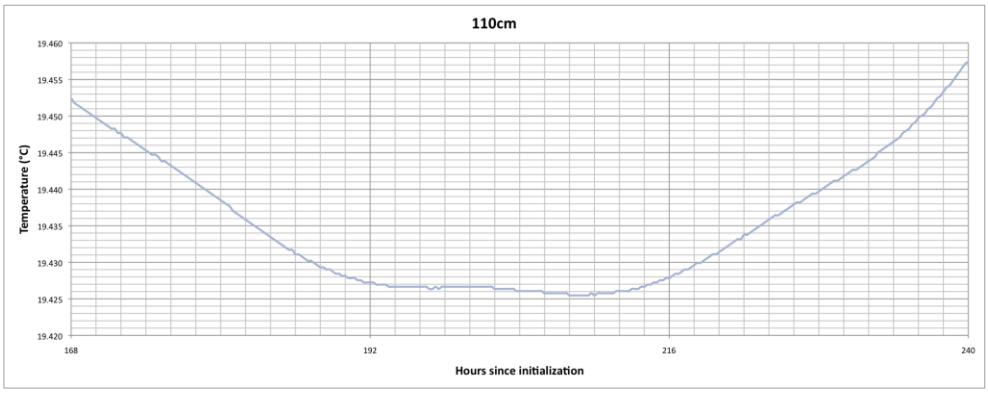

Figure 13: Data from the 110 cm deep sensor over a three-day interval at the start of the second week. Vertical grid lines denote 2-hour periods, or eight data records.

Interpretation

At the time of writing, HDR had not developed full processing and interpretation algorithms for the data. Ultimately, most of the processing and interpretation will require manipulation in the frequency domain. However, HDR presents the following interpretation of vertical thermal diffusivity as an example of the type of processing that is achievable in the time domain.

As a first approximation, the diurnal temperature cycle can be modeled as a sinusoidal pulse with a period of 24 hours. This pulse at the Earth's surface diffuses into the ground. Carslaw and Jaeger (1959, p64) gave the solution to the diffusion of a sinusoidal temperature pulse into a half-space:

Equation 3: $T_\theta = T_0 \times \exp(-\varepsilon z) \sin(\omega t - \varepsilon z)$

where T_θ is the departure from mean temperature at time (t) and depth (z); T_0 is half the peak–trough amplitude of the surface temperature cycle; ω is the radial frequency of the cycle, $2\pi/P$, where P is the period; $\varepsilon = (\pi/P\kappa)^{1/2}$; and κ is the thermal diffusivity. The variable 'ε' in Equation 3, therefore, controls both the decay of signal amplitude and the radial phase lag with depth. If either of these parameters can be measured, then ε, and hence κ, can be derived.

Figure 10 illustrated the time lag between daily temperature peaks and troughs at successive depth levels, traceable down to the deepest sensor at 110 cm (Figure 12). The specific time at which a peak or trough arrived at each depth could be detected to a precision of ±0.25 hours at best—the period at which temperatures were recorded—and only to within about ±1.5 hours where the peaks or troughs were poorly resolved in the data. However, the precision of the mean lag times could be improved by averaging the lag times of a number of successive peaks and troughs.

Table 1 shows the average lag times of 11 full temperature 'wavelets' at depths of 30 cm to 110 cm, relative to the observed signal at 10 cm depth. It took, on average, almost 31 hours for a temperature peak or trough to diffuse to a depth of 110 cm. The phase lag in radians is the lag time in hours multiplied by $2\pi/24$. The variable 'ε' is the radial phase lag divided by depth interval in meters (10 cm to 30 cm, for example, is a depth interval of 0.2 m). The vertical thermal diffusivity, κ_v, is then:

Equation 4: $\kappa_v = \pi/\varepsilon^2 P$

Table 1: Derivation of mean vertical thermal diffusivity, κ_v, between 10 cm and successive sensor depths, following the process described in the text.

	30 cm	50 cm	70 cm	90 cm	110 cm
Lag time (hours)	5.170 ±0.117	11.898 ±0.125	18.602 ±0.131	24.625 ±0.156	30.955 ±0.239
Phase lag (radians)	1.354 ±0.031	3.115 ±0.033	4.870 ±0.034	6.447 ±0.041	8.104 ±0.063
ε (m^{-1})	6.768 ±0.154	7.787 ±0.082	8.117 ±0.057	8.059 ±0.051	8.104 ±0.063
κ_v ($x10^{-7}$ m^2/s)	7.938 ±0.180	5.996 ±0.063	5.519 ±0.039	5.599 ±0.035	5.537 ±0.043

Given the assumption of a purely sinusoidal temperature pulse with a period of 24 hours, the data provide us with a mean value of vertical thermal diffusivity of 5.537±0.043 $x10^{-7}$ m^2/s between 10 cm and 110 cm depth. The uncertainties in Table 1 were derived from the precision with which the temperature pulse arrival times could be distinguished at each depth. Note that at depths greater than 50 cm, the mean vertical thermal diffusivity is determined to a precision better than ±1%.

Plugging the 'ε' value back into the exponential term in Equation 3, we find that the 10°C amplitude temperature cycle at a depth of 10 cm should decay to an amplitude of about 0.003°C at a depth of 110 cm, just within the measurement limits of the probe. Furthermore, we can derive that the diurnal temperature pulse would fall below detection limits at 110 cm if 'ε' exceeded a value of 9.2, or if thermal diffusivity was less than 4.3×10^{-7} m^2/s. This is only likely in highly carbonaceous or coaly material.

FUTURE DEVELOPMENT

In terms of developing a shallow heat flow probe, HDR has so far achieved or exceeded all the minimum requirements for precision, stability and practicality for measuring time series of temperature to a depth of 110 cm. However, we are still to achieve a number of significant development milestones. Not least of these is the inclusion of an additional component to the probes to measure vertical thermal conductivity, λ_v.

Vertical thermal conductivity is needed to translate observed thermal gradient into heat flow, the most appropriate parameter for detecting anomalous heat sources. HDR intends to follow a methodology published by Waite *et al*. (2006) to measure radial thermal diffusivity, κ_r, and radial thermal conductivity, λ_r, and hence derive the volumetric heat capacity of the ground (λ_r/κ_r). The volumetric heat capacity will then allow us to derive λ_v by simple multiplication by the vertical thermal diffusivity, which we have already demonstrated is measureable.

Much work is still required on data processing. HDR intends to apply low-pass filters to the time-series data to remove the

temperature signals for periods shorter than several weeks. The remaining longer period signals will then be corrected for variations in thermal diffusivity, and multiplied by vertical thermal conductivity to reveal relative heat flow. HDR expects that the geothermal component of heat flow will be on the order of $1/50^{th}$ of the measured heat flow, but within the sensitivity limits of the probe.

While the probes currently require manual download of the data, HDR intends to incorporate data telemetry and satellite upload components to allow regular monitoring and cumulative processing of survey data from a home base.

HDR's current calibration procedure for the thermistor sensors provides an absolute accuracy only on the order of ±0.020°C for any specific sensor. This is insufficient to reliably resolve heat flow anomalies of the magnitude we are targetting. HDR has a plan in place to refine our calibration process to provide absolute accuracy on the order of ±0.005°C across all sensors.

CONCLUSIONS

Hot Dry Rocks Pty Ltd is designing and manufacturing a tool and methodology to map relative variations in surface conductive heat flow on a local to regional scale. If successfully developed, the shallow heat flow probe will provide a means to directly map surface heat anomalies due to buried heat sources such as geothermal resources or uranium concentrations. It will provide an additional layer of geophysical information upon which to base decisions about locations to drill expensive exploration boreholes.

So far, we have demonstrated measurement and storage of ±0.001°C precision temperature data at 15-minute time intervals over seven weeks from six different depths to 110 cm. Eleven periodic temperature wavelets were sufficient to derive vertical thermal diffusivity to a precision better than ±1%, with a greater number of wavelets expected to provide even greater precision.

To date, the shallow heat flow probe has met or exceeded all expectations with respect to durability, precision, reliability, stability, power consumption and practicality. While considerable R&D challenges remain, HDR is buoyed by the successes to date, and has a clear development pathway to proof of concept and commercialization.

ACKNOWLEDGEMENTS

While HDR is the lead agency for developing the shallow heat flow probe, and retains 100% of the IP in the probe, we could not have progressed as far as we have without the strong financial and in-kind support of three sponsoring organizations—Barrick (Australia Pacific) Ltd, Green Rock Energy Ltd, and the University of Adelaide (supported by a tied grant from the South Australian Department of Primary Industries and Resources). In particular, HDR wishes to thank Matt Hope, Adrian Larking, Dave Giles and Nader Shahin from those organizations. In addition, the robust design and manufacture of the probes owes strongly to input and hard work by Chris Pierson (Flawless Fabrication), George Jung (Qwertech Solutions) and Anson Antriasian (HDR).

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