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DETAILED THERMAL PROFILING AND INVERSION FOR THERMAL CONDUCTIVITIES AND HEAT FLUXES IN THE PERTH METROPOLITAN HOT SEDIMENTARY AQUIFER PLAY OF WESTERN AUSTRALIA

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ABSTRACT

Using equipment kindly loaned to us by Geoscience Australia during a field break of their Geothermal measurement programme, the Western Australian Geothermal Centre of Excellence (WAGCoE) performed detailed thermal logging of 17 Artesian Monitoring bores in the Perth metropolitan area during June and July of 2010. The boreholes reach depths of up to 758 metres, and cut strata comprising several active aquifers in the Perth Sedimentary Basin. The Auslog A626 sonde used simultaneously measured temperature and Gamma logs, and we predominantly sampled on 5cm intervals. Temperature measurements were calibrated and reduced to match our internal standard. Calibrated downhole temperature measurements were also spatially filtered by convolving with a (low pass) Gaussian kernel using a 1σ value of 50cm and normalised to unit area.

There are several confounding factors in interpreting the profiles. First – as previously mentioned – the boreholes encountered actively flowing aquifers, which often exhibited negative thermal gradients (i.e. $dT/dz < 0$ for z positive downwards). Second, published laboratory measurements of thermal conductivities for the rocks encountered were limited to only a few samples from nearby oil wells. Third, the heat fluxes themselves were previously relatively poorly constrained. Finally, there was a clearly evident "thermostratigraphy" found in beds within the stratigraphic units encountered. To address these problems, we settled on the following strategy. Conductive vertical heat flux in an individual borehole was assumed to be constant, both above and below zones of advective activity. We assumed this because in a steady state thermal system it is a reasonable approximation to conserving heat under a cross-flowing aquifer system. Short zones of approximately constant thermal gradient were "picked" and assumed to be representative of fluctuations in both thermal gradients and (under a conductive heat transport assumption) the corresponding thermal conductivity distribution for the corresponding stratigraphic unit. Employing the Kolmogorov-Smirnov (KS) "d" statistic we compared the distributions of thermal conductivities. Minimizing the KS "d" by shifting the relative thermal gradients allowed us to simultaneously estimate the appropriate thermal gradient shift between wells and the associated probability that the measured thermal conductivities were drawn from the same distribution. Finally, an inverse problem incorporating all of the above assumptions – with initial thermal conductivities seeded by the published values – was formulated and solved using the method of weighted nonlinear least squares.

INTRODUCTION

This paper is an abbreviated version of Botman (2010). The reader is urged to consult that reference for additional details omitted here. If you wish, you will find a PDF of his full Honours Thesis online at: http://www.geophysics.curtin.edu.au/EGPPUBS/Docs/2010-002488-AWA.PDF

The purpose behind this project was to gain estimates of formation temperatures from a network of Artesian Monitoring (AM) bores in the Perth Basin. The ultimate aim was to incorporate these new measurements with older temperature data in order to estimate the equilibrium geothermal gradients for each well. An inverse problem was formulated to jointly refine the thermal conductivity estimates for a number of the lithological units encountered during the logging exercises and to establish the heat flow of each well. The geothermal potential of the well is gauged from these calculated heat flux values.

The Western Australian State Department of Water maintains the network of AM boreholes around the Perth metropolitan region of the Perth Basin, primarily to observe piezometric head variations with time in the different aquifers being actively exploited for water. WAGCoE occupied 16 of these wells during June and July 2010, obtaining detailed thermal and gamma downhole logs. A 17th well was occupied that was purpose drilled for estimating thermal gradients on the site of the proposed UWA airconditioning project.

Geology of the Perth Basin

The Perth Basin is a 1000 km long sedimentary rift basin occupying the southwest of Western Australia, bounded by the Darling Fault to the east and the continental slope to the west. Upper Cretaceous to Permian aged sediment dominates the basin's lithology with some late Tertiary-Quaternary aged sediment found at the surface. The thick, permeable sedimentary deposits reach depths up to 15 km and host a number of groundwater bearing aquifers. The native permeabilities of the sediments throughout the Perth Basin sediments are high, thus facilitating hydrothermal circulation through these aquifers at relatively shallow depths. The attainable pumped flow rate of the Perth Basin's heated water appears to be practical for Hot Sedimentary Aquifer (HSA) geothermal use (O'Bryan and Horowitz, *this volume*, 2011). Details of the stratigraphy encountered during our logging are found in section 1.4.2 of Botman (2010).

METHODS

Theory

Under a 1D vertical conductive heat flow assumption – with known stratigraphic thicknesses, heat fluxes and thermal conductivities – an extrapolated value for temperature at depth can be determined. The assumption of purely conductive heat transfer holds true if there is no component of advective or convective heat transfer by fluid flow, and if there is no source of internal heat generation such as radioactive decay. In this paper, only 1d vertical conductive heat transfer has been assumed over the modelling depth intervals as a means of approximating heat transport throughout the Perth Basin. We recognize that our own measurements militate against a purely conductive heat flow mechanism (Bloomfield, 2010), but this paper attempts to push the conductive approximation as far as possible, since it does not require modelling of fluid flows and hence renders the problem tractable with the available information.

Heat flux estimation

We assume the validity of Fourier's "law" of conduction:

$$Q_z=-\lambda \; dT/dz \qquad (1)$$

where Q_z is the vertical component of the heat flux vector (W m^{-2}), λ is the thermal conductivity of the material surrounding the borehole (W m^{-1} K^{-1}), T is the measured temperature at a certain depth (K or ºC), z is the depth in the borehole (m; positive downwards), and dT/dz is the estimated thermal gradient at a certain location (K m^{-1}). The minus sign in equation (1) arises from the opposite sense of the heat flux and thermal gradient vectors, and is ignored (with care) in the rest of this work by only considering the magnitude of the vector components.

Conservation of vertical heat flux assumption

In a purely conductive heat transport regime, in the absence of volumetric sources (e.g. radioactivity) or sinks of heat (e.g. an endothermic chemical reaction), the conservation of heat flux is a consequence of the conservation of energy. While we do estimate the radioactive heat production from the gamma logging (Botman, 2010) it turns out to be very small in magnitude, and for the purposes of this analysis we neglect its contributions.

In an actively flowing system, the situation is more complicated. We sampled in the Perth Basin aquifers where a regional hydraulic gradient flow is known to be present, and convection is at least a possibility. Hence, we need to make further assumptions for a conservation-of-vertical-heat-flux simplification of the actual situation to hold true. We assume a steady-state thermal regime, horizontal strata, and the presence of layered hydraulic seals (i.e. strata with low enough permeability for the fluid not to infiltrate across stratigraphic contacts). Figure 1 displays a cartoon of the assumed situation.

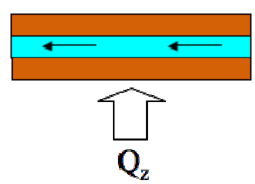

Figure 1. Horizontal strata extending to infinity are either hydraulically open (blue; aquifers) or closed (brown; seals). Water from (e.g.) a regional hydraulic gradient is flowing parallel to the boundaries (small black arrows), with zero fluid flux crossing the boundaries. The heat flux is assumed to be vertical (open arrow). A global steady state thermal regime is further assumed.

Under the assumed conditions stated, vertical heat flux is conserved within an actively flowing aquifer system. While the veracity of these assumptions is certainly open to debate, adopting them allows us to simplify the analysis to one of purely conductive heat flow.

Fluctuations in thermal gradients represent fluctuations in thermal conductivities

In the assumed situation described above, temperature gradients in a rock column are not conserved, but heat fluxes are. The detailed thermal gradients in the rocks will locally obey equation (1) reflecting the pointwise thermal conductivity of the rocks surrounding the borehole. We use this relation to infer that the statistical fluctuations in the detailed dT/dz values – quality controlled to remove clear advective effects – are in fact proportional to the statistical fluctuations of thermal conductivity in the rocks. The constant of proportionality is the heat flux or its inverse. By assuming that the statistical distribution of thermal conductivities is a characteristic of the named stratigraphic unit, thermal gradient fluctuation statistics are seen to be a "thermostratigraphic" signature of rock units.

This lays the groundwork for an inverse problem, jointly estimating heat fluxes *within* and thermal conductivities *between* wells containing the same suite of rocks.

Measurements

Logging fieldwork with Geoscience Australia's equipment allowed the acquisition of temperature and gamma data along with other measurements, including wireline tension due to the weight of the probe and the drawn voltage by the logging equipment.

Equipment

Auslog's A626-4 Conductor Gamma/Temperature Sonde contains a 43 mm temperature/gamma ray tool to assist in the investigation of heat flow. Temperature sensing is performed by a fully encapsulated AD590 solid state temperature sensor and an electrode positioned at the bottom of the probe. The AD590 is a transducer which converts temperature input into a proportional current output, which is fed up the four-conductor cable to the data acquisition system, where the data is plotted as temperature values in the WellVISION software. The A075 gamma ray tool is located 26 cm above the temperature sensor, with this offset accounted for by the WellVISION software. The tool detects the total count of natural, very high frequency gamma emissions from the subsurface lithology through a sodium iodide crystal sensor. The A626-4 temperature tool is rated to 60 ºC but both the temperature and gamma sensor are capable of operating in the temperature range of 0-70 ºC and at maximum pressures of 21000 kPa. The tool used a three second time constant to filter the thermal and gamma data.

Borehole Selection

Initial selection of AM wells to log was at the discretion of the land title holder but obstacles such as difficult terrain and fences restricted access to some of the boreholes. The goal became to log as many wells as possible around the Perth metropolitan area within the loan time of Geoscience Australia's equipment. The logged wells are shown in Figure 2.

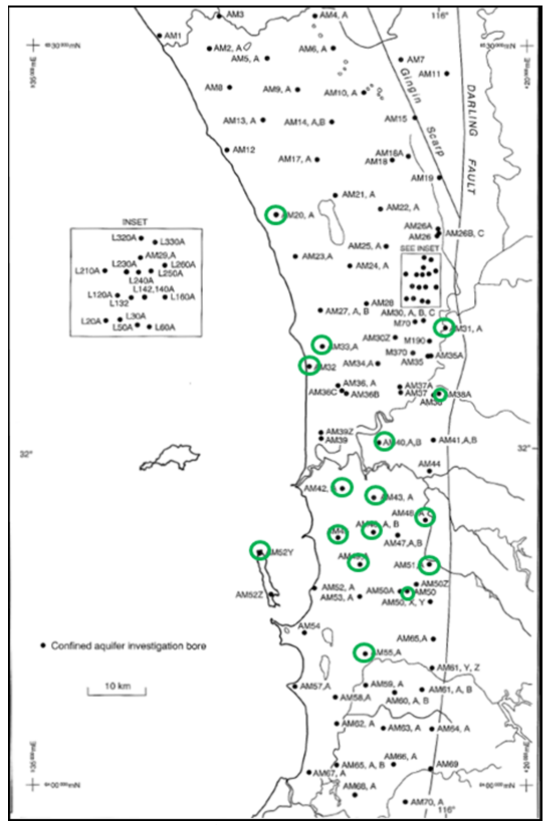

Figure 2. Record of the Artesian Monitoring wells logged during June-July 2010 (modified from Davidson, 1995). Green circles indicate the successfully logged bores. Metropolitan Perth occupies much of this region, with Fremantle located at the mouth of the major (Swan) river at about latitude 32º S.

Field Logging

Temperature logging was recorded on the downward run of the borehole to minimize the disturbance of temperature equilibrium between the borehole fluids and the formation. Ideally we do not want the temperature measurements to be influenced by the displacement of water in the borehole during logging in order to best represent the thermal equilibrium state of the water in the aquifer. Disturbances of the near surface water table were unavoidable where groundwater monitoring loggers previously installed inside the wells were removed shortly before the commencement of logging.

The WAGCoE team performed repeatability measurements in AM40 and AM40A – boreholes of different total depths located about 10m apart. The instrument proved to report highly repeatable measurements, even between the 10m apart wells. As a result of this suite of logs, we decided to standardize on a logging protocol using a sampling interval of 5cm at a logging descent rate of 5m/minute. This is in contrast to the Geoscience Australia (GA) protocol, which sampled a few AM boreholes in Perth on a 20cm interval at a 5m/minute descent rate. A discussion contrasting the effects of the different protocols may be found in Bloomfield (2010). Unfortunately, the difference in sampling intervals by GA induced gradient statistics sufficiently different from the WAGCoE measurements that we were only able to include the GA set of measurements in this analysis with difficulty.

Since the logging was performed during winter, a rapid increase in the borehole's thermal profile at a depth of less than 40m signified the water table depth. Reaching the bottom of the borehole was determined through a combination of monitoring the live gamma count to gauge where the count became relatively constant, referring to the casing depths noted in Davidson (1995) and monitoring the increase in the slack on the unwinding cable coinciding with the probe being "hung-up" at the bottom of the well. Logged data was exported in LAS format for analysis.

Thermal calibration of the probe

With every logging run of the thermal probe, a slight drift in the temperature recordings was encountered. The temperature sensor's drift was compensated through calibration of the probe. The probe was positioned in a bucket of heated water, at a temperature less than the sensor's maximum operating temperature, alongside an accurate mercury thermometer. The thermometer became the measuring standard as the temperature of the probe in counts per second was recorded at set intervals of temperature on the thermometer. A linear trend was established between the thermometer and probe's temperature measurements, and the calibrated results used for further analysis. Further calibration details are in Botman (2010).

Data Analysis

Spatial filtering and gradient estimation

We observed high amplitude spatial fluctuations of temperature in the raw data. We attribute this to the interplay between raw instrumental noise, the 5 second time constant averaging process built into the instrument, the rate of descent, and the sampling intervals of a spatial point process.

In order to estimate pointwise gradients numerically, it is well known that some kind of low pass filtering is required – in order to eliminate spurious high amplitude noise in the gradients. We chose to spatially filter by convolving our raw T measurements with a Gaussian weighting function, of 50cm standard deviation, spatially sampled at the same interval as that of the raw dataset being filtered. This decays in a short distance, resulting in measurements 2m away from the central point contributing about 3×10^{-4} of the weight of the central measurement. The Gaussian convolution kernel was numerically scaled to sum to unity in order to avoid amplitude scaling artifacts in the filtered dataset.

We estimated pointwise thermal gradients by central differences applied to the Gaussian filtered T dataset.

Quality control

A quality control analysis of the calibrated temperature data was performed in order to identify the values appropriate for inclusion in the heat flow inversion. The weight bearing load of the probe on the cable was investigated wherever recorded in the LAS files. Zones showing a change in the loading on the cable indicate the probe's progression through the borehole has been perturbed, affecting the sampling rate of the probe. In order to maintain a consistent sampling rate throughout each well, data from the zones showing a significant change in cable loading were excluded.

Near surface logged data above the borehole's water table was excluded from analysis. Fluctuating seasonal water table depths and surface temperatures along with variations in surface types are other sources contributing to near surface variations in heat flow. The greatest magnitudes in local thermal gradients were continually associated with the detection of the local water table.

With the focus of this study on conductive heat flow, local thermal gradient estimates not displaying conductive traits were excluded from the inversion process as part of the final step in the quality control on the data. Negative, linearly trending, and highly fluctuating thermal gradients were assumed to represent zones of non-conductive heat flow through the well. We subjectively "picked" zones of positive and reasonably constant thermal gradients, by visually examining their values. A reasonable interpretation of the picked conductive zones would be that they are inside impermeable zones of rock (e.g. the brown regions of the cartoon of Figure 1).

Longer intervals of nearly constant conductive thermal gradients were preferred, but the details of the logs were not always amenable to this. The thermal gradient was estimated as the mean of the picked gradients in each zone. The distribution of gradients was retained for further analysis (described in the next section). Finally, the variance within each zone was also recorded for use as weights in the inverse problem.

“Statistical Thermostratigraphy” and offsets

We hypothesized that conductive zones found in the same stratigraphic unit in different boreholes would exhibit similar statistical distributions of thermal conductivities. A non-parametric statistical test for the similarity of two distributions is the Kolmogorov-Smirnov (K-S) test (e.g. Press et al., 1992). The K-S test computes as its “d” statistic the maximum normalized distance between two cumulative distribution functions (CDFs). An associated probability for rejecting a null hypothesis that the two distributions differ is computable from “d” and other details of the distributions, such as the number of samples in each one. For concreteness, Figure 3 displays the CDFs for thermal gradients of picked zones in the Yarragadee Formation in boreholes AM20 and AM55.

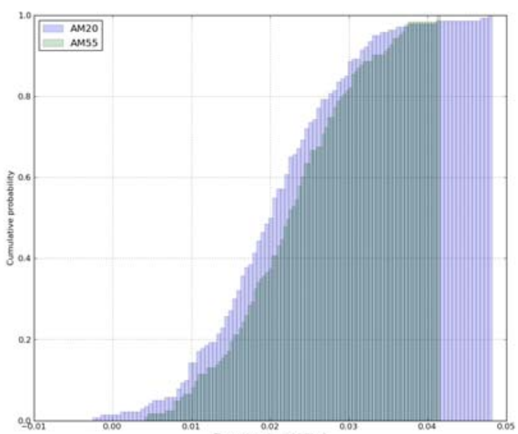

Figure 3. Cumulative distribution plots of thermal gradients from the Yarragadee Formation in wells AM 20 and AM 55. The K-S “d” statistic occurs at about 22ºC/km, and the associated probability would indicate that the two distributions differ.

While the two distributions of Figure 3 differ, the major disparity is that they seem to be laterally offset with respect to one another. In other words, a constant shift would appear to bring them into closer agreement. Figure 4 plots the K-S “d” statistic as a function of offset between the curves, estimated numerically by simply adding a range of constants to the values entering into the CDF.

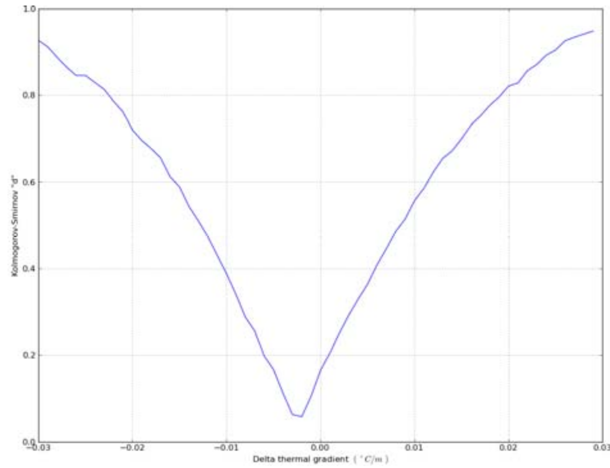

Figure 4. A change in thermal gradient of 2°C/km between AM 20 and AM 55 in the Yarragadee Formation yields a minimum K-S “d” statistic. This means that the best match between the two distributions is found if they reflect thermal gradients in the different wells that differ by 2°C/km.

Now, in the context of our heat flow estimation, such a constant shift is quite reasonable – it could merely reflect a change in the local heat flux encountered at the two different borehole locations. In fact, we will use such shift estimates later in our joint inversion to help enforce the measured thermal gradient differences between boreholes.

For completeness, Figure 5 displays the same two distributions, offset by the 2°C/km shift identified in Figure 4.

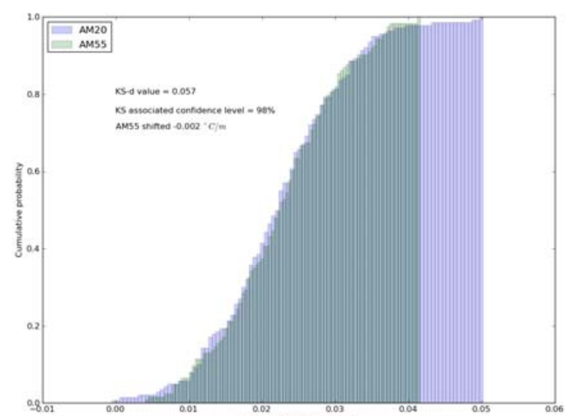

Figure 5. Shifted cumulative distributions of thermal gradients in AM 20 and AM 55 Yarragadee Formation picks. The K-S “d” value is 0.057, and the confidence level is about 98%

Such a procedure was repeated for all picks in the same formations between all possible well pairs. We accepted the resulting estimates of thermal gradient offsets in every case where the confidence level was above 50% – resulting in a total of 35 formation/well-pair offsets.

Defining the Inverse Problem

An inverse problem was formulated to refine the thermal conductivity estimates from the Hot Dry Rocks Perth Study Report (HDRPL, 2008) for a number of the lithological units encountered during the logging fieldwork, as well as to establish a conductive heat flow value in each well. Under the assumptions laid out above, the thermal conductivities for each stratigraphic unit and vertical heat fluxes in each well are the two major kinds of unknowns that need to be estimated.

Inverting for these two kinds of unknowns was performed jointly by formulating an optimization problem that minimized a weighted sum of two different classes of residuals.

The first class of residuals represents the difference between the estimated values of heat flux assigned to each well and the heat flux estimate arising from the product of the thermal conductivity and thermal gradient measured for the formation within a "picked" interval. In symbols, for the i^{th} "pick", define the thermal gradient estimate as $\partial\tau_i/\partial z = \left\langle \partial T_i(z)/\partial z \right\rangle$ where the angle brackets denote a spatial average over all the pointwise gradient estimates in the picked interval. Next the optimizer assigns a candidate heat flux for the j^{th} well – denoted as Q_j. Finally, the optimizer assigns a candidate thermal conductivity for the k^{th} formation denoted as λ_k. This assigned thermal conductivity is drawn from within a range derived from the HDPRL (2008) measurements. There is also a multiplicative weight (W_{ijk}) derived as the inverse of the composite variance of the observed gradients and assumed conductivity range. Pulling it all together, the first class of residual is:

$$r_1 \equiv \sum_{all\ picks} W_{ijk}\left(\partial\tau_i/\partial z - Q_j\lambda_k\right) \qquad (2)$$

The second class of residual is constructed to enforce the thermal gradient offsets defined in the previous section. Here, we first construct:

$$\Delta Q_z = \lambda_k\left(\partial\tau_{i1}/\partial z - \partial\tau_{i2}/\partial z\right) \qquad (3)$$

where λ_k is the formation conductivity assigned by the optimizer, the quantity in parentheses is one of the 35 formation/well-pair offsets described in the previous section, and ΔQ_z is the associated estimate for heat flux difference. The second class of residual is:

$$r_2 \equiv \sum_{valid\ pairs}\left[\Delta Q_z - \left(Q_{j1} - Q_{j2}\right)\right] \qquad (4)$$

where Q_{j1} and Q_{j2} are the heat fluxes assigned by the optimizer to the corresponding wells.

The total joint inverse problem minimizes a linear combination of residuals consisting of $R = r_1 + c\, r_2$ where c is chosen to absorb the change of units between the two classes of residuals, and to scale the residual Frechet derivatives to be of similar magnitudes, such that the optimizer uses information from both classes of residual. Note that the total residual exhibits the formal structure of a Tikhonov regularization, with the heat flux offsets playing the role of the regularization function.

The joint inversion is implemented in Microsoft Excel, using the BFGS algorithm from its built-in solver for the optimizer.

Initial conditions and constraints

Thermal conductivity measurements from HDRPL were used as initial conditions in the inversion. Constraints were applied to the thermal conductivities in the form of upper and lower bounds corresponding to the information drawn from the HDRPL measurements. The thermal conductivity values and their associated bounds are listed in Table 1. These bounds were also used to form an estimate of the variance in the thermal conductivities used in assigning values to the W_{ijk} of Equation 2.

Table 1. Initial thermal conductivity values, in Watts/m-K and their associated bounds applied to the inversion. Values are mostly derived from HDRPL (2008) with some appropriate judgment/augmentation applied for this work.

Stratigraphic Unit	Thermal Conductivity	Lower Bound	Upper Bound
Kings Park	1.70	1.392	2.088
Henley Sandstone	2.56	1.613	2.464
Kardinya Shale	1.70	1.650	2.200
Mariginiup	2.56	1.944	3.047
Wanneroo	2.56	2.187	3.047
Pinjar	2.56	1.944	3.047
South Perth Shale	1.71	1.500	1.950
Gage	1.90	1.613	1.950
Yarragadee	3.50	1.987	2.484
Cattamarra	3.73	1.818	3.744

Initial spatially constant heat flux values were assigned to each well with only positivity constraints on the heat fluxes enforced.

RESULTS

Figure 6 displays the basal ("bottom hole" but thermally equilibrated) temperatures for the logging performed. Table 2 shows the thermal conductivities estimated by our inversion process. Table 3 shows the conductive heat fluxes jointly inverted for each borehole considered. Finally, Figure 7 displays an estimated heat flux map for the metropolitan Perth region using the heat flux values resulting from this work and Kriged in ARC-GIS.

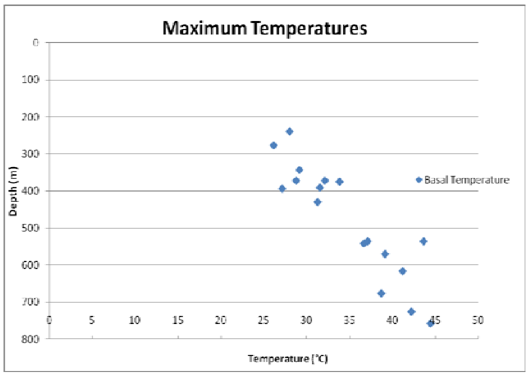

Figure 6. Recorded basal temperatures and depths for the logged wells during June and July 2010.

Table 2. Formation thermal conductivities (W/m-k) resulting from the inversion. The Kings Park shale estimate is the first known value for that formation.

Stratigraphic Unit	Estimated thermal conductivity
Kings Park	1.51
Henley Sandstone	2.35
Kardinya Shale	1.74
Mariginiup	1.94
Wanneroo	2.19
Pinjar	1.94
South Perth Shale	1.50
Gage	1.78
Yarragadee	2.38
Cattamarra Coal Measures	1.82

Table 3. Borehole heat fluxes (W/m^2) resulting from the inversion described above.

Wellbore	Estimated Heat Flux
AM20	50.64
AM31	70.75
AM32Y	67.78
AM33A	88.58
AM38A	41.53
AM40	62.15
AM42	62.33
AM43A	59.73
AM45	74.63
AM46	73.39
AM48	62.73
AM49	69.33
AM50	55.63
AM51	59.05
AM52Y	52.44
AM55	57.96
UWA TP01	57.82

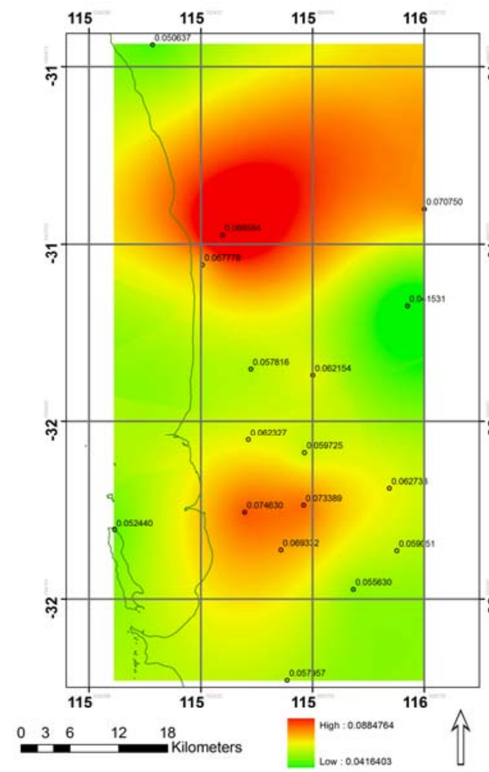

Figure 7. Kriged heat flux estimates across the Perth Basin based on the June and July 2010 logging fieldwork. The bounding box of the mapped region coincides with that of the analyzed well locations. The arrow indicates North. Wells are plotted along with their associated heat flux estimates in Watts/m^2. Some interpolation artifacts are evident, and the data density is not really high enough to support a map of this extent. This argues for a fill-in campaign to augment the heat flux measurements – or possibly an attempt to include older records digitized in Botman (2010). We leave that for future work.

DISCUSSION

Thermal Conductivities

The laboratory measurements of thermal conductivity found in HDRPL (2008) provided a starting point for our solution estimates. Unfortunately, the +/- 10%

and +/- 4% error ranges reported therein appear to be more a reflection of the two different measurement devices utilized than a reflection of the intrinsic statistical variability of the samples (Beardsmore, pers. comm., 2010). Subjective modifications of these ranges were used as proxies for the variance in building the estimates for the W_{ijk} in Equation (2). While this approach is the best we could do with the information at hand, we believe this to be fundamentally unsatisfactory. Future work along the lines of this paper would benefit from the availability of the full details of sample conductivity measurements, especially a quantitative indication of the observed measurement errors. A list of raw measurements would suffice, since the relevant variances etc. are easily estimated from such a list.

Considering the distribution of thermal conductivities implied by Figures 3 or 5, the wide range of measured values of thermal conductivities reported for individual stratigraphic units in HDRPL (2008) are unsurprising. In particular, in view of our notion of "statistical thermostratigraphy", we regard our approach potentially as providing superior regional estimates of stratigraphic thermal conductivities (such as those displayed in Table 2) than any simple statistical manipulation of a relatively small number of samples measured in a laboratory. Admittedly, the laboratory measurements occur in significantly more controlled conditions than our borehole measurements. However, the sheer number of pointwise thermal conductivity samples available via our technique provides a nontrivial enhancement of counting statistics.

Our spatial filtering technique might be improved by replacing the Gaussian filter assumed with something along the lines of filtering with a vertical geostatistical variogram derived from the data values themselves. However, such a method would present all of the usual difficulties associated with variography, with potentially only limited benefits. (Recall that the instrumental noise also plays a role in determining the data fluctuations – not just the spatial variations.) For better or worse, we chose to use the Gaussian approach, chiefly for its simplicity.

Contrasting Tables 1 and 2 reveals that the inversion estimates for conductivities are "pegged" on the lower bounds for the Mariginiup, Wanneroo, Pinjar, and South Perth formations. A better-behaved inversion would not "peg" values in this fashion. We believe that the reason for the "pegging" behavior by the optimizer is probably found in Equation (3), since minimizing the λ_k tends to drive the residual of Equation (4) to a lower value – hence r_2's contribution to the total residual R is also lowered. While this produces artifacts in our inversion procedure, time pressures compel us to leave improvements in our method to future work. Because of this issue, we believe that (at least some of) our reported thermal conductivity estimates are biased to low values. By Equation (1) this implies that our heat flow estimates are also low.

Heat Fluxes

The heat flux offsets between wells are reasonably strongly constrained by the approach of Equation (4) – at least where appropriate well-pair picks exist. However, the overall DC level of heat flux is an inversion result, and is only constrained via the interplay of multiple effects going into the construction of the total residual. By the argument in the previous paragraph, we suspect that our estimated heat fluxes are systematically biased to lower values, and a more accurate technique would reveal higher values of fluxes.

Once again, improvements to our estimates must wait for future work.

Spatial patterns

The gross patterns exhibited in Figure 7 may well be accurate, but given all of the concerns raised above – not to mention all of the assumptions going into this work – it is probably prudent not to place too much faith in this result. As with any spatial interpolation problem, denser and more accurate values would lead to a better spatial picture of the field being sampled.

CONCLUSION

We have presented an abbreviated and augmented version of the work reported in Botman (2010). While this work clearly has some problems (inherent in any exploratory data analysis of this type), we believe that the overall approach is reasonable in an HSA environment.

In particular, we believe that the notion of "statistical thermostratigraphy" described above deserves to be explored further with more detailed work, and perhaps be applied to detailed thermal logging in other geothermal systems.

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