New approach to basin formation temperature modelling

Pete Dotsey[1*] introduces a methodology developed by Ian Deighton[1] for basin temperature modelling that utilizes a large volume of properly indexed and QC'd bottom-hole temperature data for a basin or area. Results from the Delaware Basin illustrate the method.

Basin formation temperatures are an important consideration in oil and gas exploration and development because temperature controls the rates of chemical reactions in rocks such as kerogen transformation in source rocks, cementation in reservoir and permeability (seal) development. Temperature is also an important requirement for many borehole management procedures and therefore it is now commonly measured while drilling.

While basin temperature models are commonly built with sparse data sets from a variety of sources such as bottom hole temperature (BHT) data from logging runs, downhole drill stem test (DST) data and vitrinite reflectance (Ro) data, this article will focus on basin temperature models constructed from BHT data.

BHT data is recorded in the log header of most downhole logs. The temperature is commonly recorded with a thermostat attached to or incorporated into the logging tool. Of the millions of wells that have been drilled and logged around the world, most were drilled and the results were recorded in analogue form, either on paper and or microfilm. Over time many of these logs have been converted back to a digital format by first scanning to an image format and then digitizing to a vector format.

The capture of header data is most commonly done by indexing technicians; however, studies showing the evaluation of large amounts of indexed BHT data have not been undertaken on a basin or large area scale. One notable published attempt was recently undertaken at Southern Methodist University (SMU) where BHT data for approximately 1000 wells was used to assess geothermal generation of electricity from high-temperature waters produced with hydrocarbons from oil and gas industry wells (Blackwell et al., 2010). The analysis of this work was the basis for the new MaxG methodology that was applied to generate a basin temperature model for the Delaware Basin.

Delaware Basin study area

The Delaware Basin (Figure 1) is the western most basinal area of the Permian Basin located in West Texas, in the US.

Figure 1 *Delaware Basin study area with respect to the Permian Basin.*

In selecting an area for basin temperature modelling, a large area the size of the entire Permian Basin (Figure 2) was considered too complex due to lateral heatflow complications, predominantly associated with the structural complexity of the central Basin Platform. Therefore, the Delaware Basin was selected because it offers an area of relatively minimal lateral heatflow variations and can be described structurally as a fairly evenly layered asymmetrical synclinal basin.

The TGS library of available wells and the amount of wells used in the study are shown in Figure 3 and include:

- 22,865 wells in Delaware Basin – 14,702 are digitized (blue dots inside Delaware Basin outline)
- 5249 BHT indexed wells – 4055 w/ valid elevation data (red dots inside Delaware Basin outline)
- 2013 wells used to generate a lithostratigraphic framework (green dots inside Delaware Basin outline)

The wells indexed for BHT data and used for defining the lithostratigraphic intervals were selected based on vertical and areal distribution as well as curve content. The vertical distribution consideration was important since in order to assess the MaxG cloud of BHT data, a significant number

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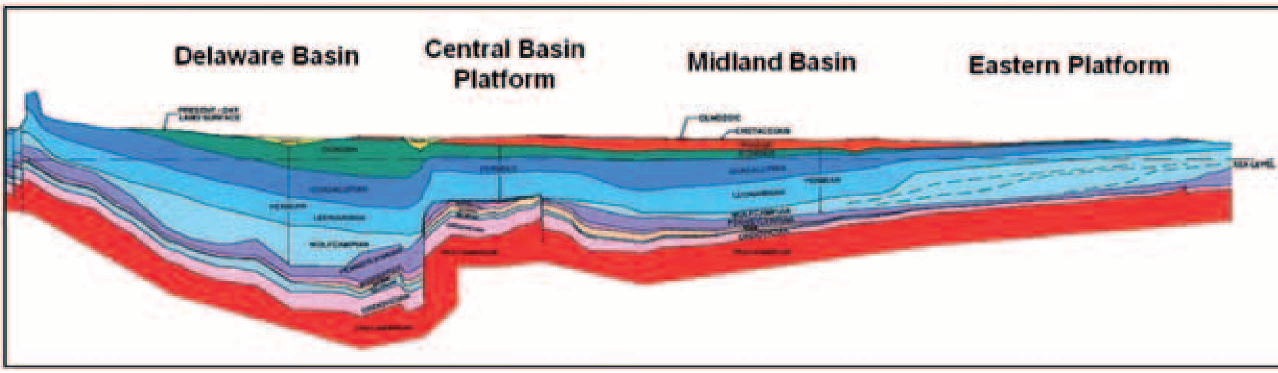

Figure 2 *A regional cross section through the Permian Basin from UTPB website generated by R.F Lindsay.*

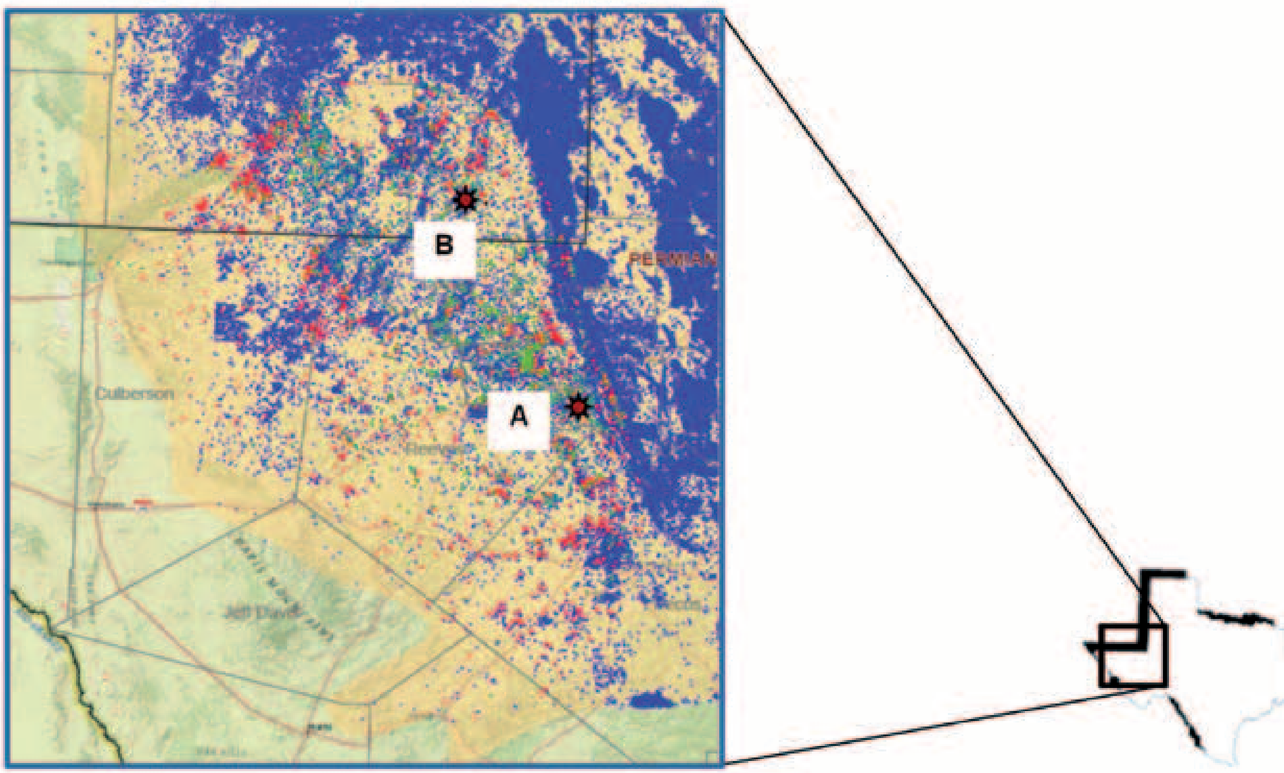

Figure 3 *Library of available well data used in the Delaware Basin temperature model.*

of wells that reached total depth or were cased in each lithostratigraphic interval were needed. Note that wells A and B above were modelled using TGS basin modelling software Fobos pro, discussed later in this paper.

BHT data evaluation

BHT temperature data is evaluated to determine or approximate formation temperature. A bottom hole temperature log reading for a formation in an area can vary greatly. The variation can result from several factors such as how long the well was open (time since circulation) and when the well was drilled because drilling fluids circulated to the surface during drilling in winter months may result in the drill mud cooling-off and affect the loggers bottom hole temperature reading.

A few 'self-evident truths' regarding BHT data evaluation are as follows:

- The longer a well has to equilibrate (i.e., the greater the TSC value) the closer the BHT will be to formation temperature.
- In most basins, TSC values are rarely long enough for BHTs to get close to equilibration.
- The higher BHTs measured for a formation in an area are considered closer to formation temperature
- Different lithologies transmit heat at different rates (sandstone > limestone > shale), therefore, the lithology

at total depth will affect the amount of time it takes for the BHT to approach formation temperature.

Geothermal gradient

Most sedimentary basins are layered with lithostratigraphic units (units with common lithologies) and each of these units has an interval geothermal gradient that can be significantly different from the overlying and underlying unit. And to further complicate the matter, the interval geothermal gradient for a specific lithologic unit varies with depth. Therefore the interval temperature gradient within each lithostratigraphic unit needs to be determined based on depth and lithology. These additional considerations need to be taken into account when building a basin temperature model. Figure 4 shows a graph of a well with downhole measured temperatures that demonstrates that interval lithologic units have varying geothermal gradients.

Analysis of Figure 4 leads to several observations:

- Average geothermal gradient is a simple equation, but a poor approximation at most depths.
- Average geothermal gradient is not representative of the temperatures up and down the borehole.
- Average geothermal gradient to TD generally underestimates the actual temperature above TD by 5–20°C and is as much as 30°C in one interval as shown by the double ended green arrow.
- Interval geothermal gradient is depth and lithology dependent.

The third bullet above is extremely significant considering that the optimum hydrocarbon window is 60-120°C.

Regarding depth-varying lithologic interval geothermal gradients in the Delaware Basin MaxG basin temperature model, the results are discussed later in this paper.

Review of SMU BHT data

Figure 5 (taken from the SMU study) describes the most common pitfalls associated with using BHT data evaluation. More importantly, the evaluation of Figures 5 and 6 led to the development of the MaxG basin temperature model methodology.

First let's look at the pitfalls. As noted in the caption, the blue dots represent the recorded BHT that occurs within 0.5^0 of a study well. The range of BHT values varies greatly. A rudimentary error would be to draw a straight line gradient to one of the BHT values and use this as a representative geothermal gradient for the study area. The second pitfall would be to apply a regression analysis to correct each BHT to obtain an 'accurate' bottom-hole temperature often using a depth based function. Because many values are extremely low – small time since circulation (TSC) value, logged in winter, etc. – the correction does not come close to estimating formation temperature. In addition, a small

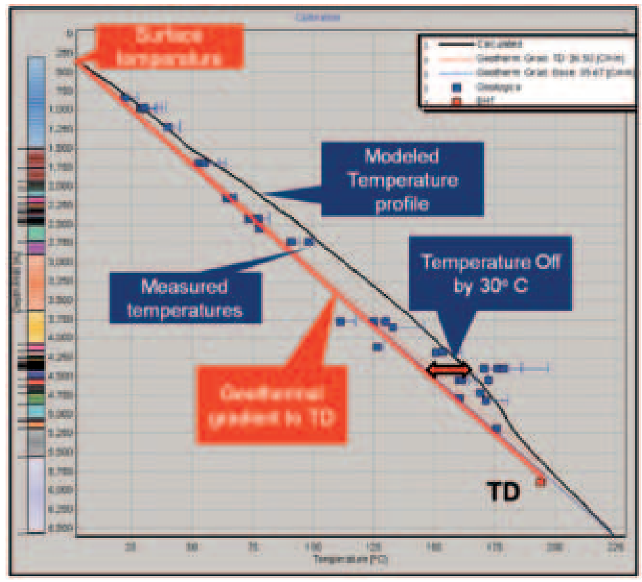

***Figure 4** A study well from the Halten Terrace offshore Norway showing lithology on left, down-hole interval temperature measurements in blue squares and the disparity between down-hole temperatures and a straight-line gradient.*

group of BHTs may be very close to having equilibrated to actual formation temperature, in which case the correction temperature would result in a corrected BHT that is greater than formation temperature.

The review of Figure 5 leads to the finding that a line, the MaxG line, can be drawn tangent to the maximum envelope of the recorded BHTs. The MaxG lines shown in green in Figure 5 are believed to have a direct relationship to formation temperature.

In the SMU study cited above, another well was evaluated and is shown in Figure 6.

Review of the data in Figure 6 led to a second finding that the line tangent to the maximum cloud of recorded BHTs was nearly parallel to the slope of the equilibrium well log in this case.

Horner experiment

An experiment was designed to test the two finding – the first being that a line tangent to the maximum cloud of the recorded BHT values could be used to approximate formation temperature and the second being that the MaxG tangent line paralleled the interval geothermal gradient.

The well-known Horner method is often used to estimate formation temperature when valid temperature data is available from successive logging runs for a well (common practice before the advent of combined downhole logging tools). The critical components that need to be recorded are the time since circulation (TSC) and BHT, values which should increases for each successive logging run.

In the experiment, an interval geothermal gradient for a formation and lithologic thermal conductivity was assumed,

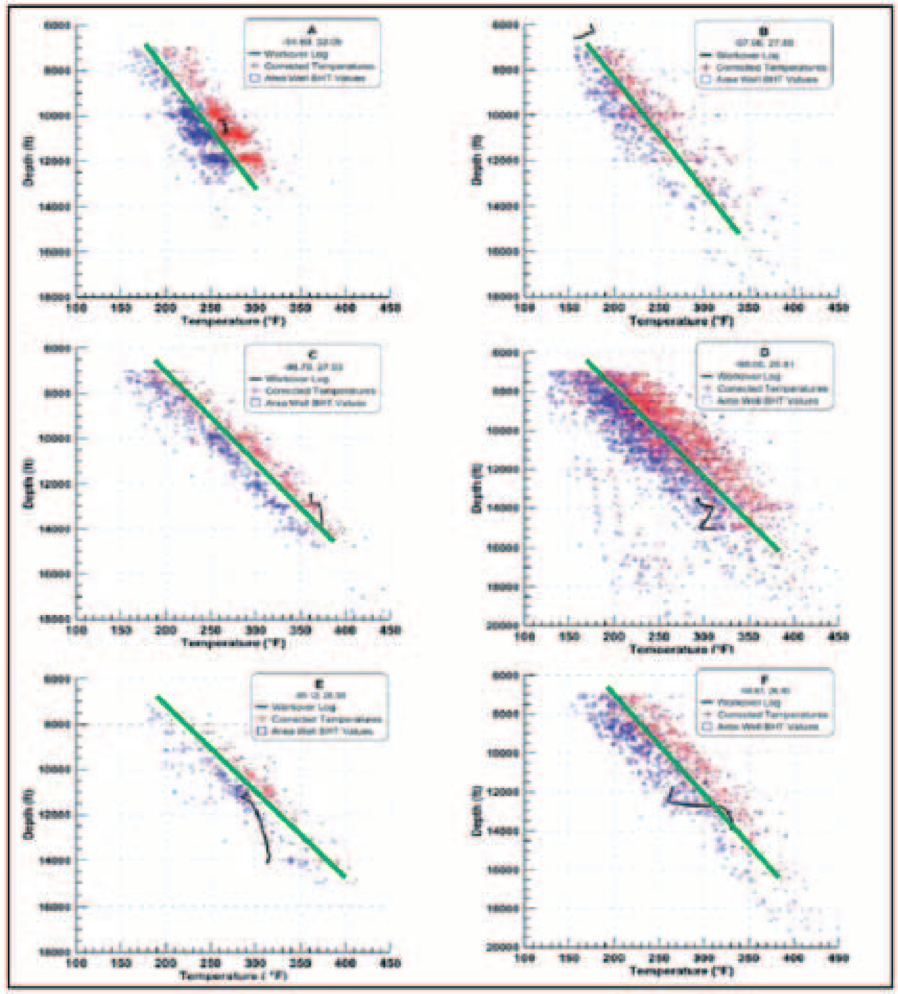

Figure 5 *Distribution of recorded and corrected BHT values within 0.50 of six wells from Blackwell et al. [2010]. Note that blue dots are recorded BHT values and red dots are corrected BHT values using regression analysis techniques. The green line drawn tangent to the maximum cloud of the BHT envelope is added in here.*

and one thousand random TSC values between one and 10 hours were used. With each TSC input value a BHT was 'back-calculated' from the following equation BHT = VRT + (H/4πK) * ln(1 + Tc/dT) where:

- VRT is virgin rock temperature (in this case modelled gradient values for a single layer)
- H is heat supply (not the same as heatflow)
- K is thermal conductivity of the strata
- Tc = circulation time, minimum is 4 hours – depths are 3-4km. According to Hermanrud et al (1990): Tc = (1.3 + D)/(1.3-0.91*D) where D is depth in km (Beardsmore and Cull, 2001, p 63)
- dT is time since circulation stopped (usually 1 to 10 hrs or more depending on number of logging runs)

Figure 7 shows the graphic display of the back-calculated BHTs where a shale lithology and conductivity were used. Analysis of the test results confirmed our findings.

The Horner experiment was repeated using thermal conductivity values for a limestone and a sandstone well. The MaxG line and maximum back-calculated BHT values are shown in Figure 8.

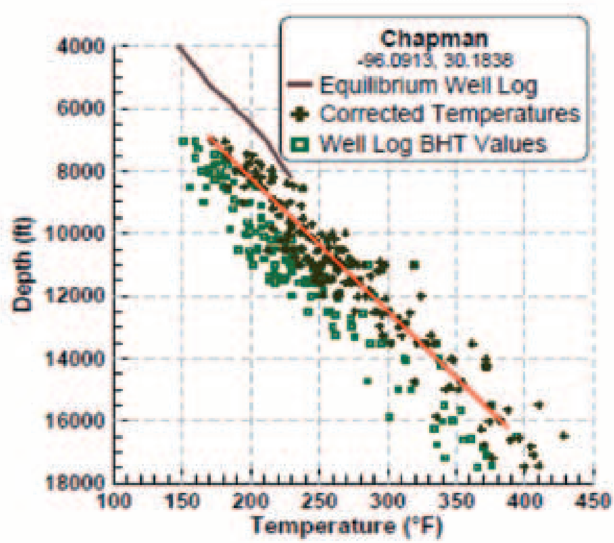

Figure 6 *Distribution of recorded and corrected BHT values within 0.50 of an equilibrium well from Blackwell et al. (2010). Green squares are recorded BHT values and black crosses are corrected BHT values using regression analysis techniques. The black line is an equilibrium well log recorded three months after drilling. The red line drawn tangent to the maximum cloud of the BHT envelope is added in here.*

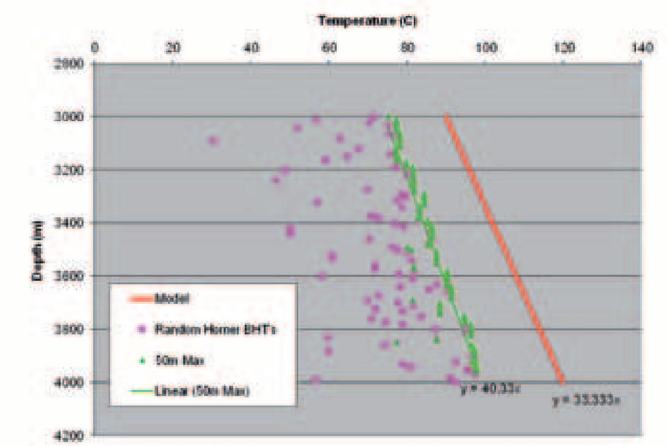

Figure 7 The back-calculated BHT values as magenta squares based on the Horner experiment. Note that the green MaxG line is drawn through the maximum back-calculated BHT values, which are shown as green squares.

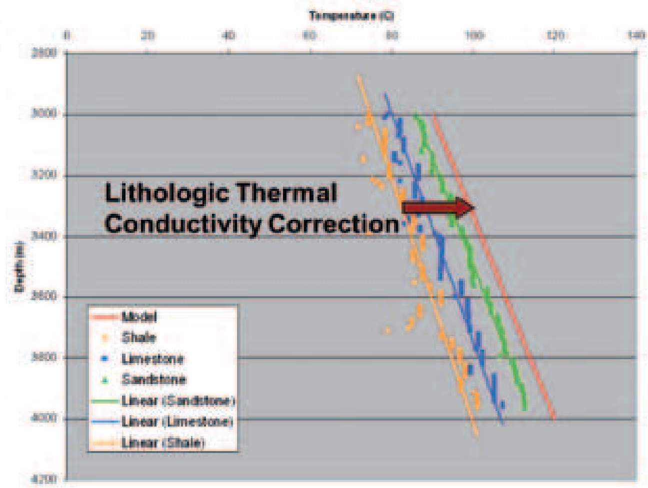

Figure 8 The back-calculated maximum BHT values based on the Horner experiment for a shale, limestone, and sandstone lithology.

It should be noted that over 3000 wells used for building the Delaware Basin temperature model had successive logging runs and that for approximately 80% of those wells, the same temperature was recorded for each successive run. This is most likely explained by only using a thermometer on the first run.

Delaware Basin MaxG Basin temperature model results

Figure 9 shows the added complexity of how interval geothermal gradients vary with depth. Figure 9 also shows the range of depth of the 13 regional lithostratigraphic intervals that were mapped for the Delaware Basin.

Since the interval geothermal gradients vary with depth for the lithostratigraphic units, a depth varying function was applied to the MaxG line drawn tangent to the cloud for each of the 13 lithostratigraphic units.

Building the model

The procedure is to construct the layered model from the surface down and/or to normalize each layer by subtracting out the overlying layers to eliminate variations that occur due to differences in thickening and thinning of overlying intervals as shown in Figure 10. Here is the stepwise approach:

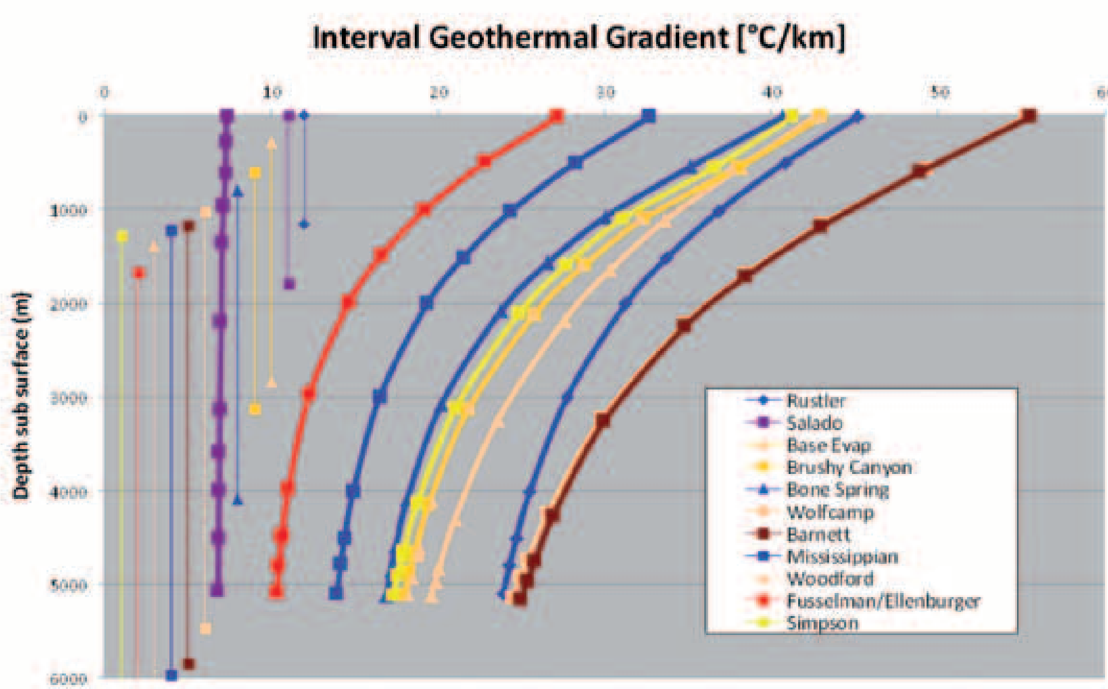

Figure 9 Variation of geothermal gradient with depth for the Delaware Basin lithostratigraphic units mapped in this study. Note that mixed lithologies were used for some of the units.

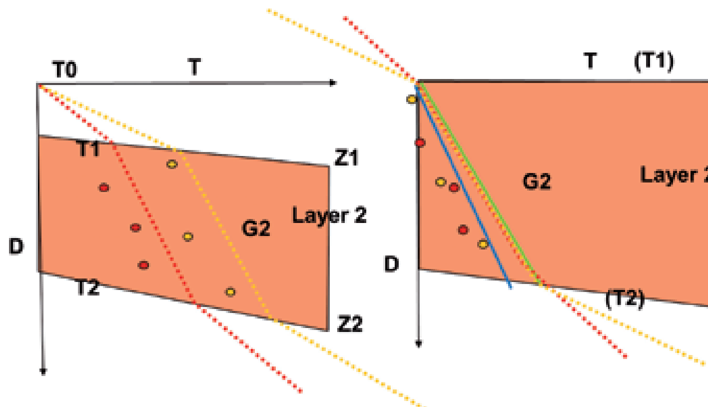

Figure 10 *MaxG procedure for building a depth varying interval geothermal gradient basin temperature model.*

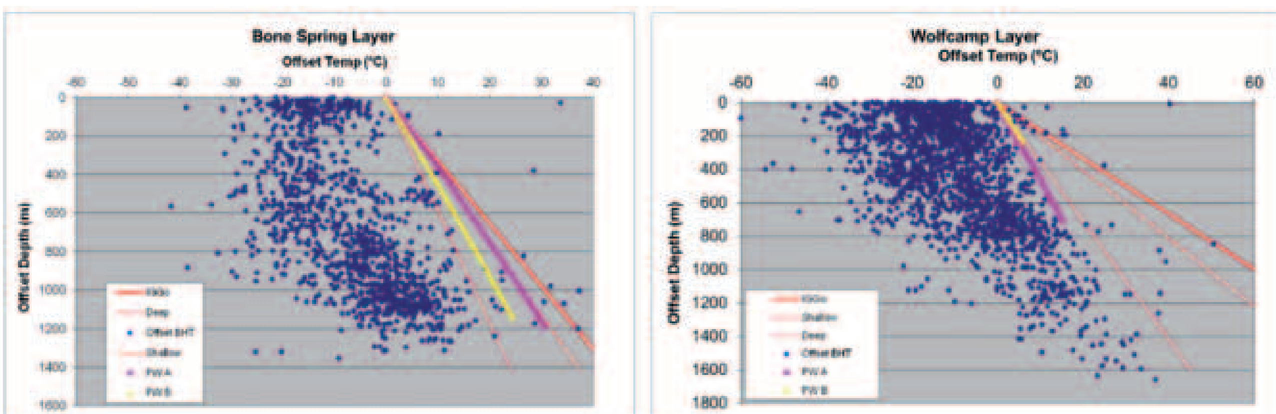

Figure 11 *BHT values for interval lithologic layers in Delaware Basin temperature model. Note that the red MaxG line and the predicted offset temperature vs. depth data for the New Mexico (magenta) and Texas (yellow) FobosPro wells are also shown.*

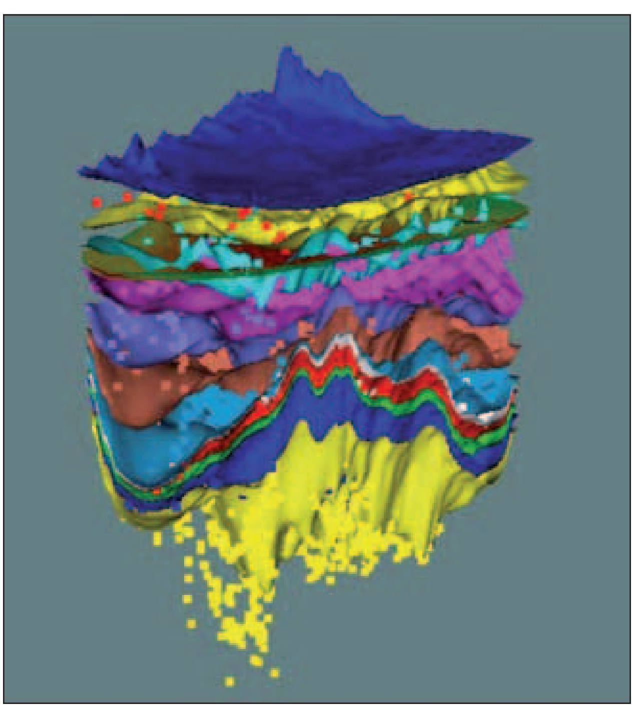

Figure 12 *3D rendering of BHT values including respect for the lithostratigraphic layered model.*

- Depth values for each layer are normalized (i.e., subtract Z1 from all depths) of BHT point data: shifts layer to surface.
- Temperature values for each layer are normalized (i.e., subtract T1 from all temperatures) from BHT point data: intercept of G2 (the IGG for this layer) is now 0.0.
- Blue MaxG line on Figure 10 is now estimated (average of maximums) and adjusted for thermal conductivity of formation to get green line shown on Figure 10.
- T2, which is the grid temperature at the base of the layer is calculated from G2 (calculated previous step, and if necessary adjusted for variation with burial depth)*Z2-Z1 (isopach) plus T1 (grid).
- This process is applied iteratively for each layer moving downwards.

Figure 11 shows MaxG graphs for two of the 13 lithostratigraphic intervals within the Delaware Basin temperature model. Also shown are temperature gradients predicted by TGS Fobos Pro basin modelling software for the two wells shown on Figure 2. Note that the Fobos Pro and MaxG interval geothermal gradient lines are in excellent agreement. Also note that the process for drawing the MaxG

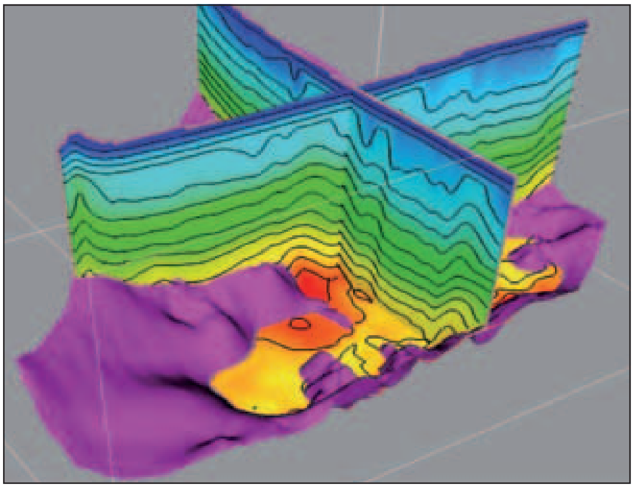

Figure 13 *Final MaxG Delaware Basin temperature model. Note that the surface unit is the Rustler and basal unit is the Ellenburger.*

line and building the model is iterative and that each time the line is re-drawn for an interval, all underlying layers need to be re-done. This shows that even though the MaxG line is not aesthetically located for the Bone Spring, the directly underlying Wolfcamp and subsequent underlying layers align better with this MaxG line.

Figure 12 shows a 3D rendering of the layers and the BHTs used to construct the model.

The final temperature volume (cube) is interpolated from the calculated depth and temperature data for each horizon in the model. Figure 13 shows two lines of section through the final temperature volume for the Delaware Basin temperature model.

Summary

A new methodology for building accurate basin temperature models has been developed based on drawing a line tangent to the maximum BHT envelope of the depth-varying interval geothermal gradients for each lithostratigraphic unit. BHT values from 12,840 logs for 4055 wells were indexed to construct the MaxG temperature volume. The results are in close agreement with those predicted from FobosPro basin modelling software.

As with any basin-wide temperature model the potential uses include:

- Cross-correlate prospective zones with temperature cube to identify optimum temperature of prospective areas.
- Cross-correlate temperature log data with temperature cube to identify areas of anomalous fluid flow and heat flow. Anomalies may be compared with:
- Gravity and magnetic data to evaluate basement architecture effects.
- Production data such as gas-to-oil ratio to identify prospective trends.
- Compare calculated pseudo-maturity (assuming present temperature is maximum) with measured temperature to identify heat flow associated with uplifted or volcanic areas.

The basin temperature volumes can be readily imported into 3D viewing and modelling software packages.

Acknowledgements

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References

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