Geothermal Mapping in Alberta - a Statistically Robust Approach

Greg Nieuwenhuis[1], Jacek Majorowicz[1], Tibor Lengyel[2], and Martyn J Unsworth[1]

[1]Department of Physics, University of Alberta, Edmonton, Canada
[2]WorleyParsons Infrastructure and Environment, Edmonton, Canada

HELMHOLTZ-ALBERTA INITIATIVE

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UNIVERSITY OF ALBERTA

Introduction

In order to obtain a robust estimate of temperature at depth in the Alberta Basin, temperature data were compiled from oil and gas measurements. Three steps were used to remove both systematic and random bias in the data:

Step1 – the dataset was manually culled based on available metadata and known issues.

Step 2 – A statistical approach was used to ensure the remaining data were regionally consistent

Step 3 – Modelling of the data to obtain robust temperature – depth estimates

The result is a regionally consistent model of temperature in the Alberta basin, which can be used to interpret heat transfer mechanisms and geothermal potential.

Step 1: Manual Data Culling

We have compiled four types of temperature estimates from oil and gas well data which are commonly available from the oil and gas industry:

BHT – Bottom Hole Temperatures. Measured shortly after drilling is complete, these are widely available, but highly affected by drilling activities

DST – drill stem test data. These include temperature measurements, ideally sampling the reservoir fluids and reporting the equilibrium reservoir temperature

WPS – well pressure survey data (including annual pool pressure survey data). These data are regularly measured long after drilling has finished, and often reflect the equilibrium subsurface temperature.

Horner Corrected BHT data – When multiple BHT measurements are made at the same depth and both the shut in time and mud circulation time are known, corrections can be applied to estimate the equilibrium temperature (e.g. Lachenbruch and Brewer, 1959).

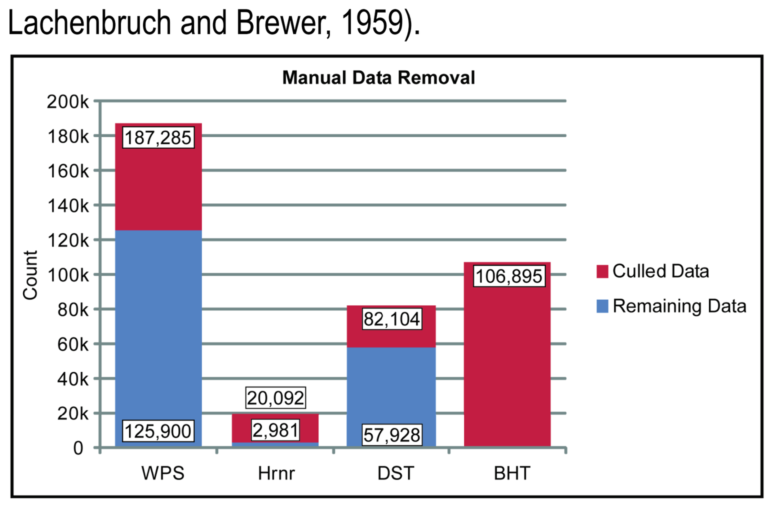

Figure 1 – Bar graph showing how much data was manually culled relative to the amount of data available.

The first step in obtaining a robust dataset was to manually remove datapoints which are incorrect due to digitization error, erroneous points which were estimated instead of measured, etc. A full explanation of the potential errors can be found in Lengyel (2013), and Gray et al. (2012). **Figure 1** shows how much data was originally available, and how much was removed in the manual data culling process.

Temperature well data before statistical culling

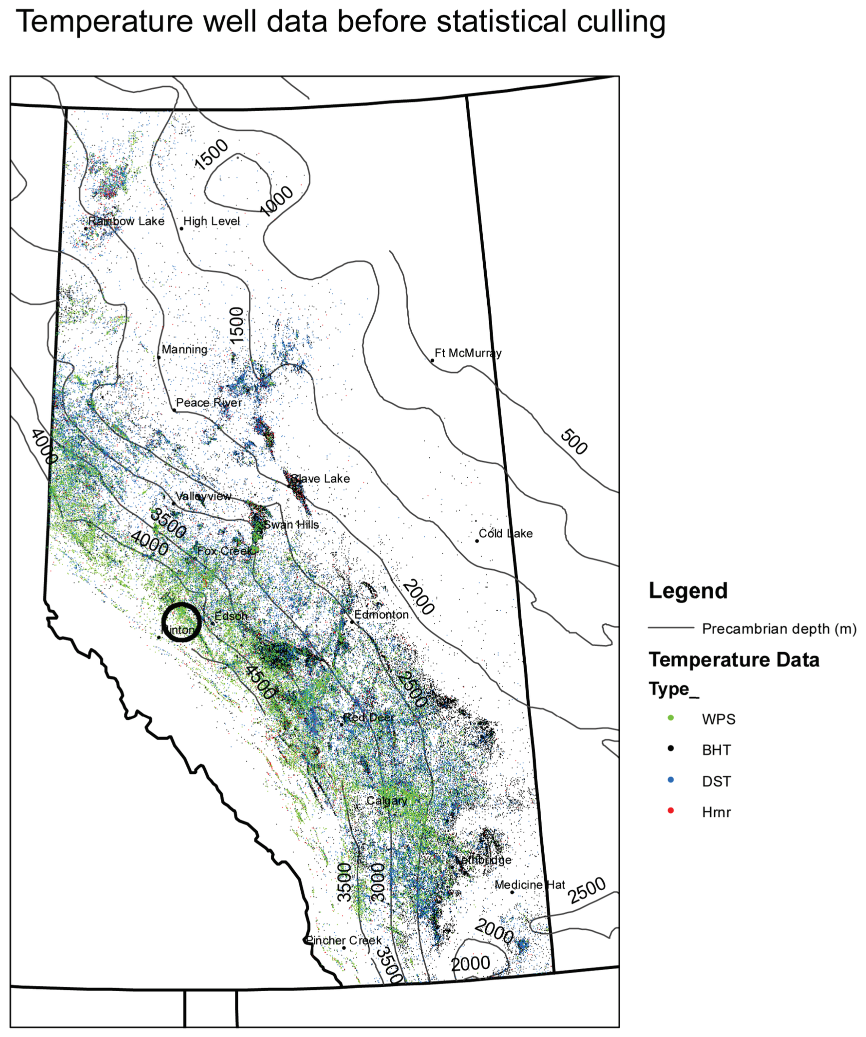

Figure 2 – Map showing the uneven distribution of temperature data available (e.g. Swan Hills area in central AB). Red dots are Horner corrected BHT data, green are WPS measurements, blue are DST measurements, and black are BHT measurements. Note that this map shows all depths, and many of the BHT and DST data are hidden beneath the WPS and Horner corrected BHT data. The data inside of the black circle is plotted in **Figure 3**.

Step 2: Statistical Data Culling

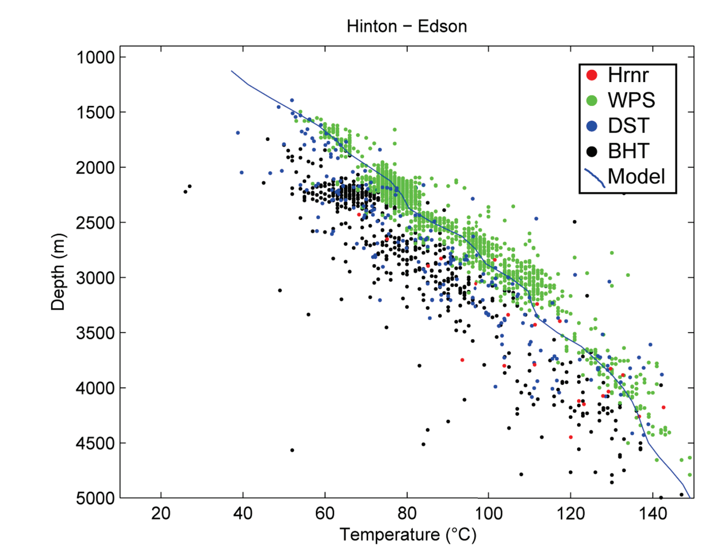

Figure 3 – Plot showing the temperature – depth distribution of the data inside of the black circle marked on **Figure 2**. The blue line represents the temperature model derived from 3D kriging of the statistically culled dataset (note that the BHT data was completely removed prior to kriging).

Figure 3 shows an example of the data within the 50 km diameter circle illustrated in **Figure 2**. The majority of the data is from WPS and BHT measurements. This figure makes it clear that the different types of temperature data are systematically different, and each measurement type contains significant scatter as well.

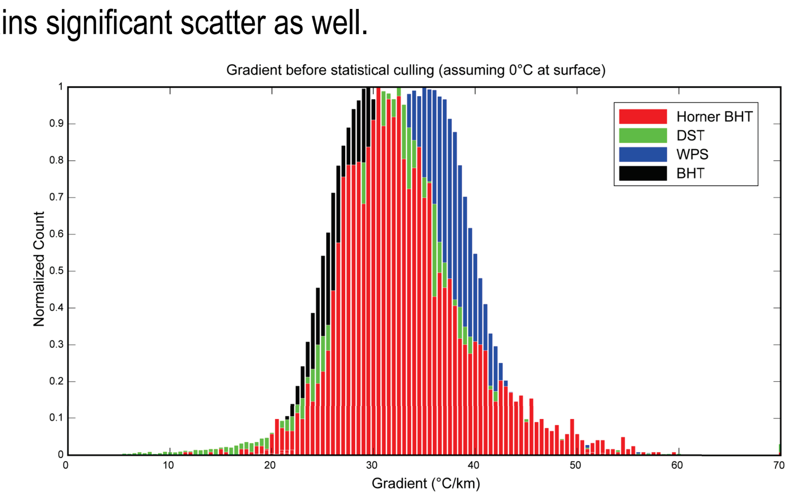

Figure 4– Normalized histogram of the temperature gradients from the four measurement methods. Note that the DST and Horner correct BHT data generally align, while WPS data has a systematically higher gradient, and BHT data has a systematically lower gradient.

Figure 4 highlights the systematic difference between data types. The temperature gradients from WPS measurements are higher on average, while BHT measurements have systematically lower gradients. In general, the Horner corrected BHT data and the DST measurements have similar temperature gradients.

Since the BHT measurements were removed, the vast majority of the remaining data are from WPS measurements (**Figure 1**), therefore by taking the arithmetic mean of the data we are biasing the average in favor of the WPS measurements (see **Figure 3**).

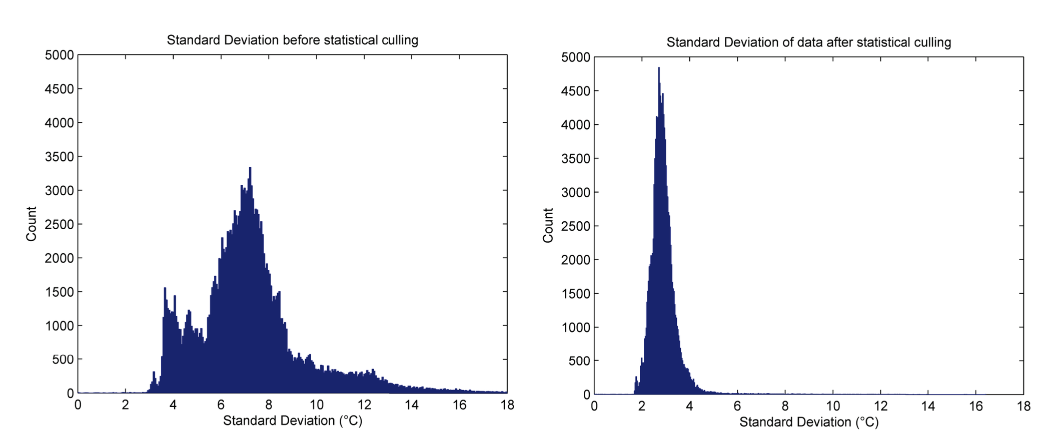

Figure 5– Histograms showing the standard deviation of the data calculated using 3D covariance weighted averaging before (left) and after (right) statistical culling.

The measurements locations are clustered in oil and gas reservoirs, and there are many outliers which do not match the nearby data and bias the average. We use an iterative jacknife method to remove the most obvious outliers first, and then tighten the thresholds more and more each iteration to ensure nearby datapoints are consistent with one another.

The result is a database where the 3D covariance weighted averages of each datapoint have standard deviations mostly below 5°C (see **Figure 5**).

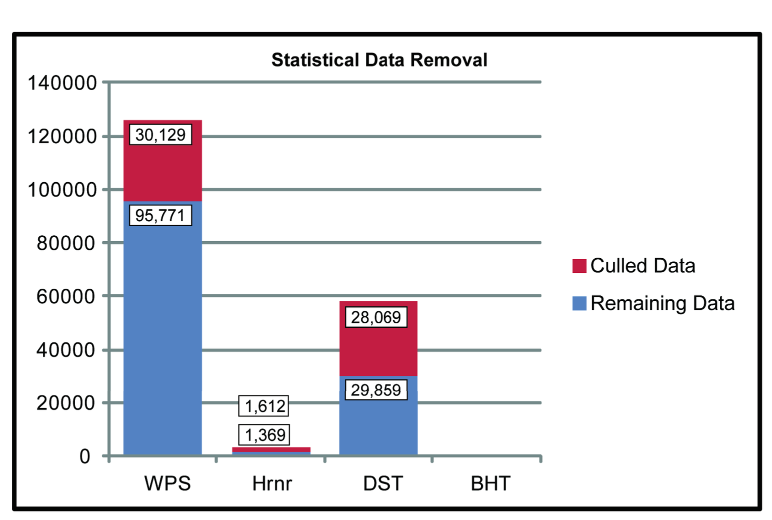

Figure 6– Bar graph showing the amount of data culled by statistical culling.

Step 3: Temperature Modelling

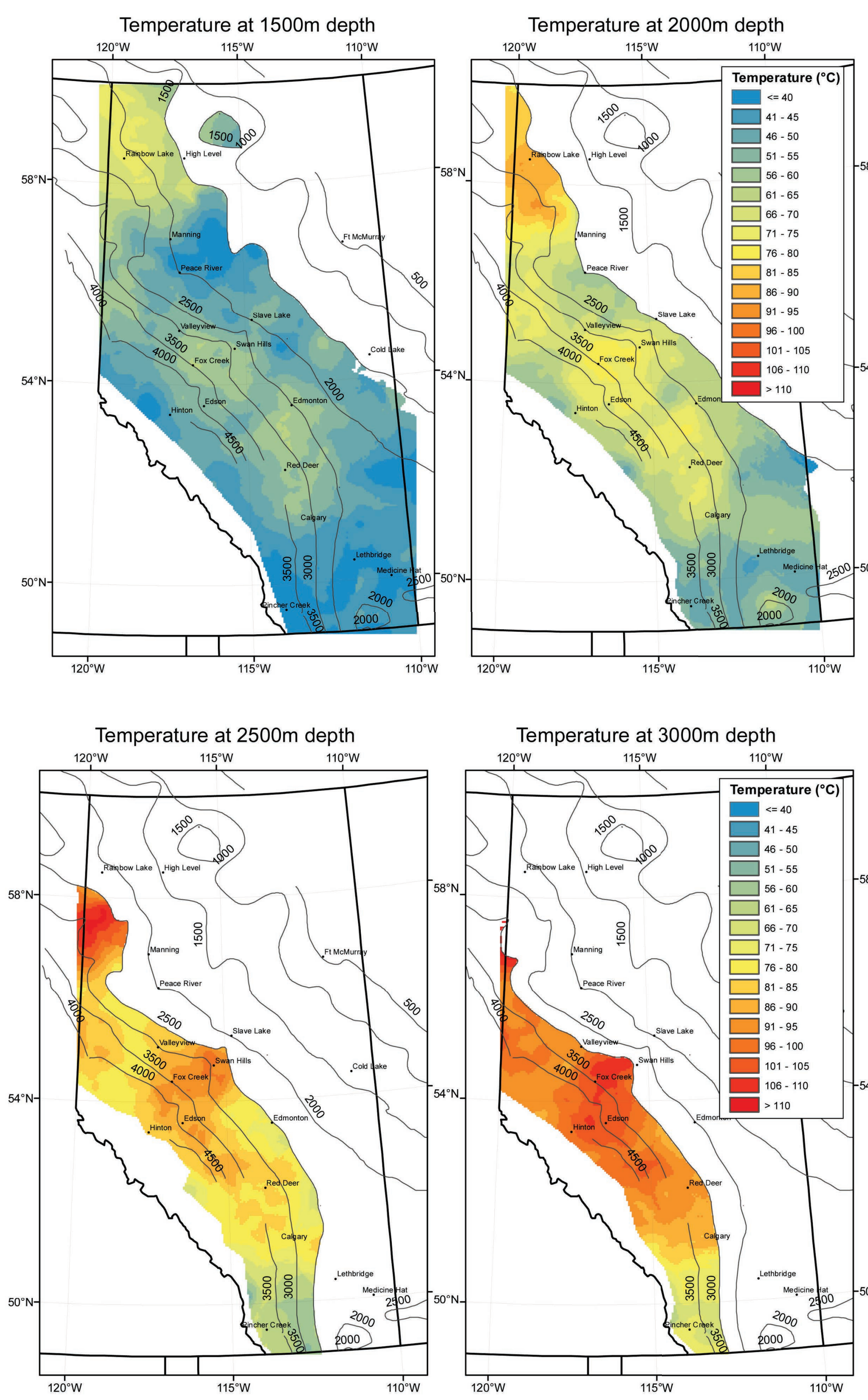

Figure 7– Maps of temperature with depth from the model. The contour lines show the depth of the Precambrian basement from the surface. Temperature highs can be noted south of Rainbow Lake, and in the region of Swan Hills, Hinton, and Edson. Southern Alberta is generally relatively cold, while northern Alberta is relatively warm at any depth slice

After the statistical culling of the dataset, the regional temperature field and associated error is estimated using 3D universal kriging. The result is a temperature model which tends to follow the trend of the WPS measurements (see **Figure 3**), while also taking into account DST and Horner data where available. **Figure 6** shows the how much data is removed in the statistical culling.

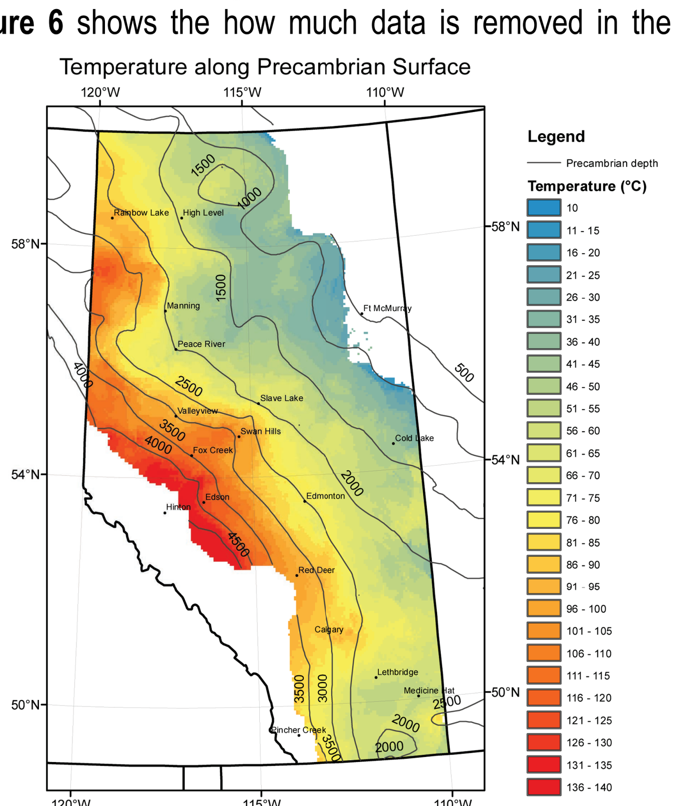

Figure 8– Temperature along the top of the Precambrian basement. This map shows the increasing temperature with depth of this surface, with a few areas, where warmer temperatures are present at shallower depths (south of Rainbow Lake and near Swan Hills). Note that the color scale is different than **Figure 7**.

References

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Heat Flow through the basin

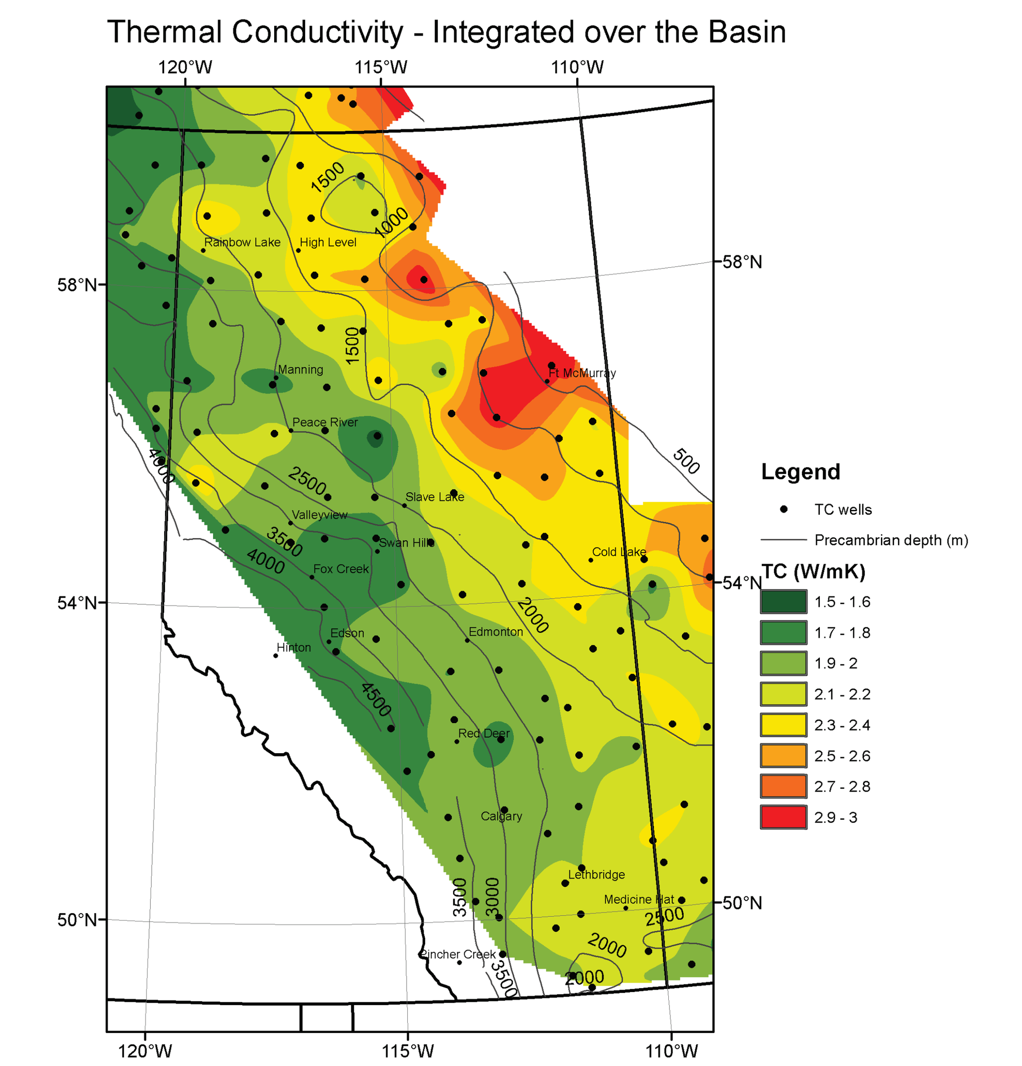

Figure 9 – The thermal conductivity model used to calculate heat flow through the basin in the following **Figure 10**. The thermal conductivity data has been compiled based on lithological logs through the basin, whose locations are marked by the green dots. This map shows the thermal conductivity integrated over the basin depth.

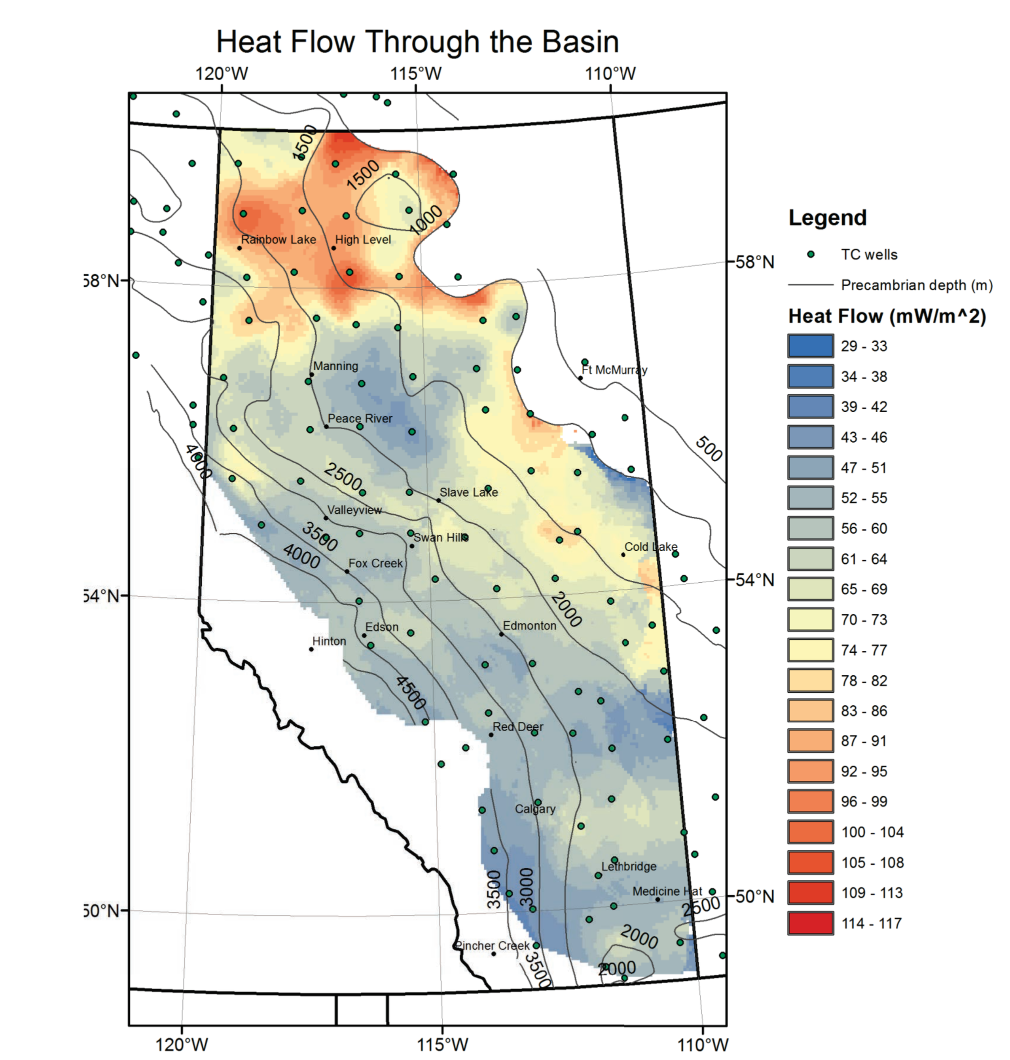

Figure 10 – Heat Flow calculated over the entire basin. The heat flow is generally similar over much of the basin, but shows a significant high in the northwest.

The heat flow through the basin can be calculated using the temperature difference between the top and bottom of the basin, along with estimates of the total thermal conductivity through the entire basin. The temperature difference we used is from the data shown in **Figure 8**, as well as assuming the surface temperature is 0°C. The thermal conductivity model was made by using thermal conductivity measurements of Alberta basin rocks by Beach et al. (1987), and assigning values based on lithology to lithology logs available across the basin. **Figure 9** shows the integrated thermal conductivity through the basin, and **Figure 10** shows the calculated heat flow.

The heat flow anomaly in the northwest corner of the province has been identified in other studies (e.g. Majorowicz et al., 2013), and the advantage of this new temperature dataset is the ability to interpret the anomaly in more detail than before.

The next step in this study is to begin to interpret changes in heat flow with depth, which can be associated with a divergence from purely conductive heat transfer such as fluid flow.

Acknowledgements

We would like to thank the Alberta Geological Survey for access to BHT data which could be used for the Horner correction, as well as for the depth to the Precambrian surface which was provided through the Geological Atlas of the Western Canadian Sedimentary Basin.