Using Oil and Gas Data to Assess Geothermal Resources Within the Western Canadian Sedimentary Basin in Alberta

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Western Canadian Sedimentary Basin, Alberta, Oil and Gas, geoSCOUT, geothermal gradient

ABSTRACT

The Alberta No. 1 Project is a planned geothermal power and direct heat use project in the province of Alberta that has been awarded funding from Natural Resources Canada's Emerging Renewable Power Program. The program stipulates that the geothermal project must produce 5MWe net of power; as such, a regional study was undertaken to identify areas in the Alberta portion of the Western Canadian Sedimentary Basin where (1) the temperature is sufficiently high for power production, (2) there are formations at the depths targeted with known high fluid flows, and (3) there is adequate existing infrastructure that supports low-cost power grid connection as well as direct use applications. Nine such areas were identified and assessed for these three constraining factors. This paper focuses on temperature studies that were undertaken for each area. A fluid temperature of at least 120°C at depths of 4,500m or less is required to profitably operate the plant. Here, we use the extensive oil and gas database in the province and compare several methods of interpreting this data in an effort to determine true gradient and bottom-hole temperature.

1. Introduction

Exploring for geothermal resources in nearly flat-lying, stratigraphically continuous sedimentary rocks in tectonically stable basins has more in common with oil and gas exploration than with normal geothermal exploration. There are differences and similarities between both that inform exploration strategies. Like oil reservoirs, geothermal reservoirs require threshold levels of porosity and permeability. Unlike oil reservoirs, which may require traps such as pinch outs and geological histories that lead to kerogen generation, geothermal waters are essentially everywhere below a target isotherm. One common characteristic shared between low enthalpy sedimentary geothermal, high enthalpy fracture-based geothermal, and oil and gas deposits is that they rarely have any surface manifestations. Given this limitation, the strategy is to use all available data to find temperature and permeability that would indicate an economic resource.

There are two primary sources of heat: heat flow from the mantle and radioactive heat generation in the crust. This implies that there are not likely large lateral variations in subsurface temperatures. In Canada the heat flow generally increases from east to west as the overlying sedimentary sequence thickens (Figure 1). Not evident in this figure, but based on other work (Hickson et al., 2020) heat flow and geothermal gradient in the Alberta portion of the Western Canadian Sedimentary Basin (WCSB) also increase from east to west. Other secondary heat sources include regional groundwater flow and up-flow on faults. These features can be delineated by analysis of subsurface temperature data which, in the case of the Alberta No. 1 Project, is the abundant bottom-hole temperature (BHT) data from oil and gas exploration.

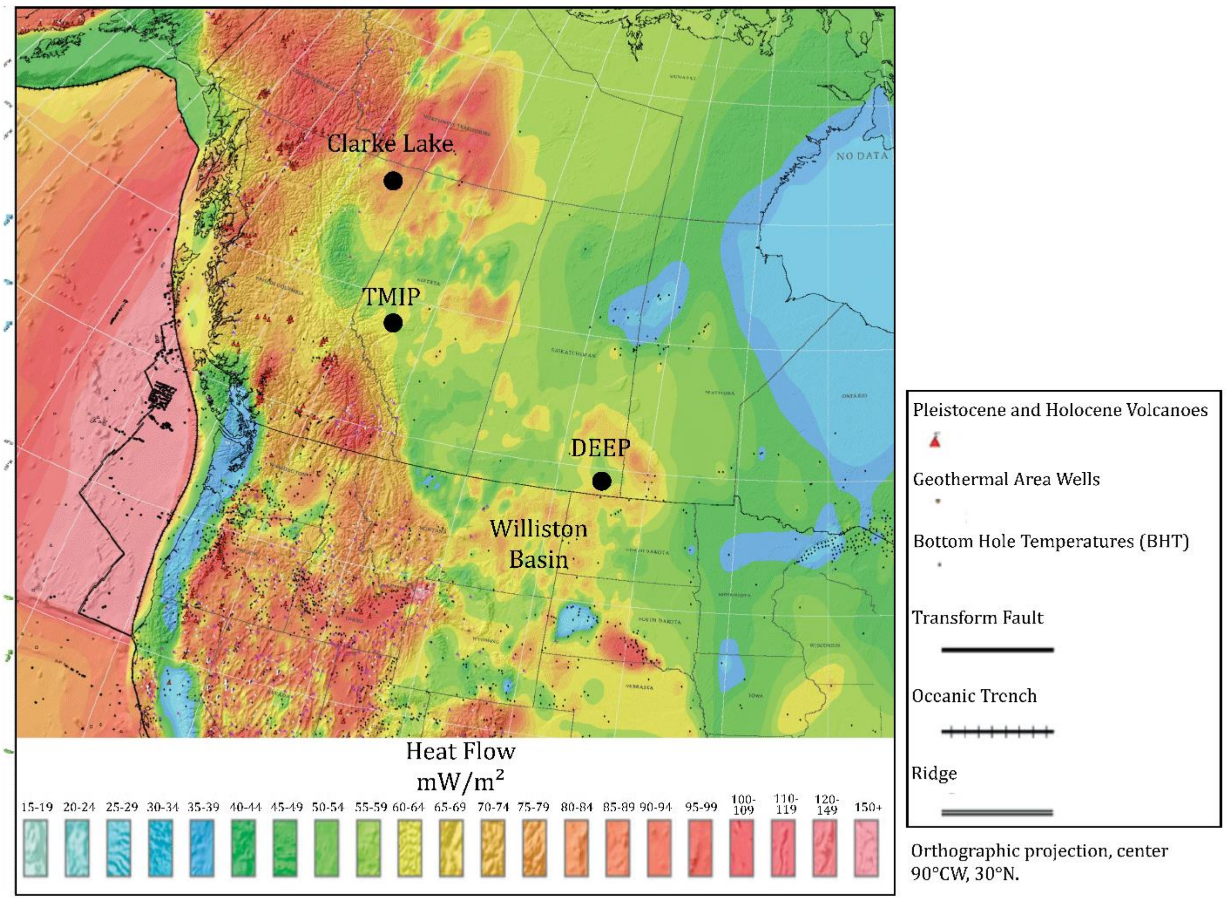

Figure 1: Geothermal map of North America, showing heat flow and the geothermal projects discussed in the report (adapted from GENI 2016).

In this study, BHTs, well depth, and calculated temperature gradients were considered for each study area. The temperature data were collected using the geoSCOUT database; the data were then analyzed and correction methods were compared. From the results, viability for electricity production was assessed.

2. Background

The Western Canadian Sedimentary Basin (WCSB) covers an area over 1.4 million km^2 in the west-central part of Canada and makes up most of Alberta's subsurface (Figure 2). Since the Leduc No. 1 well was drilled in 1946, hundreds of thousands of oil and gas wells have been drilled throughout the WCSB.

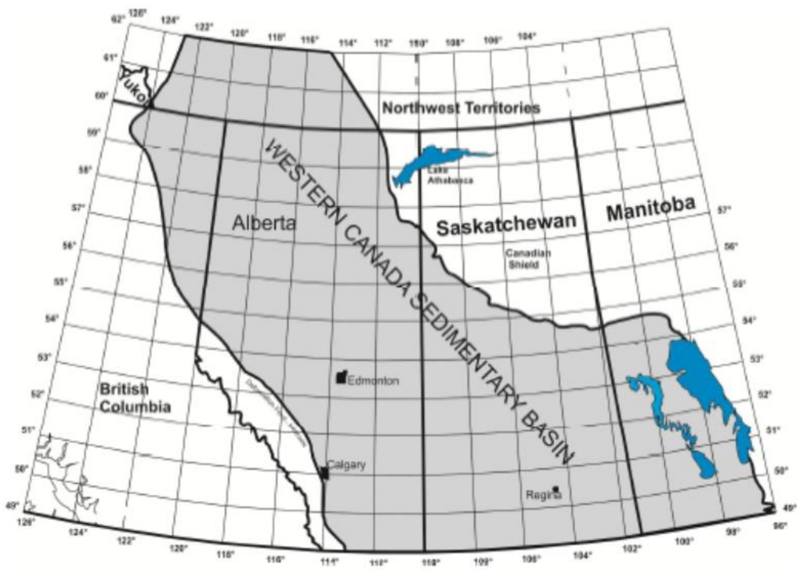

Figure 2: Geological map showing extent of the Western Canada Sedimentary Basin (based on Mossop and Shetson, 1994).

Based on initial assessment on temperature, fluid flow, and infrastructure, the following nine areas were chosen for Alberta No. 1 for additional studies (Figure 3; Hickson et al., 2020a; Hickson et al., 2020b):

1. Rainbow Lake
2. TMIP (Grand Prairie-Greenview)
3. High Prairie
4. Swan Hills
5. Grande Cache
6. Edson
7. Whitecourt
8. Drayton Valley
9. Caroline

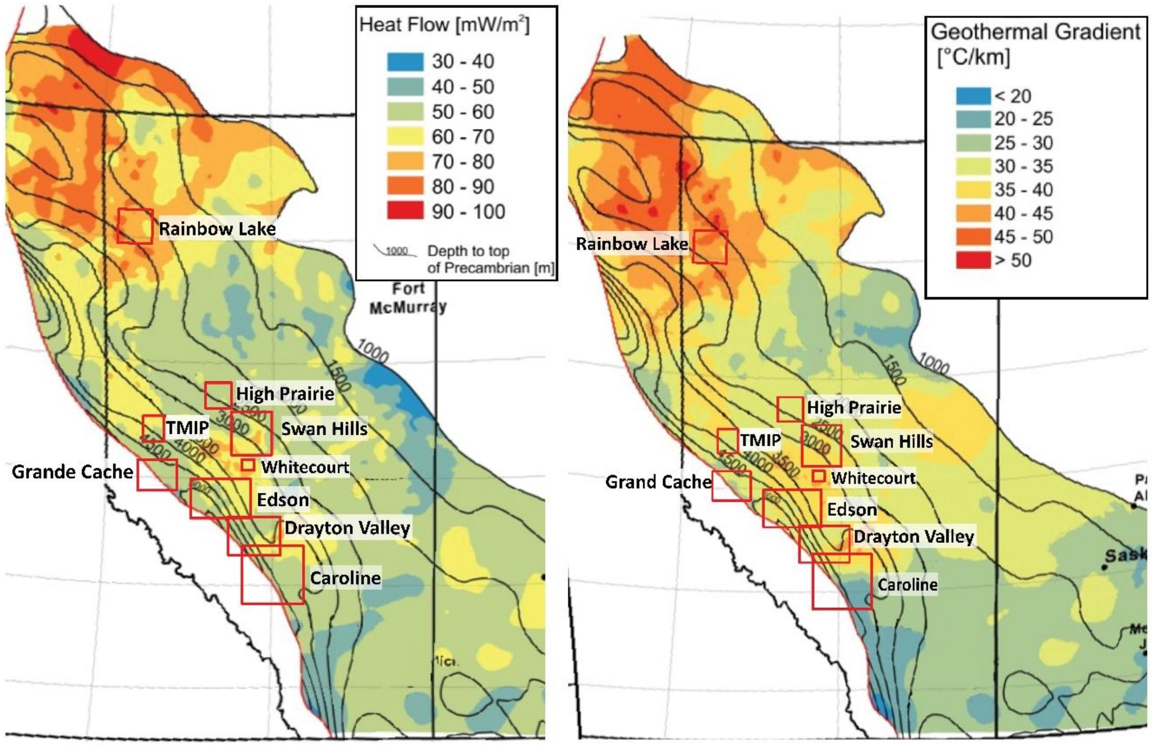

Figure 3: Heat flow map (left) and geothermal gradient map (right) of the WCSB showing the depth to the crystalline basement and the nine study areas. The coloured area shows the extent of the Western Canada Sedimentary basin (adapted from Weides & Majorowicz, 2014).

The Williston Basin, a sedimentary basin in the U.S., can be considered analogous to the WCSB when assessing geothermal resources. The work of Gosnold et al. (2016) in the Williston Basin illustrates the impact of understanding the heat flow within the regional context of a large sedimentary basin. The heat flow map for North America in Figure 1 shows both more and less promising areas but does not allow accurate predictions as to the drilling depths required to access the desired temperatures. Temperature gradients and regional heat flow are required to evaluate the suitability more thoroughly for specific target areas. This has been done in several studies such as work by Weides and Majorowicz (2014); the geothermal gradient and heat flow maps are shown in Figure 3.

In a sedimentary basin, the rocks generally become less porous and denser (and are therefore more thermally conductive) with increasing depth. As the heat flow is the product of temperature gradient and thermal conductivity, the temperature gradient will decrease with depth (assuming constant heat flow).

Taking the Williston Basin as an example (Figure 4), there is a significant decrease in the temperature gradient near a depth of 6000’ (approximately 2 km). This indicates a stratigraphy of relatively soft or poorly consolidated rocks above with a sharp change to denser rocks below. In other basins, this change could be more gradual if the densification is more gradual but is largely dependent on the details of the local stratigraphy within the basin or region.

The temperature log shown in Figure 4 also illustrates the importance of continuous temperature logging in a well and provides a well-documented and precise curve against which single BHT points can be compared at any depth for calibration purposes. An inspection of the profile shows that extrapolating the gradient above a depth of 4000 feet (1220 m) would calculate the anticipated BHT at 9,000 feet (2740 m) to be closer to 300°F (150°C) rather than the measured 240°F (121°C). This 30°C temperature difference could result in an excessively optimistic estimation in the possible viability of a geothermal project.

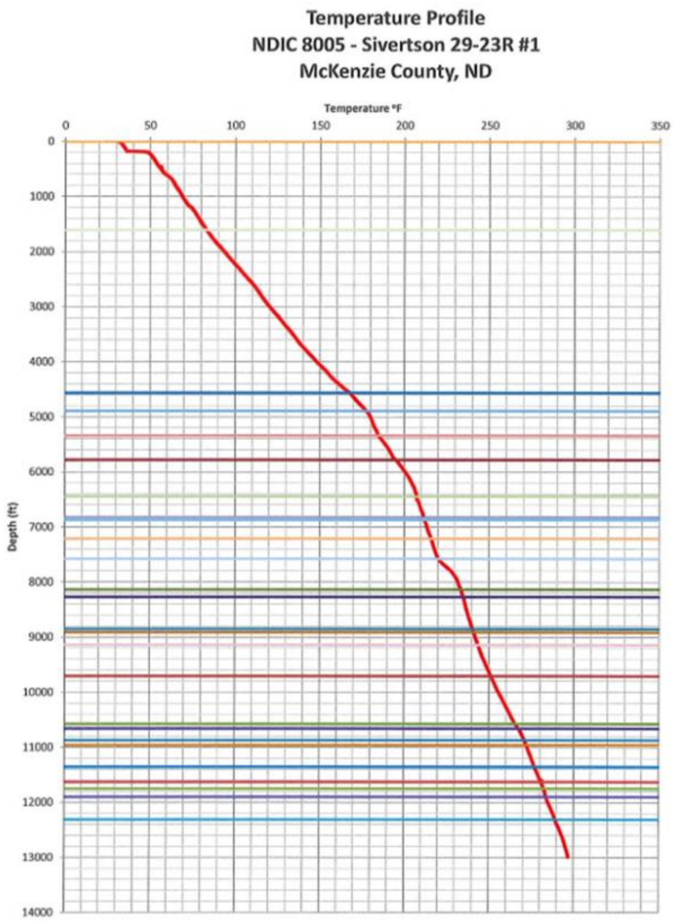

Figure 4: Temperature profile of a well drilled in the Williston Basin in North Dakota. The coloured horizontal lines indicate depths of formation tops. The profile is from a continuously logged well bore and shows fluctuations in slope (temperature gradient) as well as smaller and more localized inflections downhole between formations with differing thermal conductivities (McDonald, 2015).

3. Oil and Gas Data for Geothermal Exploration

Although more than 500,000 oil and gas wells have been drilled in Alberta, the resulting data differ from the data that would typically be collected for geothermal exploration. Interpretation of geothermal resources from BHT data has been the subject of a considerable amount of research (Harrison et al., 1983; Horner, 1951, Stutz et al., 2012, Weides et al., 2014a; 2014b). The chief difficulty faced by geothermal developers when interpreting BHTs is that the temperatures taken for hydrocarbon development are a perfunctory data point at the end of completion of the well.

The data are used for surface engineering designs, especially if the temperatures are high. Wells with BHT data have generally been measured with single, unequilibrated BHT measurements. In comparison, considerable care is taken to obtain accurate and equilibrated temperatures throughout the wellbore for geothermal exploration. This includes the process of allowing the bottom of the well to heat up to thermal equilibrium conditions following drilling. During and after this heat up period, continuous logs are run from top to the bottom. To account for such discrepancies, several correction methods have been created and used to predict equilibrated temperatures at depth. Another challenge is that temperature is usually an insignificant parameter for oil and gas drillers and therefore not usually recorded to provide high-quality data (Gray et al., 2012). Past studies have taken great care to filter the poor quality data (Harrison et al., 1983).

As in the example of the Williston Basin, the geothermal gradient is generally not linear throughout the entire length of a deep (over ~2 to 3 km depth) well (Figure 4). Therefore, the uncorrected gradient fitted to the data is not representative of the gradients at differing depths shown by a single data point throughout the length of the well. The Harrison correction method (Harrison et al., 1983) is used in some studies that use oil and gas data to assess geothermal resources (Crowell, 2015) as it takes into account that the actual temperature gradient of the bottom one third (approximately) of the well is likely lower than the average calculated gradient. However, as later described in the results, the Harrison correction is not suitable for the data in the WCSB as temperature gradient does not appear to change significantly with depth.

Other geothermal studies in Alberta have used the relationship between heat flow, heat generation, and thermal conductivity to calculate temperature at depth (Majorowicz and Grasby, 2010). The Horner correction (Horner et al., 1951) is another method that has been used to estimate temperature at depth. This requires input of elapsed time between cessation of circulation in the well bore and the temperature measurement. It is best when several temperature measurements have been made at regular time intervals. Since these data are not available, the Horner correction could not be applied to our data set. Although there is an abundance of data from oil and gas wells in Alberta, the data set is lacking essential information for typical geothermal methods to analyze geothermal resources at depth within a sedimentary basin. Therefore, the raw, filtered BHT data is taken as the most suitable for predicting temperature at depth in this study.

4. Methodology

No thermally equilibrated temperature logs were found for any of the deeper wells in the WCSB in Alberta to serve as possible calibration points for the BHTs, so the accuracy of BHT values is unknown and, as such, the data have be taken with caution.

For each study area, BHT and True Vertical Depth (TVD) were collected from all available wells. The first step was to eliminate all points that did not include both temperature and depth data by sorting. The points with missing data were saved in a separate spreadsheet in case the missing data could be recovered by further efforts. The average temperature gradient (°C/km) from the surface for each data point was calculated using Equation 1 (thermal gradient – uncorrected and unfiltered, orange data clusters in figures).

$$Gradient = 1000 * \frac{(BHT - ST)}{TVD} \quad (1)$$

where BHT is bottom hole temperature, ST is surface temperature, calculated from mean annual temperature, and TVD is true vertical depth. Mean annual temperature of Alberta from 1961-1990 was 0.6°C (Schneider, 2013). The data were then plotted both by temperature vs. depth and thermal gradient vs. depth (Figure 5).

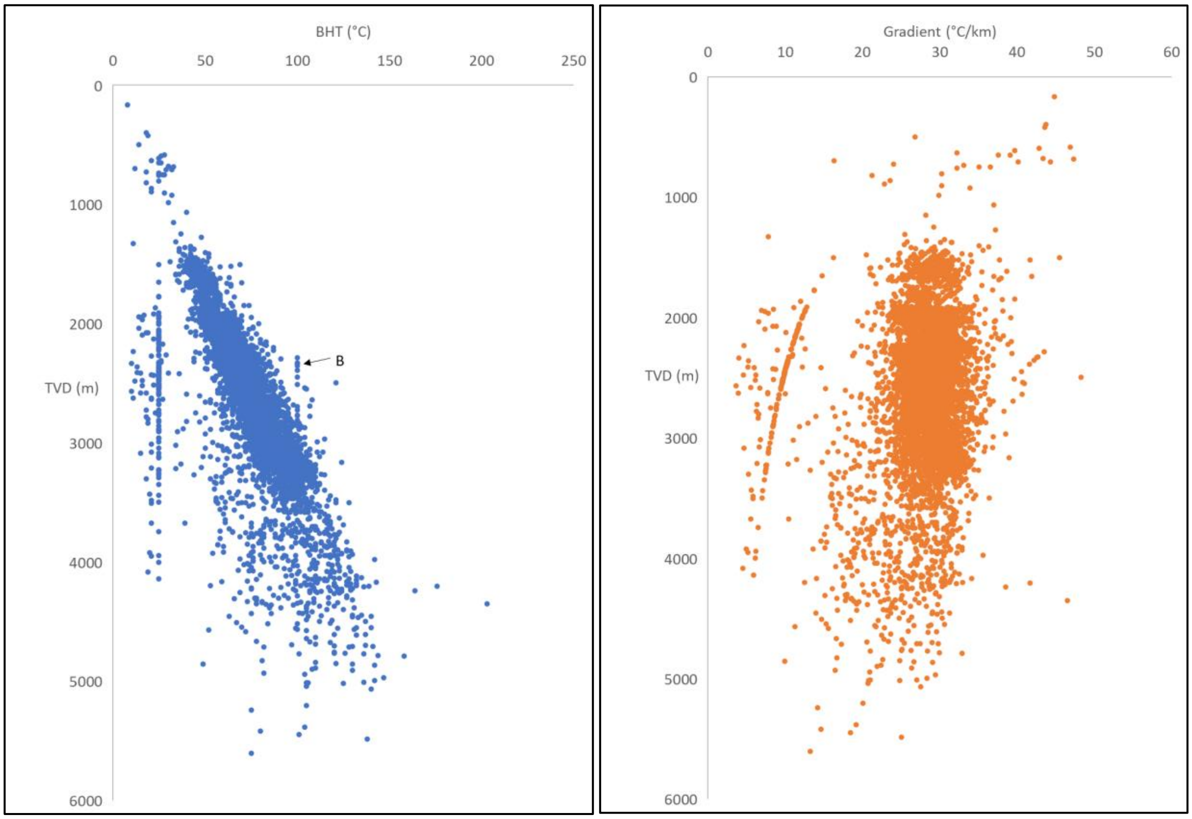

Figure 5: An example showing the filtering process. Raw, unfiltered data are graphed as BHT vs measured depth (left) and temperature gradient versus depth (right). Some drillers may have accidentally reported the same BHT for multiple wells with different depths. 25°C was recorded for multiple wells with depths ranging from around 2000-4000m (labelled A), and 100°C for other wells (labelled B)- these data are clearly erroneous and must be removed to avoid biasing the interpretation.

Next, the obvious outliers were removed including wells with unusually high or low temperature gradients; in this case, the data points were removed because they were not consistent with conductive heat flow (which does not allow for significant variability). The outliers of anomalously high temperatures at high depths were kept for future research, as it may be valuable to look at each data point to assess the legitimacy of the recording.

Other obvious outliers included wells where companies reported the same temperature for multiple wells with different depths (labelled A and B in Figure 5). Also, temperature measurements for wells <1km depth have been shown to be biased (Weides and Majorowicz, 2014). These results are consistent with most data sets in this study, as shown in the temperature plots for Rainbow Lake, which have significantly different gradient values from surface to 1km (42.1°C/km), and 1km and below (21.3°C) (Figure 6). Therefore, data points from surface to ~1km depth were removed. From the work of others, individual outliers at greater depths are likely Fahrenheit (F) recorded as Celsius (C), and outlier groups at shallow depth are likely due to various factors such as incorrect reading or resetting of the maximum reading thermometers (which give anomalously high temperatures) and, occasionally, recording TVD and BHT as the same value (Gray et al. 2012). These errors provide insight into the quality of the data and illustrate how much care must be taken to assess the viability of each data point.

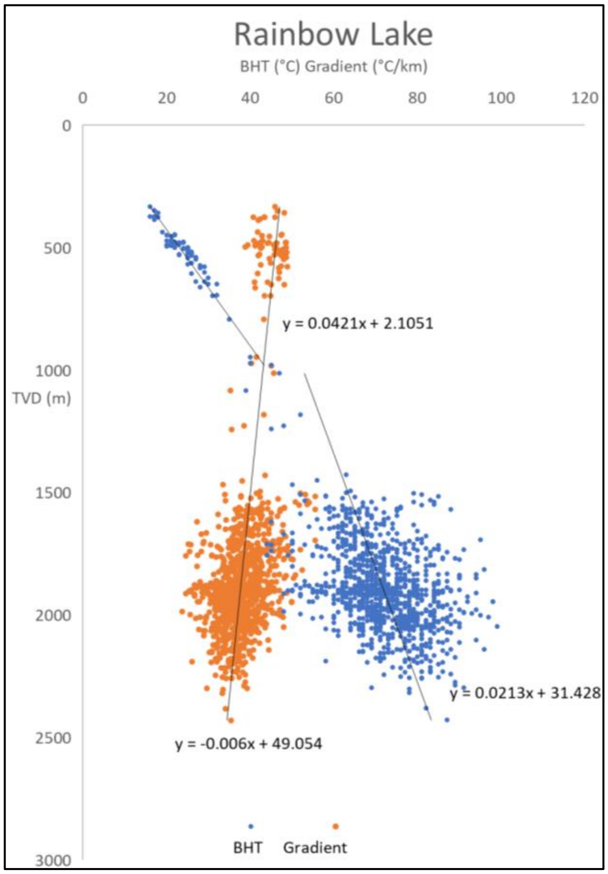

Figure 6. Data from wells less than 1km deep were removed. In the Rainbow Lake study area, the gradient from the surface to 1km depth is 42.1°C/km, while the gradient for 1km and below is 21.3°C/km.

The filtering was done at the discretion of the analysts (K. Huang and W. Gosnold). University of North Dakota professor Will Gosnold completed the temperature analysis for Edson and Whitecourt, which is why the data sets show relatively less scatter. It is important to note that this is not due to less scatter in the raw data set.

When the data filtering was complete, the BHT vs. depth data were fitted with a linear trendline to calculate the averaged uncorrected regional thermal gradient of the data (blue point in Figure 7). The gradient vs. depth data were also fitted with a linear trendline to assess the change in gradient with depth (orange points in Figure 7). For future research, areas with scarce data (Rainbow Lake, High Prairie) should be expanded to include more wells. Because the gradient is drastically different between the upper 1km and below 1km, and it would be difficult to fit a linear trend if data from the upper 1km were eliminated, the results from High Prairie and Rainbow Lake are not considered to be reliable.

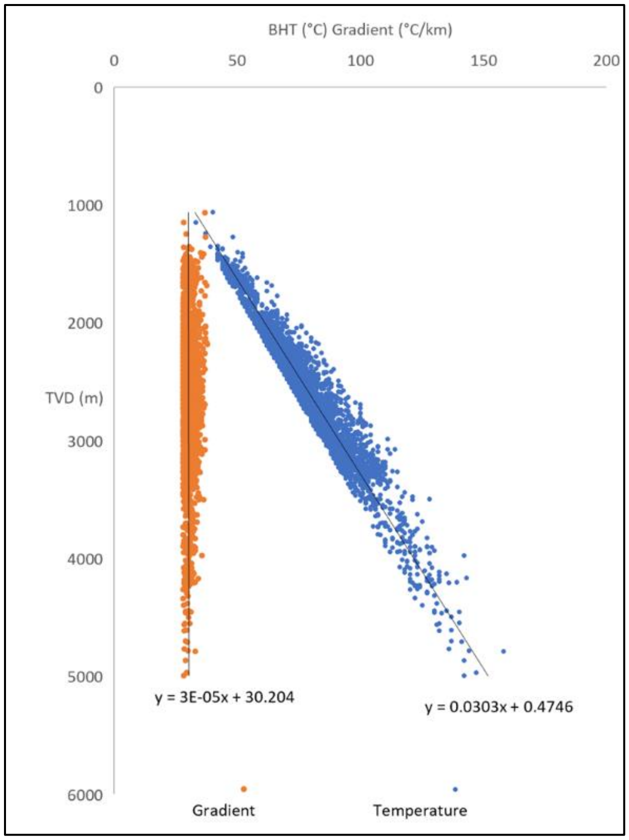

Figure 7: An example showing the filtering process. This graph shows the final, filtered data sets of temperature (blue) and gradient (orange) with depth after points with gradient less than 28°C/km and over 40°C/km were removed as they were not consistent with regional heat flow.

4. Results and Discussion

Graphs of BHT vs. TVD and gradient vs. TVD for all nine study areas are shown in Figure 8. Average thermal gradient and change of gradient with depth for each area are summarized in Table 1. When the data were plotted, it became apparent that stratigraphy of these study areas (Figure 3) within the WCSB do not follow the same general conductivity patterns as the stratigraphy in the Williston Basin. Rather, the thermal gradient does not change significantly with depth; for example, the linear fit for the TMIP study area calculates a gradient decrease of 0.7°C/km. Further, the linear gradient fits the BHT vs. depth data very well, as opposed to a 2nd order polynomial fit which was done in the Williston Basin. This can likely be explained by the generally consistent formation properties with depth in the WCSB. The stratigraphic columns in Figure 9 illustrate that the study areas are underlain dominantly by sandstones, shales, and carbonates which all have relatively similar heat flow and conductivity properties.

The exceptions to this trend are the Rainbow Lake and High Prairie study areas where the gradient changes -9.2°C/km and -2.6°C/km, respectively. These study areas have relatively more sparse data sets and more scatter within the data, which could contribute to the apparent change in gradient with depth.

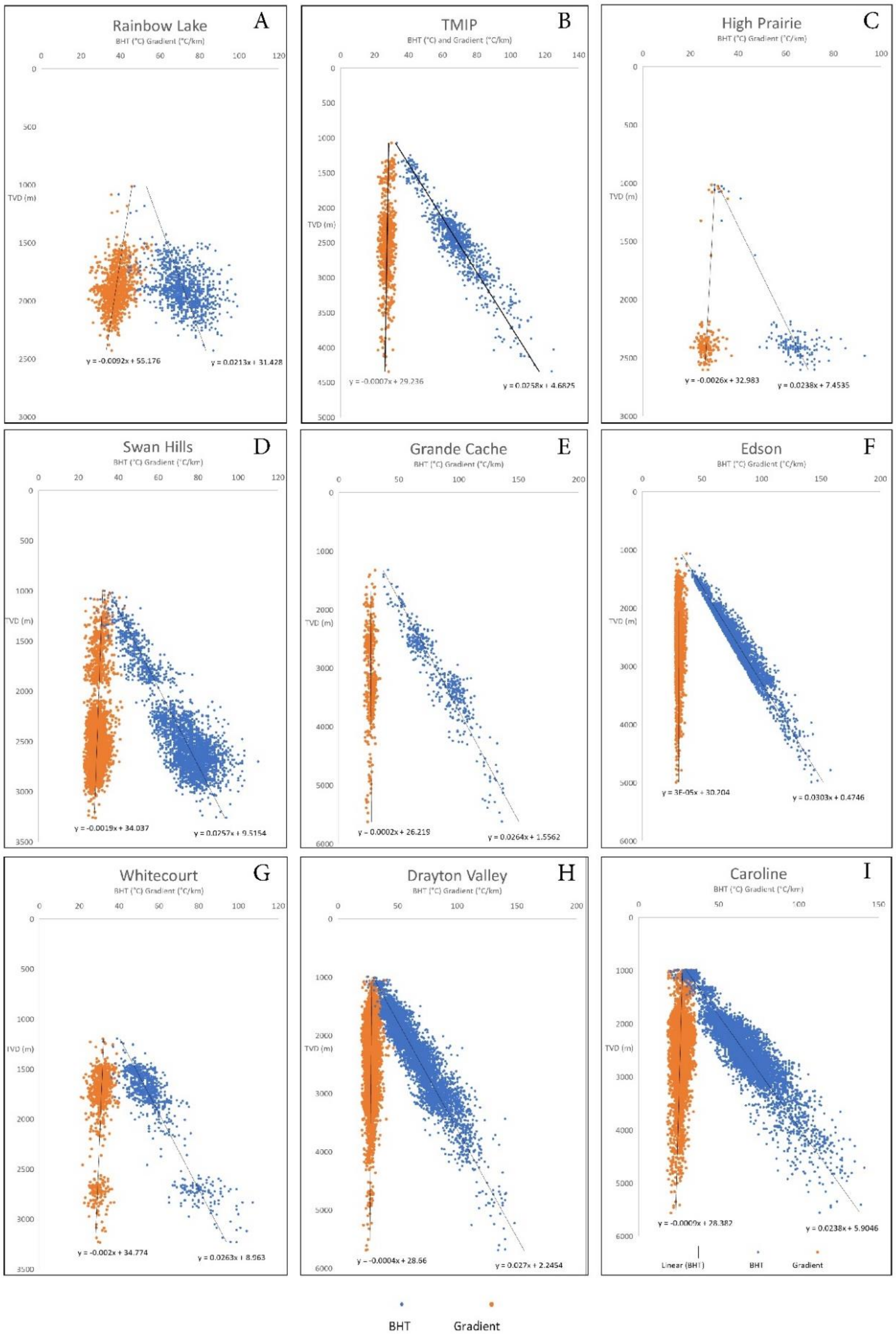

Figure 8: Graphs of BHT and Gradient with depth for Rainbow Lake (A), TMIP (B), High Prairie (C), Swan Hills (D), Grande Cache (E), Edson (F), Whitecourt (G), Drayton Valley (H) , and Caroline (I).

Table 1: Summary of average thermal gradient and change of gradient with depth for each area.

Study Area	Average Thermal Gradient	Average Gradient Change with Depth
Rainbow Lake	21.3°C/km	-9.2°C/km
TMIP	25.8°C/km	-0.7°C/km
High Prairie	23.8°C/km	-2.6°C/km
Swan Hills	25.7°C/km	-1.9°C/km
Grande Cache	26.4°C/km	0.2°C/km
Edson	30.3°C/km	-0.0006°C/km
Whitecourt	26.3°C/km	-2.0°C/km
Drayton Valley	27.0°C/km	-0.4°C/km
Caroline	23.8°C/km	-0.9°C/km

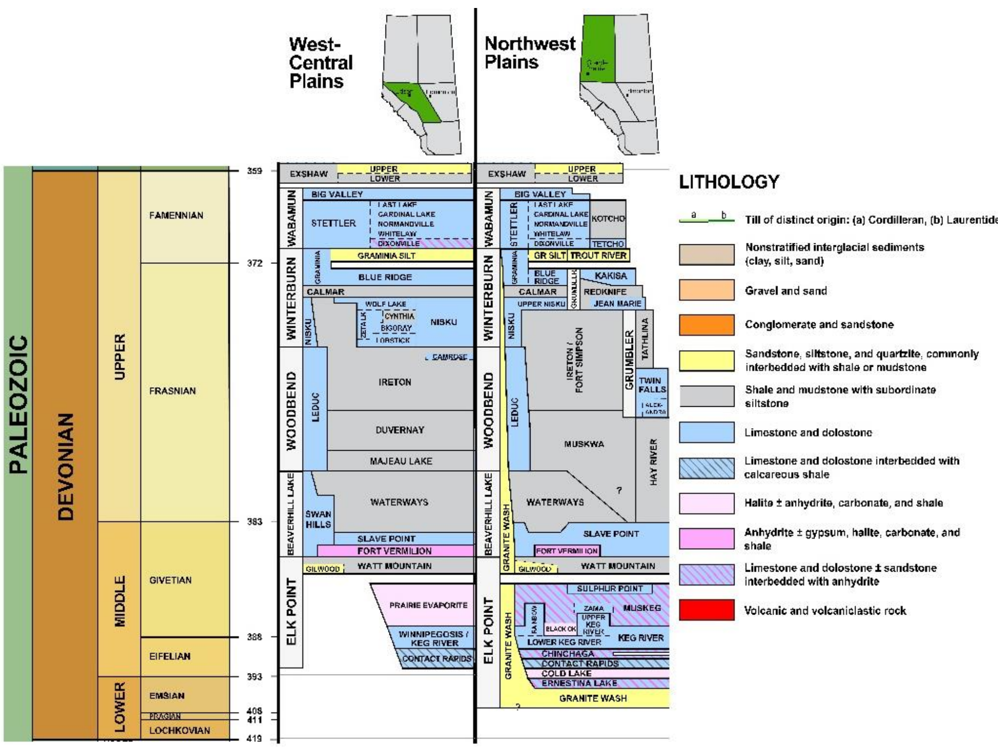

Figure 9: Detailed stratigraphy of the project area and surrounding areas of Northwest and West-Central Plains (adapted from AER 2019).

Overall, the results indicate that the Edson area has the highest average thermal gradient at 30.3°C/km, followed by Drayton Valley, Grande Cache, Whitecourt, TMIP, Swan Hills, and Caroline. There are not enough data to draw conclusions from the Rainbow Lake and High Prairie study areas. These gradients are surprisingly low compared to previous studies, which have reported gradients of over 40°C/km in remote NW Alberta near Rainbow Lake (Majorowicz et al., 2013) and 36°C/km in the Hinton-Edson area (Weides et al., 2013; Lam and Jones, 1985). The geothermal gradient map produced by Weides and Majorowicz (2014) suggests that the study areas have much higher gradients than our results (Figure 3). These previous studies have used correction methods which increased the expected temperature at depth based on the BHT.

The correction methods previously described have been utilized to account for differences in BHT measurement methods between geothermal and oil and gas exploration. Based on our results, however, the oil and gas BHT data may not be as inaccurate as is commonly suggested. Circulation during drilling does involve heat exchange between the fluid and the rocks, but it occurs for only a short period of time at the very bottom of the well. The upper parts of the hole are more disturbed because circulation continues longer there. Circulation after TD is reached could last from the time it takes to retrieve cuttings from the bottom of the hole, which may be only 1 or 2 hours. Cleaning a drilled hole for logging also takes only a few hours, but it does disturb the bottom of the hole with what may be fresh, cold water from the surface. The flow is about 250 l/s (Wang 2020, personal comm.), and would move at 3 km/hour in an 8-inch hole. Therefore, the time to clean and sweep the hole may only be a couple of hours. However, it is still valuable to assess individual wells logs to estimate circulation time, as this can vary significantly between wells.

The extensive oil and gas database in Alberta contain scant information on time between circulation cessation and logging, yet this favours selecting the higher BHTs in a data set to represent equilibrium more accurately than lower BHTs. A reasonable lower limit can be defined from estimating the geothermal gradient from regional heat flow and a general thermal conductivity.

Although gradient values differ between our results and previous studies, the relative gradients between all nine study areas are fairly similar. Based on the geothermal gradient map in Figure 3, the gradients around Edson, Drayton Valley, Grande Cache, Whitecourt, TMIP, and Swan Hills are very similar and higher than Caroline, which our results corroborate. The actual temperature at depth will not be known until wells are drilled and measured using standard geothermal exploration temperature recording methods. The true temperatures at depth are likely somewhere between our uncorrected results and previous, corrected gradients.

5. Conclusions

The results from the temperature analysis suggest that thermal gradient from raw, filtered data may be more reliable than previously thought. In the WCSB, thermal gradient does not appear to change substantially with depth; therefore, correction methods typically used that account for such changes are not suitable for this sedimentary basin. Other studies that assess geothermal gradient within the WCSB have used correction methods which give higher gradients than our results. This study suggests that the Edson area has the highest temperature gradient, followed by Drayton Valley, Grande Cache, Whitecourt, TMIP, Swan Hills, and Caroline. The data from the Rainbow Lake and High Prairie areas are too sparse to confidently calculate temperature gradients. This temperature analysis is being used in conjunction with studies of flow rates and proximity to infrastructure that is necessary to support power and heat use in order to constrain the area within the Alberta portion of the WCSB most suitable for this geothermal project.

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