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Catherine Hickson

Katie Huang

Darrell Cotterill

Will Gosnold
University of North Dakota, william.gosnold@UND.edu

Dick Benoit

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A Relook at Canada's Western Canada Sedimentary Basin for Power Generation and Direct-Use Energy Production

Catherine Hickson[1], Katie Huang[1], Darrell Cotterill[2], Will Gosnold[3] and Dick Benoit[4]

Keywords

Alberta, Western Canada Sedimentary Basin (WCSB), Carbonates, BHT, Brine Chemistry, Greenview,

ABSTRACT

The Alberta No. 1 Project, under the terms of Canada's Federal government's Emerging Renewable Power Program (ERPP), must produce 5MWe net. The goal of this study was to identify areas where three essential constraining conditions overlap; (1) the temperature gradient is sufficiently high that 120°C brines at depths of 4,500m or less are potentially available, (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 a direct use application. A fluid temperature of at least 120ºC is needed to profitably operate the plant. Temperatures below this require increasingly greater amount of fluids to be pumped and injected making them uneconomic. Three hundred liters per second (l/sec) of 120ºC water is required to generate 5 MW net of electrical power with an Organic Rankin Cycle (ORC) binary plant. A depth cut off from a project economics perspective is about 4,500m for large diameter geothermal wells. Fortunately, these formations don't need to be thick to supply these volumes of water to the well bore and thin permeable formations are expected to be laterally extensive in the regional layer cake (Western Canada Sedimentary Basin, WCSB) geology of Alberta. Thus, targeting known high fluid producing geologic units, rather than narrow faults is an important aspect of developing a geothermal project in the WCSB. Alberta No. 1 identified nine study areas to assess for geothermal potential. Of these, the Tri-Municipal Industrial Park (south of Grande Prairie) was determined to be the most suitable for both power production and development, followed by Edson (west-central Alberta). Other areas were identified as being most suitable for basement EGS to produce power, as well as direct use from shallower formations.

1. Introduction

Canada is the largest country in the world by landmass that has no operating geothermal power plants. This, however, is not for lack of geology, knowledge, or effort. Volcanoes within British Colombia's Garibaldi Volcanic Belt have erupted in the Holocene and Western Canada has over 140 thermal springs. The Geological Survey of Canada has extensively documented the potential geothermal resources of Canada (Figure 1) (Grasby et al., 2012). Mount Meager has been extensively studied and drilled over the last four decades and is now being re-evaluated (Grasby, 2019). Additionally, dormant direct use projects such as the University of Saskatchewan's project (Vigrass et al., 2007) in Regina are being reassessed. The collapse of the price of crude oil has also increased impetus to look at alternatives to get rigs and crews back working in Canada (Graney, 2020). This is in addition to three power projects being funded by Natural Resources Canada, Emerging Renewable Power Program (ERPP).

Previous geothermal exploration efforts in Canada have understandably been focused on what appear to be the hottest and most easily accessible conventional geothermal systems, where upwelling water brings high temperatures up to shallow depths. 25 years ago, this was the only economically viable exploration strategy, as binary power plants were not very efficient and temperatures below about 175ºC were below the economic viability of flash-type plants. Ongoing efficiency improvements in binary power plants have resulted in commercial utilization of 125ºC fluids. An example is the Don Campbell project in Nevada where electrical generation of 125ºC brines began in late 2013. With this history in mind, the Alberta No. 1 (AB No. 1) team began a second look at some other potential geothermal sites in Alberta which are now approaching economic viability.

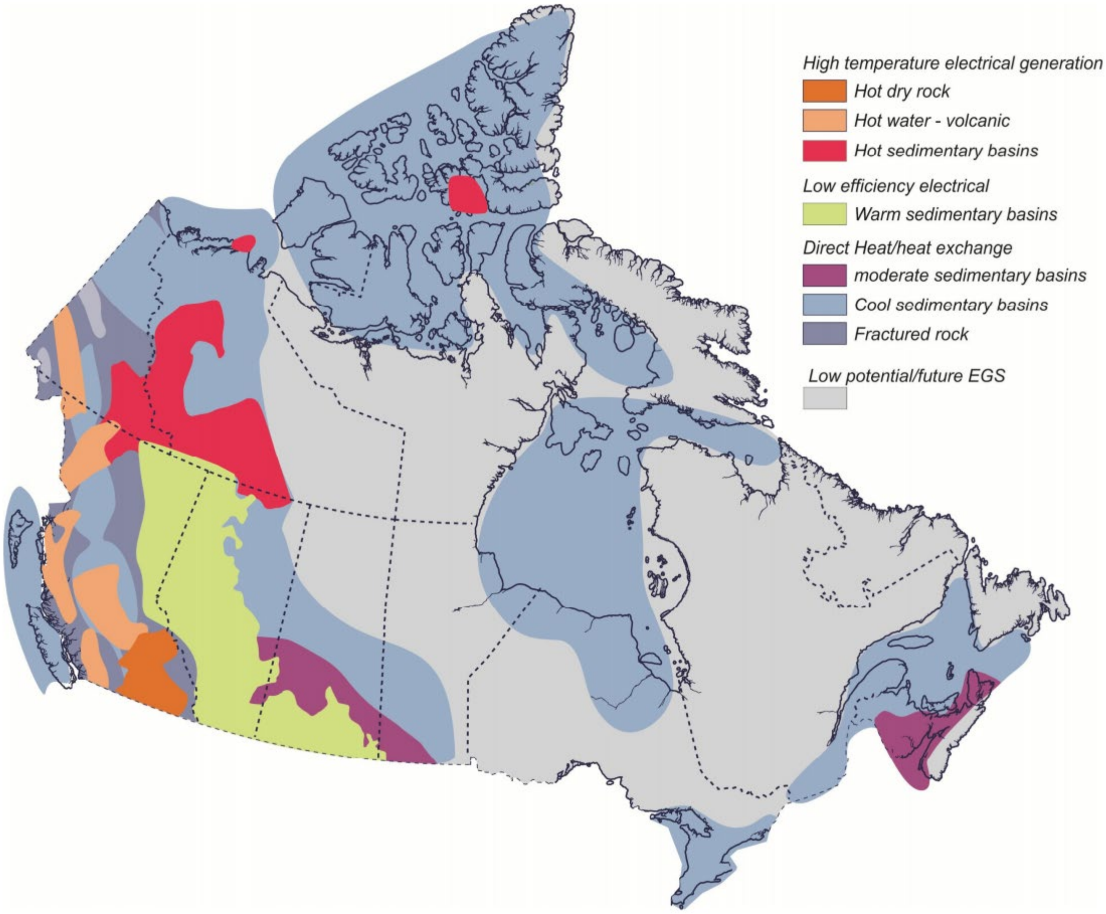

Figure 1: Map showing distribution geothermal potential in Canada based on end use (from Grasby et al., 2012).

2. Western Canada Sedimentary Basin

One of the major potential geothermal reservoirs that requires additional investigation is the Western Canada Sedimentary Basin (WCSB) which covers an area over 1.4 million km^2 in the west-central part of Canada (Figure 2). The WCSB is composed of thick sequences of shales, sandstones, carbonates and other sedimentary basinal rocks (Figure 3). The basin reaches a maximum thickness of nearly 6000 m in the west. Hydrocarbons are known to occur in many of the rock units due to extensive exploration.

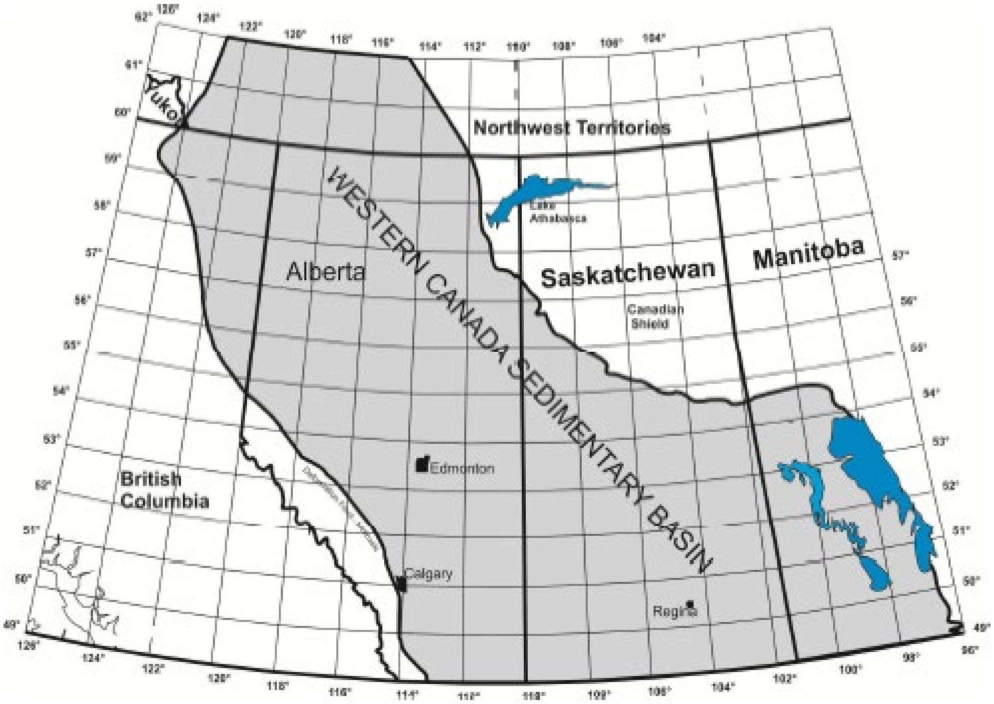

Figure 2: Schematic outline showing extent of the WCSB (based on Mossop and Shetsen, 1994).

Since the Leduc No. 1 well was drilled in 1946, hundreds of thousands of oil and gas wells have been drilled throughout the WCSB; as such, its subsurface geology is very well documented and understood. Unfortunately, there do not appear to be any thermally equilibrated temperature logs available from these deep wells despite there being an abundance of “bottom-hole temperature” (BHT) measurements. The term “bottom-hole temperatures” as used in this paper also includes single point temperatures obtained at depths well above the bottom of the hole during logging and other drilling operations (Figure 4). The vast majority, if not all, of these BHTs are obtained with mercury in glass maximum reading thermometers.

The BHTs define a very broad trend of increase in temperature with depth and contain numerous questionable outlier points, both unbelievably hot and cold for their reported depth. This data set must be masking some natural variability in temperatures and heat flow throughout the basin as well as measurement errors and variability of the technique. As noted by Grasby et al. (2012) “these data can be used…. To observe gradient variations within the basin”, but this apparently has not previously been done with a commercial power project in mind.

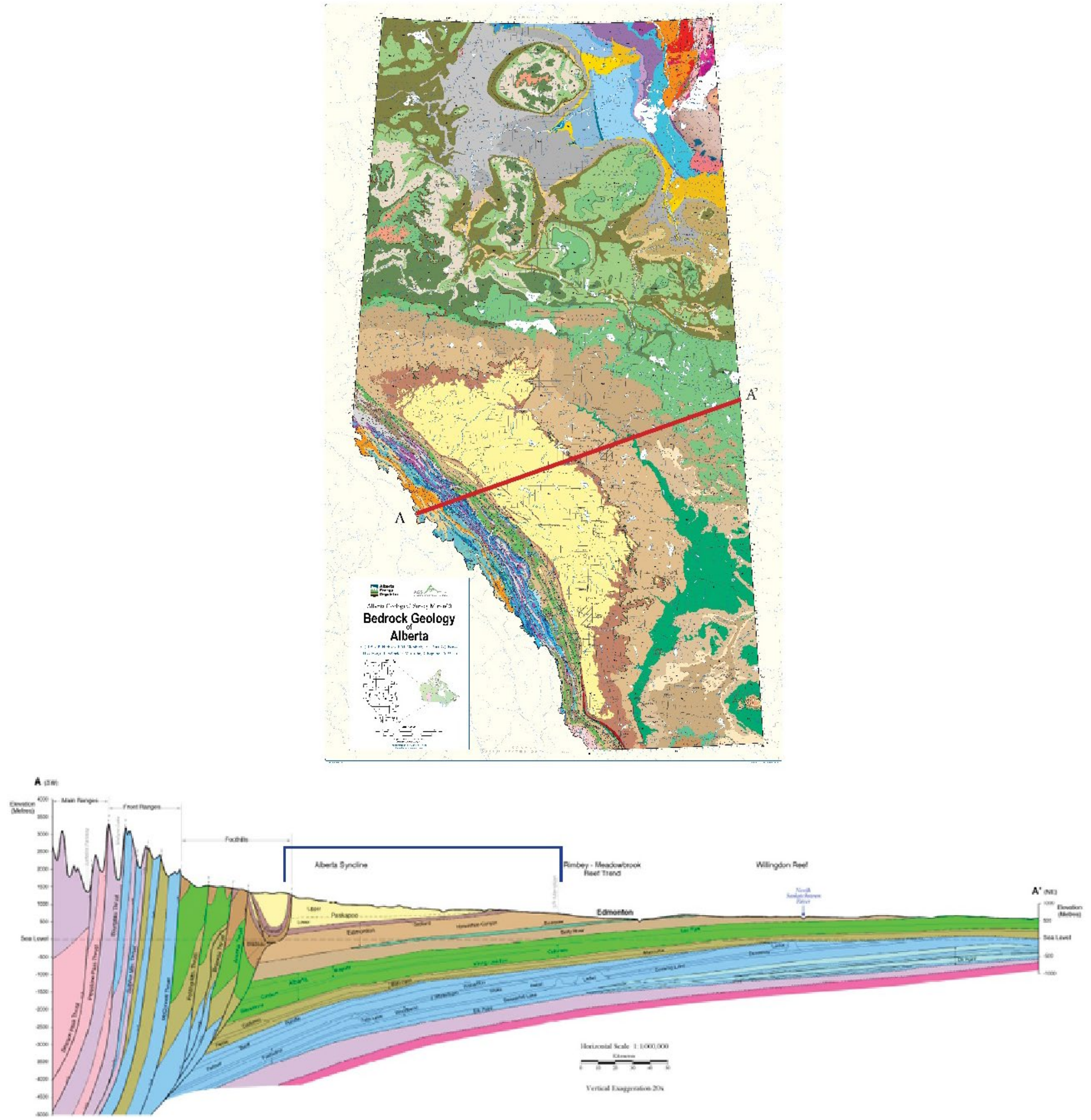

Figure 3: Top: Bedrock geology of Alberta map with A-A' cross section line (adapted from Prior et al., 2013). Bottom: Generalized cross section A-A' of the WCSB (adapted from Graf, 2009). The blue bracket is inclusive of the study areas (Figure 10). The major units are shown as laterally extensive in the east, becoming more deformed along the western margin where topography rises and they have been highly disrupted by the tectonic uplift of the Rocky Mountains. Structural complexity makes predicting the depths of various stratigraphic units more difficult toward the west but it should be noted that the overall thickness is over 6000 meters.

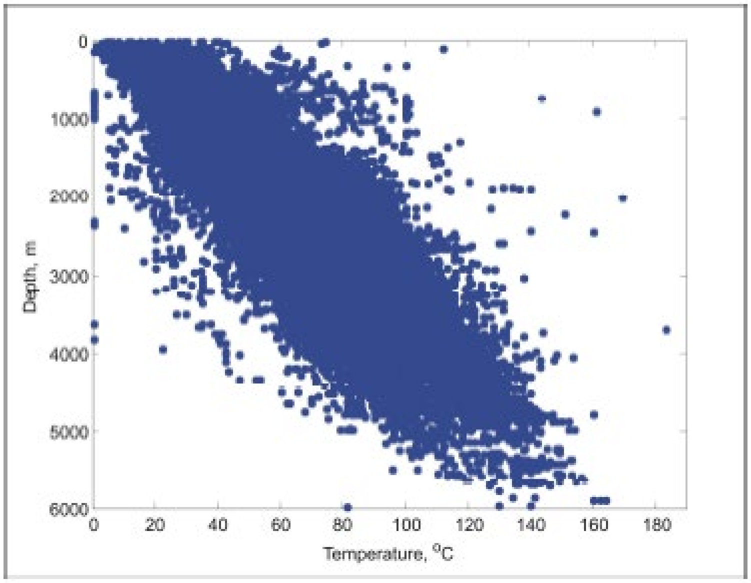

Figure 4: Temperature-depth plot of a small subset of bottom-hole temperatures in the WCSB (from Grasby et al., 2012). Obviously, the mass of data in this plot are of very limited value in deciding if and where there are potential economic prospects within the basin as there is about a 60°C variation in temperature at any given depth.

3. Literature Review

Numerous studies have been conducted over several decades to map geothermal resources and assess the geothermal potential of the WCSB for both EGS production and direct heat use. EGS systems are most suitable in deep, low-porosity and low permeability sedimentary rocks or the crystalline basement with some pre-existing fracture permeability (Majorowicz and Grasby, 2010). Studies assessing potential for EGS focus on sedimentary basins and the crystalline basement due to these units hosting conduction-dominated systems within the WCSB (Majorowicz and Moore, 2008; Majorowicz and Weides, 2012). Majorowicz and Moore (2014) concluded that wells in far western Alberta that are drilled to depths of 4-5km access fluids of 120-150°C. With EGS development, flow rates are expected to range from 5-50 l/s [well bore size was not specified]. Heat flow studies have suggested that high heat flow in northeastern Alberta is due to thick sedimentary cover and has good potential for EGS development (Majorowicz and Grasby, 2010).

Studies that focus on direct heat use potential within the WCSB typically focus on spatial distribution and thickness of high potential formations, as well as rock properties such as porosity and permeability, to identify possible geothermal aquifers with moderate temperatures. Majorowicz et al. (2013) concluded that geothermal gradients over 40°C/km exist in NW Alberta while areas around oilsands operations typically have low (<30°C/km) gradients. Paleozoic carbonate formations appear to have the highest potential for hosting aquifers suitable for geothermal development (Lam and Jones, 1985; Lam and Jones, 1986; Weides et al., 2012; Weides et al., 2013; Ardakani et al., 2016).

The study areas have also been analyzed for thermal gradients to understand temperature at depth (Hickson et al. 2020; Huang et al. 2020).

The WCSB has also been divided into warmer and colder sections by Grasby et al. (2012) (Figure 5) with the deeper western half being warmer at depth simply due to its greater thickness of low thermal conductivity sedimentary rock. It is interesting to note that there are no thermal springs present in the warmer part of the WCSB (Figure 5), implying that the warm water is not actively convecting to the surface and presumably there is relatively little subsurface convection.

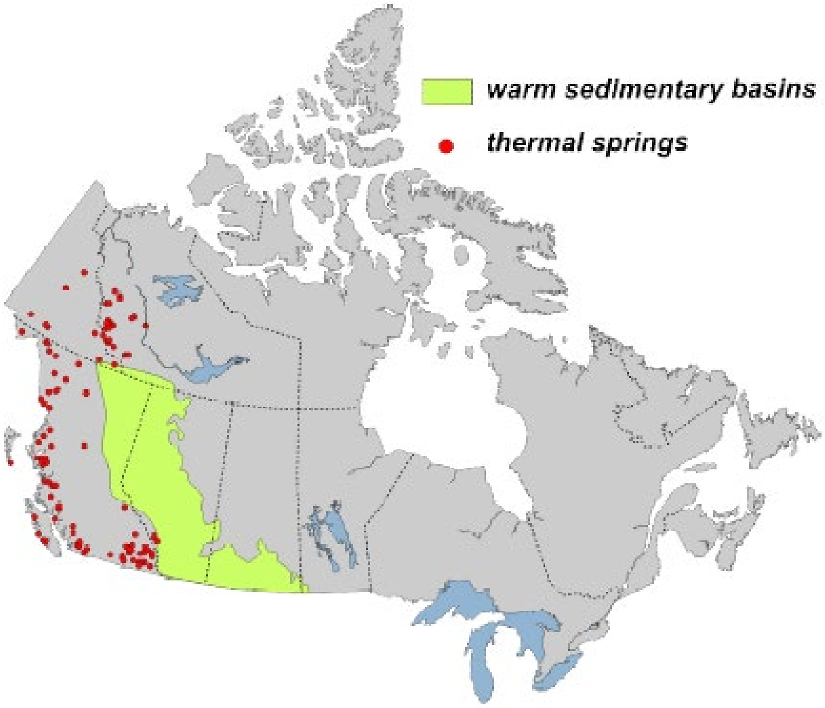

Figure 5: Map showing geographic distribution of sedimentary rocks with known temperatures between 80 and 150°C suitable for thermal (direct-use) energy extraction or binary geothermal power systems (from Grasby et al., 2012). The green area covers the deeper western half of the WCSB (Figure 3) where temperatures potentially suitable for electrical power generation are present within the sedimentary rocks of the basin, but deeply buried.

There is a huge amount of water stored in the WCSB; Grasby et al. (2012) estimate 265 x 10^{15} kg but recognize that only a few percent of this fluid will be hot enough for power generation. However, there is still significant reserves of presumably stagnant, non-potable, stored water at depth for thermal energy extraction. A generalized regional temperature cross section of the entire WCSB shows temperatures near 100°C can be present at depths near 3000 m (Figure 6) in the western part of the basin but gives no indication if the formations at these depths contain extractable brine, nor does it show the actual topography of the cross section.

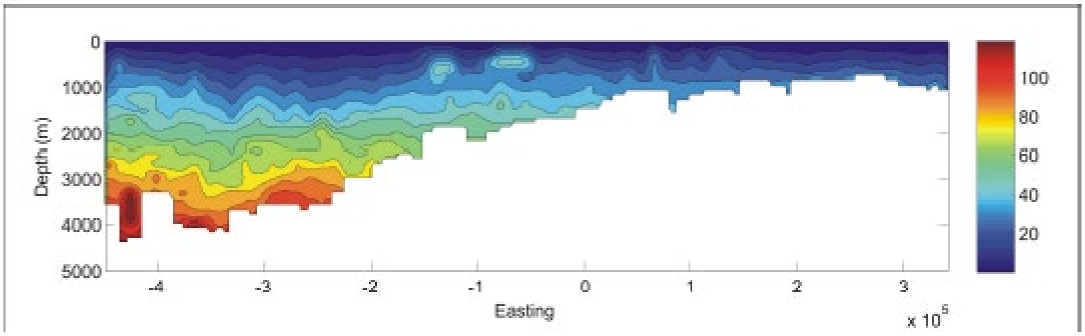

Figure 6: Temperature cross section of the WCSB (from Grasby et al., 2012).

The regional temperature distribution at the base of the WCSB (Figure 7) shows the highest temperatures exceeding 140ºC, but these are at depths of 5000 to 6000 m below land surface due to the westward rising topography (Figure 3).

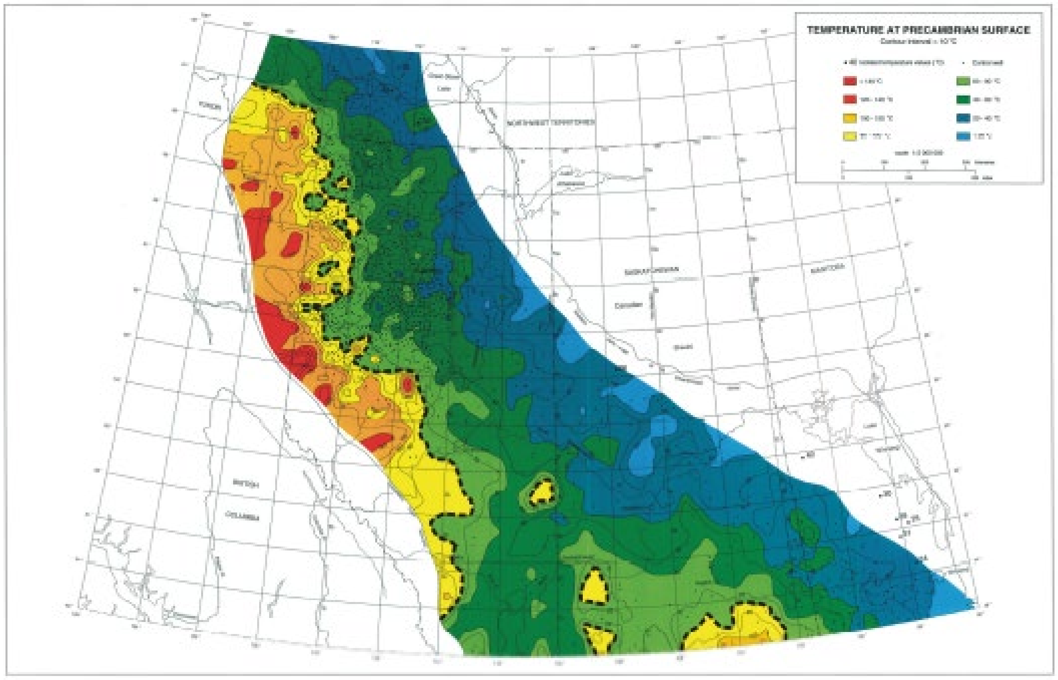

Figure 7: Temperatures at the bottom of the WCSB. The dashed lines divide areas with temperatures above and below 80 ºC. The deepest part of the basin is along its western margin (from Grasby et al., 2012).

The challenge in developing a commercial geothermal project in the WCSB is to find prospects where viable temperatures ≥120 ºC coincide with permeable formations at economic drilling depths. In modern conventional geothermal exploration in other parts of the world, the targets are generally steeply dipping fractures associated with faults in extensional environments. These have large vertical extent but can have very limited lateral heat and permeability extent requiring fairly precise wellbore targeting. In the WCSB the heat is regional and the flat to gently dipping stratigraphy (Figure 3) is also expected to be largely regional in extent. Evaluating for project potential becomes a matter of defining which, if any, individual formations in the basin have high permeability and the ability to penetrate those formations at the desired depth.

4. Permeability

The most likely formations to have high permeability in the deeper parts of the WCSB are carbonates, of which a wide variety have been recognized and described (e.g. Ludovic et al., 2015; Sanyal and Butler, 2009; 2010). These units host a large number of oil fields (Figure 8) and are also targets for excess wellfield fluid disposal. The most productive carbonate units seem to be hydrothermal dolomite reservoirs of Devonian and Mississippian age (Davies and Smith, 2006). Notably, Paleozoic carbonates in Turkey have in recent years become drilling targets for a number of now-producing geothermal fields.

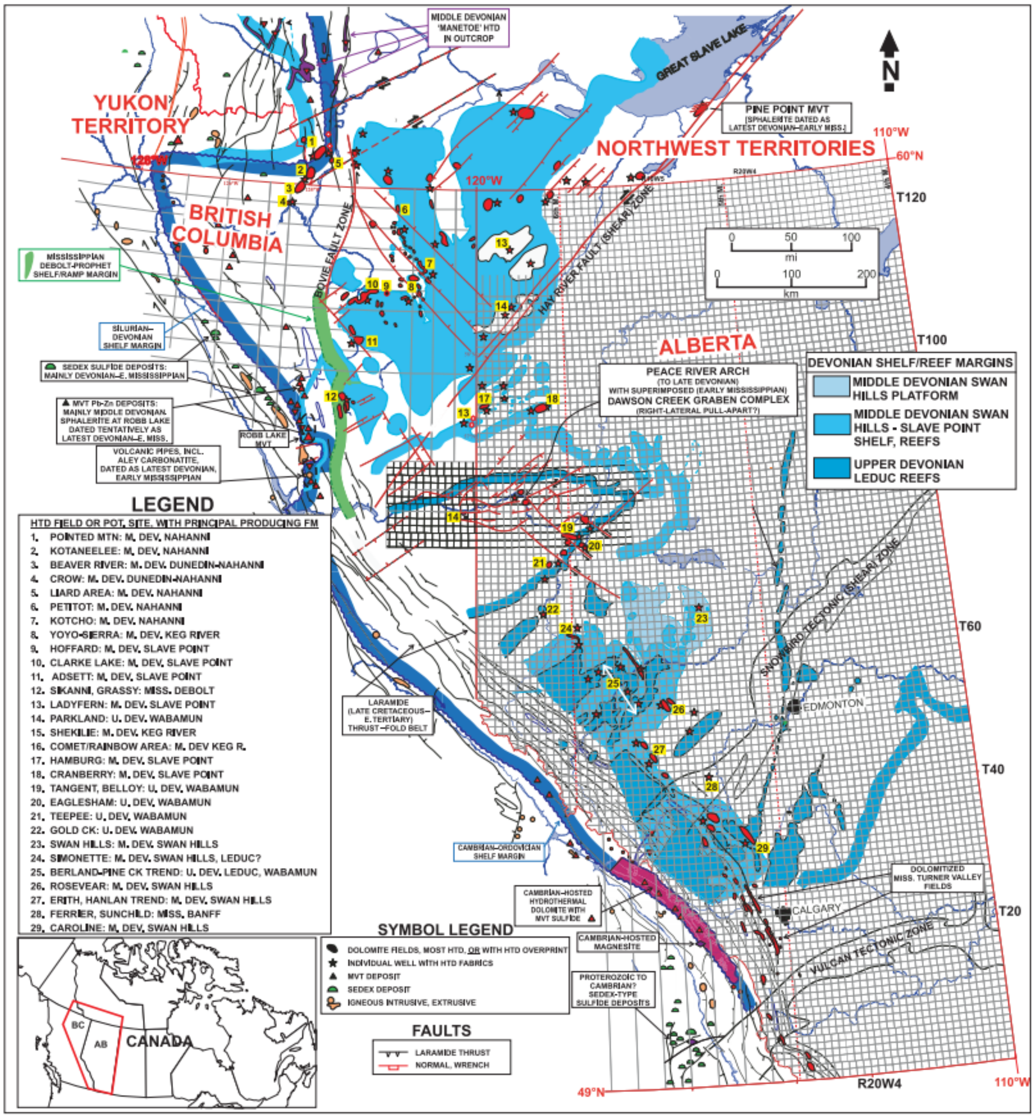

Figure 8: Map showing locations of Devonian aged reef formations, major structural features and selected oil field locations (from Davies and Smith, 2006).

The detailed stratigraphy of the WCSB is well known (GAWCSB, 1994) and specific carbonate formations such as Leduc, Swan Hills, and Slave Point are recognized as potentially being highly permeable. Within these formations, it can be reasonably expected that the permeability will be highly variable (Figure 9). Therefore, to minimize dry hole or low permeability risk, it will be necessary to access the existing wealth of drilling and geological information and expertise of the local petroleum industry in either accessing existing wells or in siting locations for new wells. If any accessible existing wells are available for a more detailed geothermal evaluation, the AB No. 1 team will seek to reenter these wells and run equilibrated temperature logs to both verify the BHT reliability and/or allow for an improved calibration of the regional BHT data.

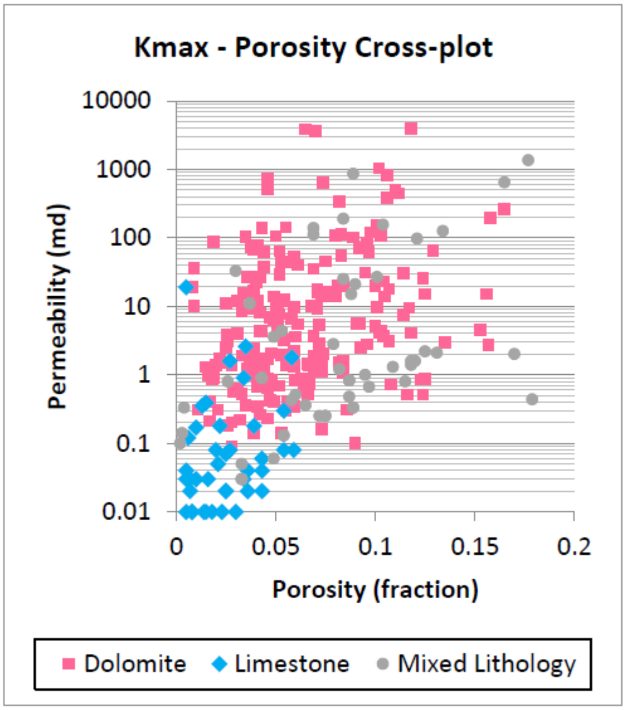

Figure 9: Graph showing the relationship between permeability and porosity from different lithologies within the Slave Point Formation at the Clarke Lake area in northeast British Columbia (from Harris et al., 2020).

AB No. 1 selected nine study areas (Figure 10) in western Alberta as potential targets for geothermal electrical power generation. The areas were selected based on 1) communities that had expressed interest in pursuing geothermal projects, 2) areas where wells were colloquially known to produce hot water and 3) areas identified by Weides and Majorowicz (2014) to have high heat flow and thermal gradients.

The northernmost area (Rainbow Lake) is sited in an area of high regional heat flow (Figure 7) and temperature gradient (Weides & Majorowicz, 2014). The other eight areas are all in areas of similar and normal regional heat flow but can be divided into two groups with substantially differing depths to the top of the Precambrian crystalline basement rocks.

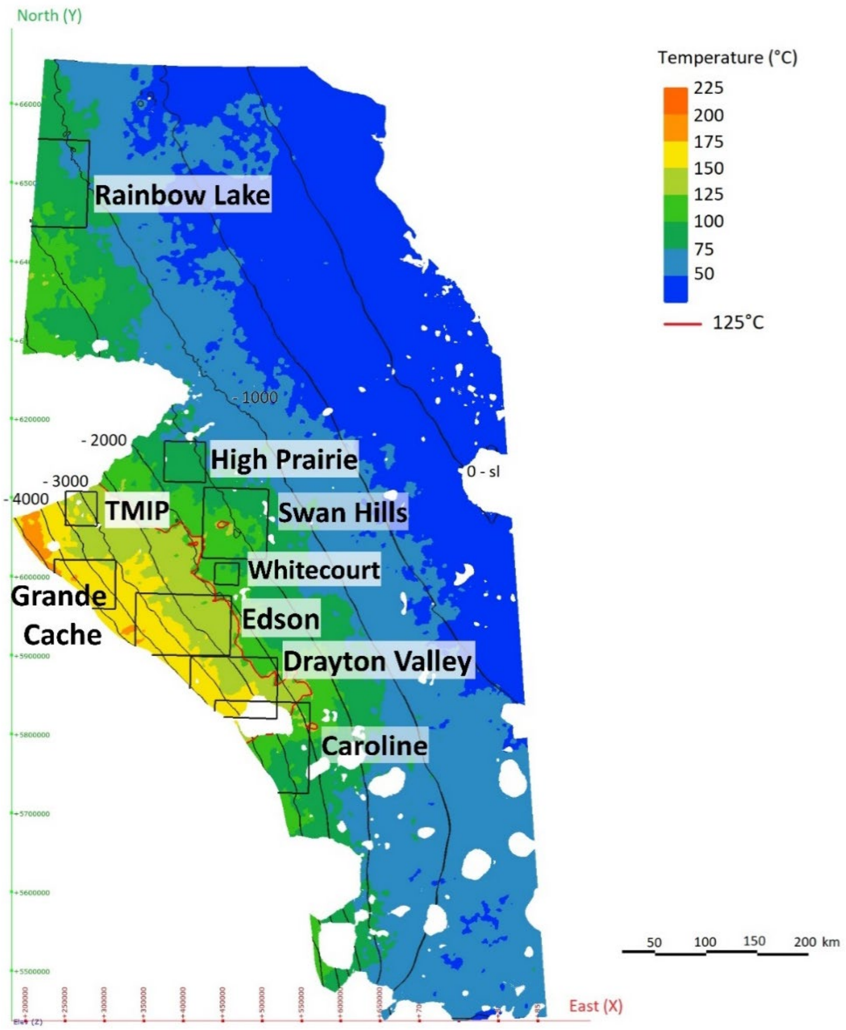

Figure 10: Map showing location of the nine AB No. 1 study areas at the top of the Devonian aged, carbonate Swan Hills Formation. Colours show the distribution with elevation BSL indicated in 500 m intervals. Note that with rising topography the drill depths would be 1000 to 2000 m deeper than the indicated elevation in the western part of the map area. The image was generated using LeapFrog 3D software (Courtesy B. Poux) and derived from data available from the Alberta Geological Survey 3D data project (MacCormack et al. 2019). The image shows the deepening of the Formation from east to west. The 125°C contour is shown in red.

For each study area, BHT and True Vertical Depth (TVD) were collected from all available wells (Hickson et al. 2020; Gosnold et al 2020). 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 Figure 11).

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

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 for all nine study areas (Figure 11). The blue points represent BHT at depth while the orange points represent the average uncorrected temperature gradient from the surface to the reported measured depth; linear gradient lines are fitted to both data sets. The average linear geothermal gradients and gradient changes with depth for all areas are summarized in Table 1.

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	42.1°C/km (upper 1000m) 19.5°C/km (below 1000m)	-6.1°C/km
TMIP	25.8°C/km	-0.7°C/km
High Prairie	22.5°C/km	-4.6°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	-2.1°C/km
Drayton Valley	27.0°C/km	-0.4°C/km
Caroline	23.9°C/km	-1.2°C/km

Overall, the results indicate that the Edson area has the highest thermal gradient at 30.3°C/km, followed by Drayton Valley, Grande Cache, Whitecourt, TMIP, Swan Hills, and Caroline. 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 reliable and therefore conclusions on thermal gradients for these areas are not drawn.

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). A geothermal gradient map produced by Weides and Majorowicz (2014) suggest that the study areas have much higher gradients than our results (Figure 12). These previous studies have used correction methods which clearly increase the expected temperature at depth. However, the relative gradients between all nine study areas are fairly similar between our results and previous studies. Based on the geothermal gradient map in Figure 12, the gradients around Edson, Drayton Valley, Grande Cache, Whitecourt, TMIP, and Swan Hills are very similar and higher than Caroline, which our results corroborate.

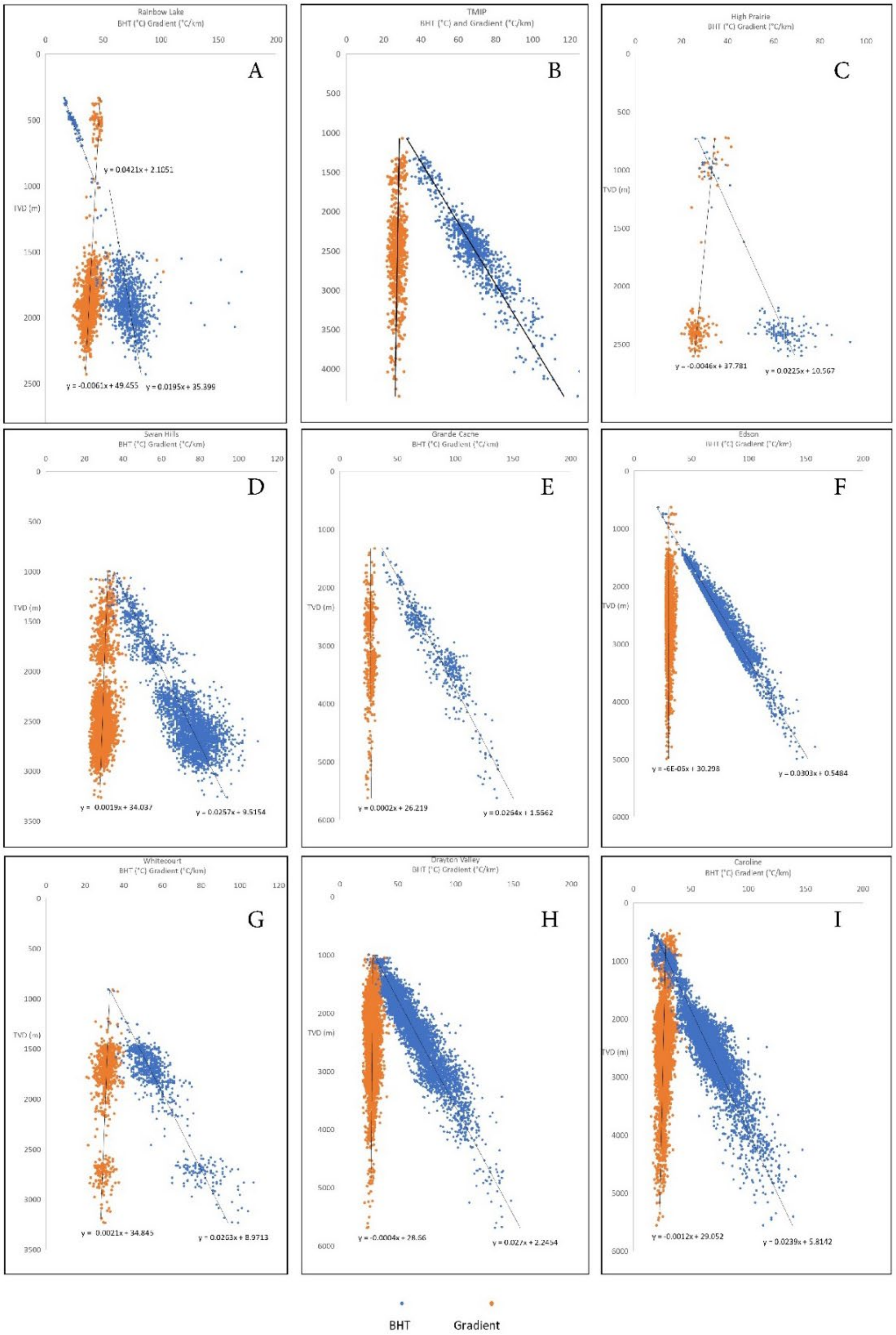

Figure 11: Graphs of BHT and Gradient with depth for Rainbow Lake (A), TMIP (B), High Prairie (C), Swan Hills (D), Grande Cache (E), Edson (F), Whitecourt (G), Drayton Valley (H) , and Caroline (I) (Figure). The blue points represent BHT at depth while the orange points represent the average uncorrected temperature gradient from the surface to the reported measured depth; linear gradient lines are fitted to both data sets.

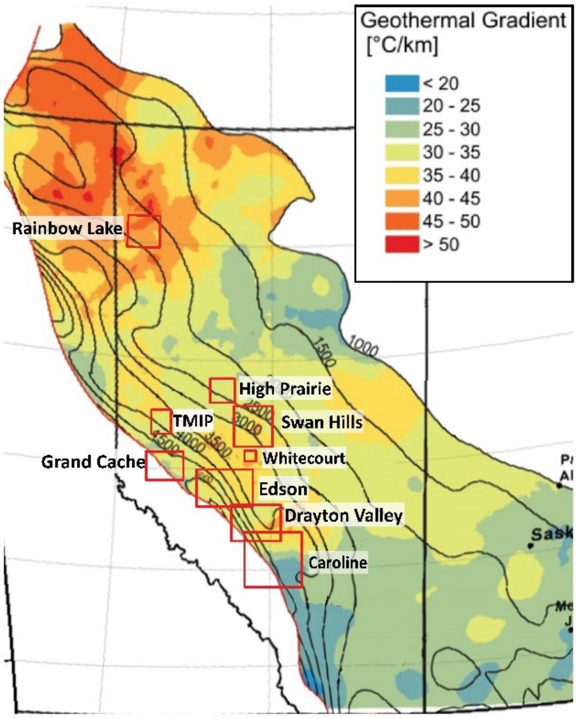

Figure 12: Geothermal gradient map (adapted from Weides and Majorowicz, 2014) suggests gradients are higher than the results of this study.

5. Brine Chemistry

The waters hosted deep in the sedimentary basement show no thermal indications or other features (such as hot springs) that suggest that the water is actively circulating. Stagnant water at this depth is not being flushed by circulation and can therefore reasonably be expected to be saline. Water salinities in the Devonian aquifer system range from at least 20 g/l to over 300 g/l (Figure 13) but Grasby et al. (2012) report localized values as high as 600 g/l in the WCSB. This water chemistry will be an additional engineering challenge for geothermal power generation and will require injection back into aquifers of similar salinity. However, the oil industry has managed to coexist with this water for decades so it should be technically possible for the geothermal industry to also do so. However, the effects of chemistry on the economics of a geothermal project is not known at this time.

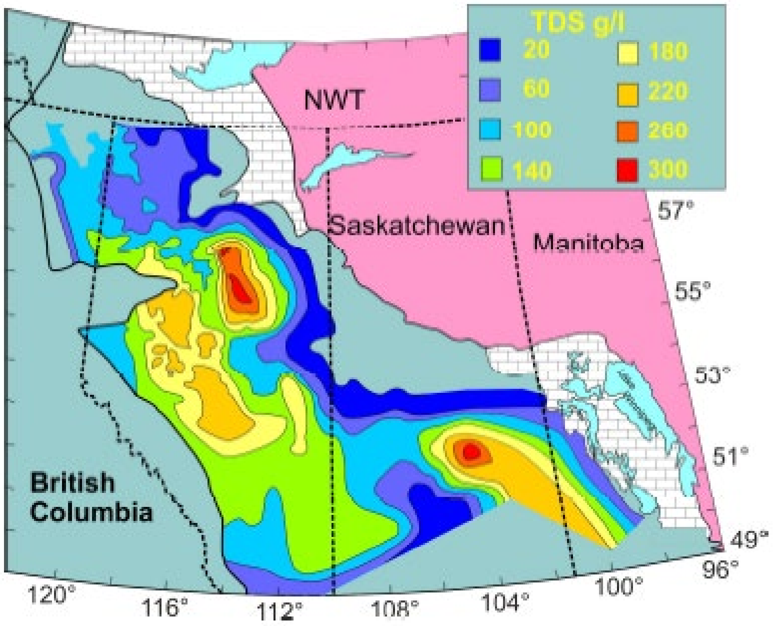

Figure 13: Map showing total dissolved solids content in water in the Devonian aquifer system in the WCSB (from Grasby et al., 2012)

6. Direct Use

Several areas in Alberta have been assessed for geothermal direct use potential, especially around communities in areas with high geothermal gradients that rely on natural gas for heating, industrial use, and agricultural applications. In the Central Alberta Basin (around the Hinton-Edmonton area) hosting thick sedimentary sequences, the geothermal gradient is reported to be around 36°C/km (Weides et al., 2013). Devonian carbonates were found that have temperatures of 22-87°C, while the underlying Basal Cambrian Sandstone unit has temperatures of 62-122°C (Weides et al., 2012). Flow rates in some these units are expected to be up to 194 l/s (Lam and Jones, 1986). 3D modelling in a study by Ardakani et al. (2016) indicated that the sedimentary basin in northeastern Alberta are not suitable for direct use, due to its low gradient and thin cover. Our studies of the nine areas of interest corroborate these studies and further reinforce that there are significant areas underlain by dolomitized carbonates with temperatures between 40 and 120°C that are additionally shallow enough to be suitable for direct-use applications. One of the areas studied in more detail was Whitecourt (Figure 10) where temperatures of 70 to 100°C are found at depths less than 3000 m within the sedimentary sequence (Hickson et al. 2020). The Town of Whitecourt is particularly keen to investigate the options.

As a consequence of the low price of crude oil, there are an ever-growing number of orphan wells in Alberta. These wells are of various ages, have a variety of completions, and are of unknown integrity. They are not suitable for power production unless on a very limited scale, or used as co-production. However, if an orphan well is located near infrastructure, had a history of high water cut (≥ 30 l/sec) we would advocate that the well history be reviewed and the well tested for its suitability for a short term direct-use application. These conditions are likely met in less than 1% of all the orphan wells, so this is not a solution to the orphan well "problem", but might see some of the assets put to limited use. The economics of doing so have not been evaluated (will need to be done on a case-by-case basis) and this suggestion may have no commercial viability. However, Razor Energy Corp. has been funded by NRCan's Clean Growth Program and Alberta Innovates to develop a technically viable and commercially sustainable solution to recover geothermal waste heat from hydrocarbon wells.

7. Conclusions

Our regional study shows that the commercial conditions for power generation are met in only limited parts of Alberta, restricted to the extreme western and northern parts of the WCSB. There is, however, ample evidence for waters lower in temperatures that may be suitable for direct use applications. The AB No.1 project used this regional study to reaffirm the project location within the Tri Municipal Industrial Project (TMIP; Figure 10) which is within the Municipal District of Greenview. At the conclusion of the study (Hickson et al. 2020), the project is targeting strata of the Devonian aged, carbonate Swan Hills Formation and deeper sandstone units at a drilling depth of 4000 to 4500 m.

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