St. Lawrence Lowlands Bottom-Hole Temperatures: Various Correction Methods

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ABSTRACT

The Cambro-Ordovician sedimentary basin of the St. Lawrence Lowlands (SLL) in the province of Québec located in eastern Canada is actually under exploration for its low-temperature geothermal resources. The goal of this actual work is to better correct BHT data in order to evaluate the undisturbed subsurface temperature with more certainty and then improve the quality of the resource assessment.

Very few subsurface temperature data collected in thermal equilibrium exist in the SLL basin. We realised new corrections in order to reduce uncertainty of the estimated rock formation temperature. BHTs were initially corrected following Harrison method. The maximum and minimum gradients enclosing the data corrected by Harrison method are approximately 14-37 °C/km and 14-34 °C/km for the caprocks and the reservoir rocks respectively. Horner corrections were additionally performed for temperature measurement series collected in wells where sufficient information was available. The maximum gradients deduced for BHTs corrected with Horner method are 23.0 and 24.0 °C/km for the caprocks and the reservoir rocks, respectively. The comparison of BHT data corrections for the St. Lawrence Lowlands (SLL) sedimentary basin show that the Horner method is yielding a narrower range of temperature and is potentially generating less uncertainty compared to Harrison method.

Analysis of the results, with the help of a 3D model of the basin, indicate that the Cairnside and the Covey Hill formations, at depths of more than 3 km, are targets for low-temperature geothermal systems, since temperatures in these units can potentially be above 80 °C.

1. Introduction

Power cycles are currently in improvement and/or development processes in order to generate electricity more efficiently by using relatively low-temperature geothermal resources. Successful development of these technologies will expand capabilities to exploit deep geothermal resources from sedimentary basins hosting groundwater at temperatures near 120 °C. Such resources are abundant in Canada and have the potential to provide a large amount of energy with a low carbon footprint. One such target is the Cambro-Ordovician sedimentary basin of the St. Lawrence Lowlands (SLL) in the province of Québec located in eastern Canada.

Previous work was done to estimate geothermal gradients, surface heat flow and temperatures at depth in the SLL basin in order to define its geothermal potential (Majorowicz and Minea, 2012; Raymond et al., 2012). However, there is uncertainty associated with those estimations and more work has to be done to improve the quality of the resource assessment.

The first uncertainties that can be reduced are the ones associated with the estimation of the undisturbed subsurface temperature from bottom-hole temperature (BHT) data. The goal of this actual work is to better correct BHT data in order to evaluate the undisturbed subsurface temperature with more certainty. This would improve reliability of subsequent resource assessments.

2. Geological Setting

The SLL basin is located in the southern part of Québec province and covers an area of about 20 000 km^2 (Figure 1). The relatively non-deformed Cambro-Ordovician platform sequence unconformably overlies the Precambrian basement of the Canadian Shield. Its thickness increases to more than 3000 meters toward the south-east as normal faults affects the sequence (Figure 2).

The upper rock units (Figure 3) are fine-grained siliciclastic rocks of the Queenston, Loraine, Sainte-Rosalie and Utica groups, which are considered as caprocks of the sedimentary sequence (Konstantinovskaya et al., 2014). These units, dominantly made of shale, can potentially form insulating layers of low hydraulic and thermal conductivity. The underlying limestones of the Trenton, Black River and Chazy groups, dolomites of the Beekmantown Group and sandstones of the Potsdam Group, that are known to contain deep saline aquifers, are generally considered as potential reservoirs units (Konstantinovskaya et al., 2014; Tran Ngoc et al., 2014).

The average porosity and permeability of the potential reservoir units have been determined from analyses of core samples, geophysical logs and drill stem tests (DST) (Bédard *et al.*, 2013; Tran Ngoc *et al.*, 2013; Tran Ngoc *et al.*, 2014). Those properties show that the Cairnside and Covey Hill formations of the Potsdam Group globally have the highest porosity and permeability and that they also are the thickest units of the sedimentary sequence. These data indicate that the two formations are among the best targets for further studies of the geothermal potential of the SLL basin. The underlying Precambrian basement is another potential target for enhanced geothermal systems where reservoir stimulation could improve fracture permeability to potentially circulate water and extract heat.

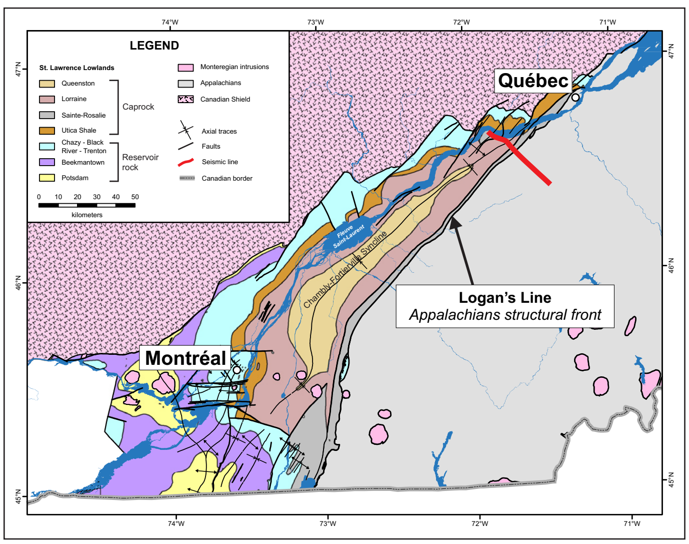

Figure 1. Geological map of the SLL basin (MRNF, 2008; Comeau et al., 2013). The red line shows the location of seismic profile M-2001 (Figure 2). The yellow dots indicate the wells where heat flow measurements have been performed (Misener et al., 1951; Saull et al., 1962; Fou, 1969).

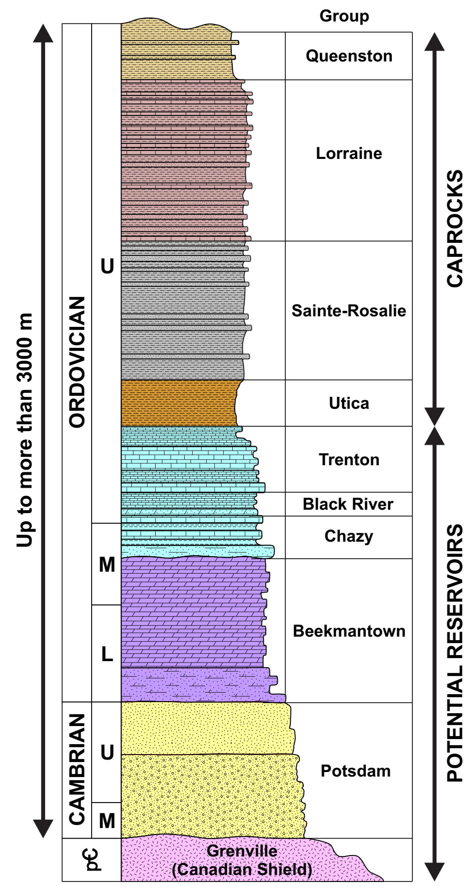

Figure 3. Simplified stratigraphic column of the SLL basin sedimentary sequence. Thickness of the sedimentary sequence is up to 3000 m in the deeper part of the basin. Modified from Comeau et al. (2013).

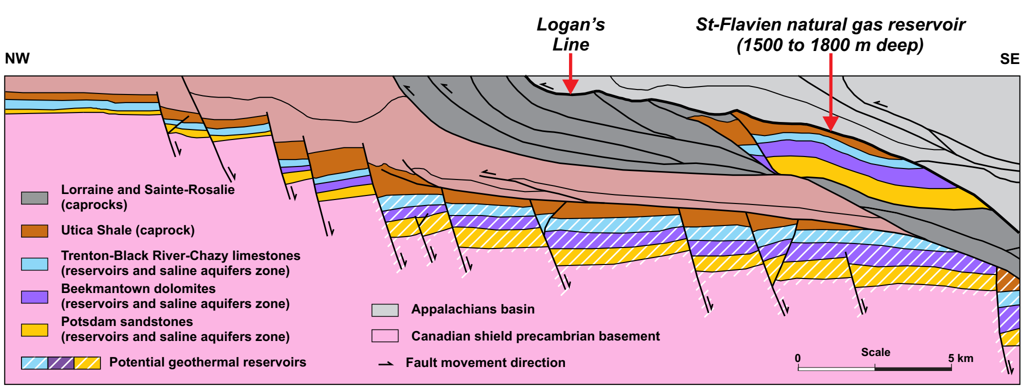

Figure 2. Interpreted cross-section based on M-2001 seismic profile (Castonguay et al., 2010) showing the potential geothermal reservoirs. Location of the seismic line is given in Figure 1.

3. Subsurface Temperature Data

Initial work to correct BHTs was realised by Majorowicz and Minea (2012), who used the Harisson and SMU correction methods (Harrison *et al.*, 1983; Blackwell and Richards, 2004; Blackwell *et al.*, 2010) to estimate subsurface equilibrium formation temperatures. Vertical variations of temperature and surface heat flux were calculated from corrected temperatures, accounting for estimated heat generation due to decay of radioactive elements in the crustal rocks. An average surface heat flux density of 57 mW/m^2 was calculated for the Appalachians and the SLL basin, with higher values of 60-75 mW/m^2 in some regions of the SLL basin (Majorowicz and Minea, 2012). Estimates of temperatures at greater depths were extrapolated to produce temperature distribution maps at various depths.

Very few subsurface temperature data collected in thermal equilibrium exist in the SLL basin. However, 125 temperature measurements were logged in 82 oil and gas exploration wells. We realised new corrections in order to reduce uncertainty of the estimated rock formation temperature. The goal was to compare different correction methods and evaluate the approximate magnitude of errors for geothermal gradients in the SLL basin. All depth data reported are true vertical depths (TVD) from the surface.

All BHTs between the depths of 914 and 3932 meters (3000 to 12900 feet) were initially corrected following Harrison method (Harrison *et al.*, 1983):

$$\Delta°C = -16.51 + 0.01827z - 2.345 \times 10^{-6} z^2$$

where z is depth in meters.

For wells deeper than 3932 meters, the data were corrected by adding 0.028 °C every 152.4 meters (0.05 °F every 500 feet) starting from the maximum value of the SMU-Harrison correction, 19.06 °C (34.3 °F) (Blackwell et al., 2010). Finally, the shallower temperatures, less than 914 meters, were not corrected, as the correction uncertainty can be important for those depths.

The maximum and minimum gradients enclosing the data corrected by Harrison method are approximately 14-37 °C/km and 14-34 °C/km for the caprocks and the reservoir rocks respectively. These gradients are similar to those reported by Majorowicz and Minea (2012) that used the SMU-Harrison method and which were approximately 16-36 °C/km.

Horner corrections (e.g. Horner, 1951; Goutorbe et al., 2007) were additionally performed for 27 temperature measurement series collected in 23 wells where sufficient information was available. Such a correction is based on the infinite line source equation used to model temperature recovery after wells have been drilled. The difference of temperature between BHT measurements recorded at different times after the end of drilling is plotted against time to evaluate the rock formation equilibrium temperature. The method assumes that drilling and mud circulation disturbance become negligible after a given elapsed time compare to the end of drilling/circulation. The results of the corrections are shown in Figure 4.

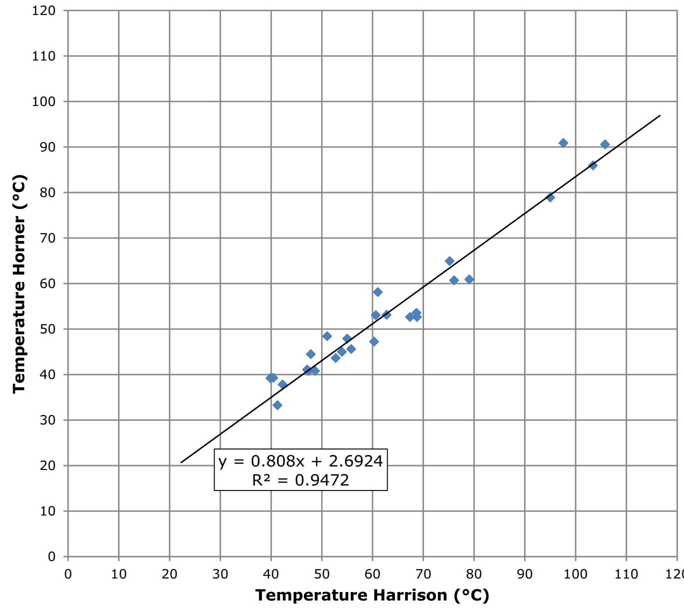

Figure 5. Difference between temperatures corrected with Harrison and Horner corrections.

The corrected data show that BHTs corrected with Horner method are less scattered in terms of temperature compare to Harrison correction method. The maximum gradients deduced for BHTs corrected with Horner method are 23.0 and 24.0 °C/km for the caprocks and the reservoir rocks, respectively. The variability associated with this method in the SLL basin appears to be lower than that of the Harrison and Harrison-SMU methods. However, Horner corrections cannot be applied to all the wells with temperature data because it requires several temperature measurements conducted at different time after drilling stopped, which is not often the case in the SLL basin. Some of the wells with higher BHT could not be corrected with Horner method.

When comparing equilibrium temperatures obtained with the Horner method, which is analytical, and the Harrison method, which is empirical, it appears that the Harrison method is giving a higher rock formation temperature than the Horner method (Figure 5).

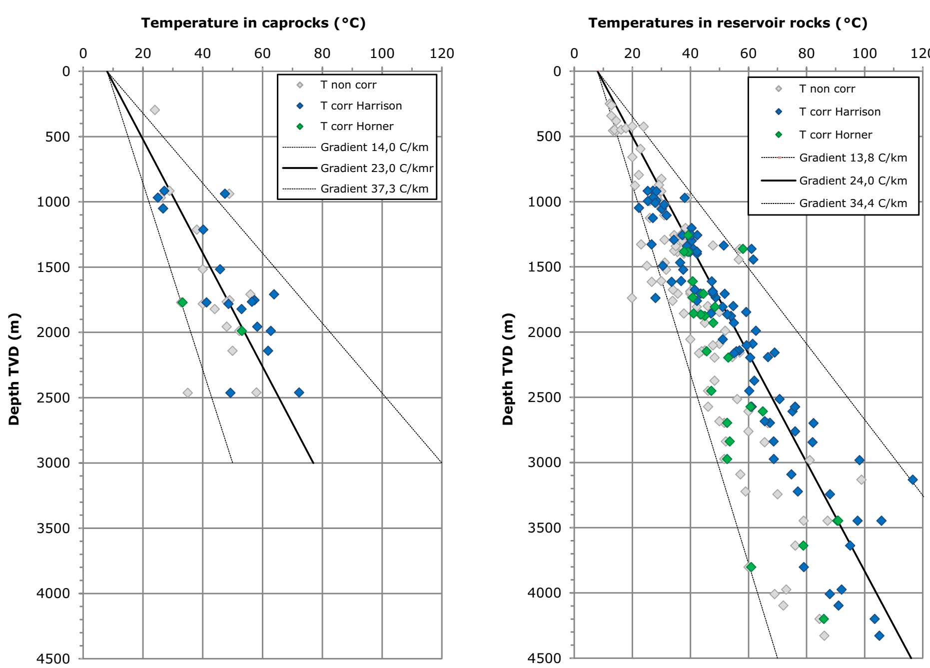

Figure 4. BHT data in caprocks (left) and in reservoir rocks (right) from oil and gas exploration wells in the SLL basin. The dashed lines represent the approximate minimum and maximum geothermal gradient of the corrected temperatures. The solid line shows the maximum gradient of the data corrected with Horner corrections.

4. 3D Geological Model and Geothermal Anomalies

A 3D geological model of the SLL basin was built by combining the regional surface geological map, the structural map of the basement and the depth of geological contacts from oil and gas exploration wells (Bédard *et al.*, 2013). Depths of geological units were extracted from the 3D model and mapped in 2D horizontal planes, over which BHT measurements of corresponding depth have been superimposed (Figures

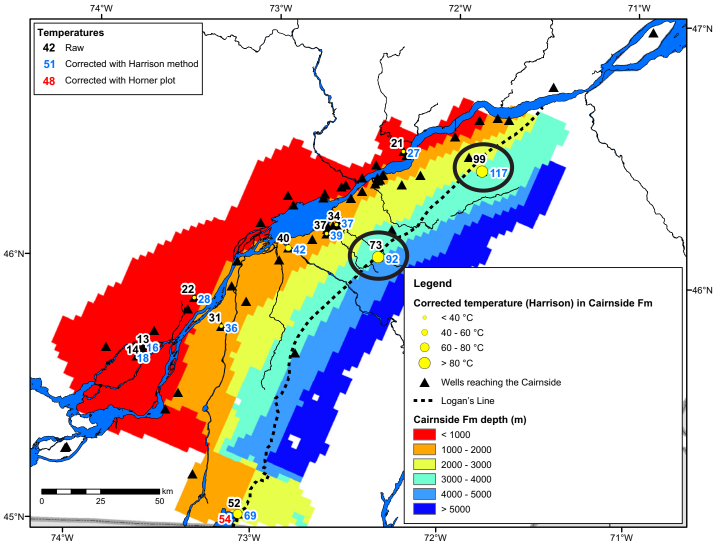

Figure 6. Depth of the top of the Cairnside Formation and temperature data that intersected this unit. Black circles indicate the wells in which temperature is the higher.

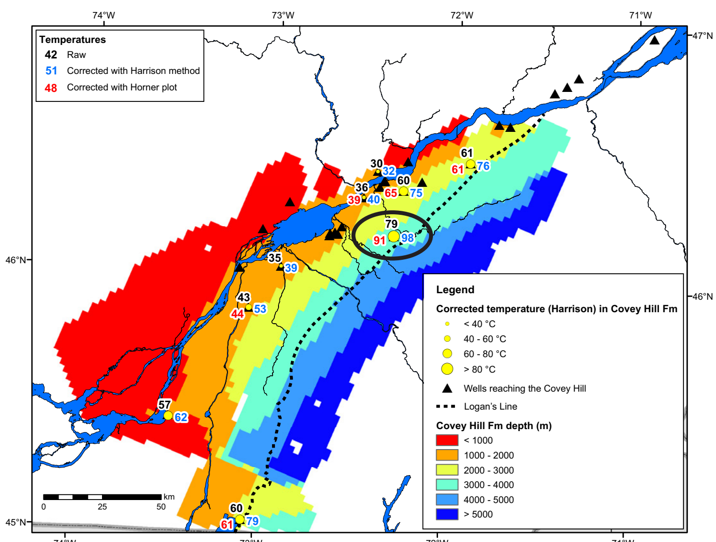

Figure 7. Depth of the top of the Covey Hill Formation and temperature data that intersected this unit. The black circle indicates the well in which temperature is the higher.

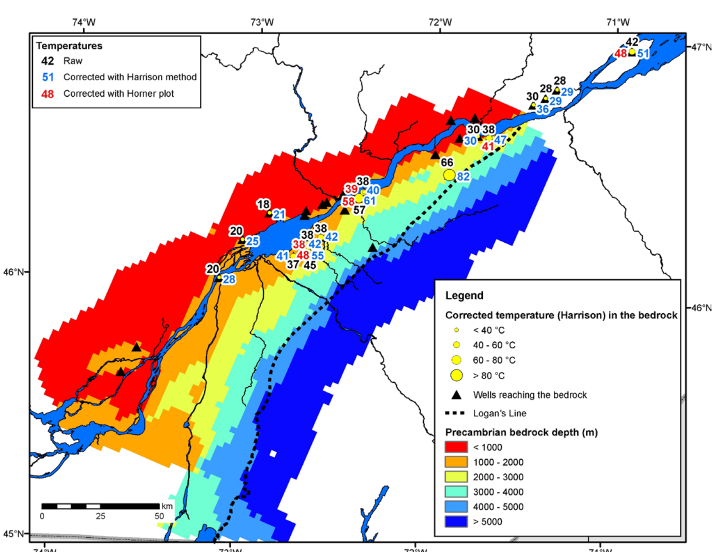

Figure 8. Depth of the top of the Precambrian basement and temperature data that intersected this unit.

6, 7 and 8). 77 temperature measurements taken from 41 wells were plotted on the maps; 38 measurements were recorded in the Cairnside Formation, 18 in the Covey Hill Formation and 21 in the basement. The temperature value at each well is shown on the maps with a circle that increases in size with increasing temperature.

Wells with the highest uncorrected BHTs (70-100 °C) intersect these formations between the depths of 3 and 4 km in the southeastern part of the basin (Figures 6, 7 and 8).

5. Discussion and Conclusions

The comparison of BHT data corrections for the St. Lawrence Lowlands (SLL) sedimentary basin show that the Horner method is yielding a narrower range of temperature and is potentially generating less uncertainty compared to Harrison method. However, Horner corrections are not always possible because of the lack of sufficient number of BHT data. Horner corrections are additionally time consuming when compared to empirical methods. Moreover, the Horner correction methods cannot be used if the time between the end of circulation and the temperature recording is too short compare to the time of circulation or if the well has a too large radius compare to elapsed time (e.g. Drury, 1984; Goutorbe *et al.*, 2007).

The next step for this study is to determine if a new correction method could be developed specifically for the SLL by comparing results from Harrison and Horner corrected data, DST data and well equilibrium temperature data. Deep equilibrium formation temperature data are currently unavailable in the SSL basin. Work performed by Saull et al. (1962) to estimate heat flow in the SLL reports equilibrium temperature measurements that reached less than 420 m. This is a major drawback to perform Harrison-SMU corrections which are based on comparison with local equilibrium temperature data. More work should be done to collect deep temperature observations in the SLL basin. This can help to reduce uncertainty related to temperature corrections as there is presently no option to compare results with real data.

In the previous studies of the geothermal potential of the SLL basin, the estimation of surface heat flow and extended temperatures at greater depths did not account for vertical changes of thermal conductivity according to the spatial variation of rock units. A further step to estimate heat flow that will be carried out is to determine the thermal conductivity of each unit of the sedimentary sequence with laboratory measurements. This will allow, in conjunction with the 3D model and the corrected temperatures, to calculate with more accuracy the heat flow and, consequently, to better define the spatial distribution of underground temperatures.

Maps presented in this paper (Figures 6, 7 and 8), which were generated from a 3D geological model of the SLL basin, indicate that the Cairnside and the Covey Hill formations, at depths of more than 3 km, are targets for low-temperature geothermal systems, since temperatures in these units can potentially be above 80 °C. All the temperature data in the Precambrian basement are shallower than 3000 m and therefore did not revealed hot locations of interest. However, the basement is an additional target for enhanced geothermal systems. In fact, the basement temperature, at given locations, should be higher than the temperature measured in deep wells reaching the Covey Hill and Cairnside formations because temperature is increasing with depth.

Viable development of EGS needs further studies to be confirmed, especially because of economic arguments. There is abundant cheap hydroelectricity and the drilling depth to reach adequate temperatures is important in Québec. However, temperatures above 60 °C found at shallower depths indicate resources that could be used for direct geothermal industrial and district heating systems in southern Québec (Minea and Majorowicz, 2012).

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