CHARACTERIZATION OF GEOTHERMAL RESERVOIR UNITS IN NORTHWESTERN ALBERTA BY 3D STRUCTURAL GEOLOGICAL MODELLING AND ROCK PROPERTY MAPPING BASED ON 2D SEISMIC AND WELL DATA

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ABSTRACT

Foreland basins such as the Western Canada Sedimentary Basin (WCSB) host a variety of geoenery resources. Often, the focus is on hydrocarbon resources but in times of discussions about climate change and environmental aspects, additional green energy resources are under examination. This study explores Paleozoic formations in the north western WCSB with regard to their usability as geothermal reservoirs. The study focuses on an area around Peace River in north - western Alberta. This research site covers an area of approx. 90 km * 70 km with a basin depth of 1.7 km to 2.4 km. Potential geothermal reservoir units are the siliciclastic Granite Wash unit, unconformably overlying the Precambrian basement, the Gilwood Sandstone member and Devonian carbonate units.

A regional 3D lithostratigraphic model of the study area is developed based on well log data from about 1000 wells. Structures are interpreted from seven seismic lines with a total length of about 177 km and will be integrated into the model. This model enables us to quantify the subsurface conditions and to analyse the orientation of faults. Porosity and permeability of the Paleozoic formations is derived from data from about 10,000 core analyses and mapped with geostatistical methods to detect positive porosity and permeability domains. Formation temperatures within the Paleozoic strata are estimated by a newly calculated geothermal gradient and the reservoir depth range derived from the 3D model.

The siliciclastic Granite Wash unit is presumable the most suitable horizon for geothermal development. In the south-western part of the study area its temperature is above 70 °C and the effective porosity is estimated with 10 % to 15 %.

Geothermal heat could play a role as energy source for district heating. In energy intensive in-situ oil sands extraction processes geothermal heat could be used for preheating of water for steam production. This would lower the amount of natural gas used in oil sands production and reduce climate gas emissions.

INTRODUCTION

The Western Canada Sedimentary Basin (WCSB) as foreland basin of the Rocky Mountains is known for its resources of oil, gas and coal. Due to its characteristic flexure of the foreland lithosphere this basin type deepens significantly towards the orogenic belt. These foreland deeps host potentially sedimentary layers with hot fluids and structurally or facies controlled high permeability domains. Bachu (1995) has pointed out that large convection cells dominate the hydrogeologic regime in such basin geometry with fluid flow from the hot deeper to shallower parts of the basin. Effectively, foreland basins form excellent geothermal systems with potential resources even in shallower parts. Although exploitation is focused on hydrocarbons in Alberta, recently renewed efforts to develop renewable energy technologies as part of Alberta’s future energy plan has rekindled interest in Alberta’s geothermal energy potential (Majorowicz and Moore 2008; Bell and Weis 2009; Grasby et al. 2011; Weides et al. in press). With an average geothermal gradient of 25 °C/km to 35°C/km and a heat flow of 50 mW/m² to 70 mW/m², Alberta has been characterized as a low enthalpy region.
considering Alberta’s climatic conditions with long cold winters (average annual temperature in Edmonton is 2.4 °C, average temperature in January is -13.5 °C; from National Climate Data and Information Archive 2000) its demand for geothermal energy would likely be focused on heat provision rather than electricity production (Grasby et al. 2011). Geothermal energy could play a role as an energy source for district heating and/or in replacing some fossil-fuel generated heat energy used within industrial processes. A possible industrial application for the production of geothermal heat is the provision of warm water for rapidly growing oil sands industry. Oil sands production is both energy and water intensive, as large quantities of warm or hot water are used to separate oil from sand. This energy is commonly provided by the burning of natural gas. In the deeper basin of north western Alberta, oil sands are produced with in-situ methods such as Cyclic Steam Stimulation. Geothermal heat produced from deep aquifer systems could be used for preheating of water in steam production and help to reduce the amount of fossil fuels used in the oil sands extraction.

For a successful utilization of the geothermal resource in this area the development of Enhanced Geothermal Systems (EGS) is required. The concept of EGS emphasises an integration of engineering and geosciences, aiming to adapt subsurface conditions to surface technology (Huenges 2010). Only with help of an integrated geothermal exploration concept the resource can be exploited efficiently.

**Heat demand**

The province of Alberta has a high demand for heat that currently is mainly provided by the utilization of fossil fuels. The major part of this heat is used in industrial processes and for space heating of residential, commercial and institutional buildings. The largest energy consumer in Alberta’s industrial sector is the rapidly growing heavy and bituminous oil recovery industry with a share of 65.5 % of Alberta’s total industrial energy consumption (727.6 PJ in 2009, increase of 273 % from 1990; (Natural Resources Canada 2009). A large part of this energy is used in oil sands mining extraction processes where heated water is used to separate highly viscous bitumen from the host sediments. In oil sands in situ extraction as it is practiced in the study area, steam is produced at temperatures ranging from 250 °C in Steam Assisted Gravity Drainage (SAGD) to 300 °C – 340 °C in Cyclic Steam Stimulation (Ko and Donahue 2011). Most of the heat consumed by the mining industry is provided by natural gas (398.2 PJ in 2009, increase of 773 % from 1990; National Resources Canada, 2009), which has led to a concomitant increase in greenhouse gas emissions (GHG). In 2009, 41.9 Mt of CO₂ were emitted from the oil sands industry which represents 37.1% of GHG emissions of the Alberta’s industrial sector (Government of Alberta 2011) or almost 18 % of Alberta’s total emissions (Environment Canada 2011).

Geothermal energy has the potential to decrease Alberta’s fossil fuel consumption and its related GHG emissions. A standard geothermal doublet system that produces a modest 40 °C temperature gain at a flow rate of 15 l/sec would have a thermal energy of 2.5 MWth and produce 72 TJ per year for 8000 full load hours. 300 of these standard geothermal doublet systems would produce 21.6 PJ per year and save 1.2 Mio t of CO₂ emissions compared to burning of natural gas (IPCC 2006).

**Focus of the study**

This study is the first detailed investigation of the geological-geothermal subsurface conditions of an area in north western Alberta. It demonstrates the specific exploration methods that can be applied in a situation where a large amount of geological and geophysical data is publicly available and has to be re-evaluated and re-interpreted for geothermal exploration. The area of investigation, approx. 90 km x 70 km in size, is located to the east of the town of Peace River (Figure 1).

Figure 1: Study area with oil sands distribution (modified from Creaney et al, 1994); size of the study area is about 70*90 km; basin depth is ranging from 1.7 km to 2.4 km.

In this area, the thickness of the sedimentary succession of the WCSB from ground surface to the top of the
Precambrian crystalline basement is between 1.7 km and 3.5 km. The aim of geothermal exploration is to delineate potential geothermal reservoirs and to describe the distribution of relevant rock parameters that are necessary to quantify the producible geothermal energy in place. Most important parameters are porosity, permeability, reservoir rock thickness and temperature to estimate flow rate and temperature gain.

A 3D structural geological model is developed based on 2D seismic data and stratigraphic information from the database of the Alberta Geological Survey (AGS). This model enables the investigation of geological structures such as faults and the analysis of geometry, spatial distribution and thickness of the deep formations. Porosity and permeability of the formations are investigated with the help of core analysis data from the Alberta general well data file. The spatial distribution of these parameters is analysed through geostatistical methods. An estimation of temperature in the subsurface is given based on a geothermal gradient analysis for the Paleozoic formations analysed in the 3D modeling study.

This paper presents the status quo of the on-going study.

GEOLOGICAL SETTING

Western Canada Sedimentary Basin
The WCSB consists of a north-eastward tapering sedimentary wedge that unconformably overlies the Precambrian crystalline basement. The sedimentary succession reaches a thickness of over 5 km close to the Rocky Mountains in the southwest and thins towards the northeast, where it is terminated by erosion or non-deposition.

Peace River Arch region
The Peace River Arch region (PRA) is a roughly east-northeast-striking zone in the northwestern WCSB, in which a long history of tectonic activity has been recorded. It represents one of the few large-scale tectonic elements in the WCSB that has significantly disturbed the Phanerozoic cover of the craton (O’Connell 1994). The history the PRA can be divided into three phases that resulted in three main structural manifestations (O’Connell 1994): a) a late Proterozoic to early Paleozoic arch b) a late Paleozoic to earliest Mesozoic Embayment, and c) a zone of enhanced subsidence of the Mesozoic foreland basin.

Potential geothermal reservoirs
The aim of this study is to investigate the Paleozoic sedimentary strata and assess their usability for geothermal applications. Seven lithostratigraphic units form the major aquifer systems in the study area: The siliciclastic Granite Wash unit, the Gilwood Sandstone member, the carbonates of the Slave Point-, Swan Hills-, Leduc- and Nisku formations, and the Wabamun Group. This paper focuses on the properties of the Granite Wash unit.

Granite Wash unit
The Granite Wash is diachronous, siliciclastic, lithostratigraphic unit that overlies the arch (O’Conell 1994). The unit consists of reworked material of the predominantly granitic and metasedimentary rocks of the uplifted basement. Sandstone and conglomeratic sandstone are dominant, and the composition varies from arkosic to arenitic (Trotter 1990). The ages of Granite Wash sediments are unknown except for where they interfinger with Middle and Upper Devonian strata arch (O’Conell 1994).

Gilwood sandstone member
Reworked sandy deposits around the Peace River Highland in a nearshore, deltaic and lagoonal sediment of the Gilwood Member (Jansa and Fischbuch 1974)

Devonian carbonates
Five Devonian carbonate formations are investigated for their potential to be utilized as geothermal reservoirs. These are the platform carbonates of the Slave Point Formation (Beaverhill Lake Group), Nisku Formation and Wabamun Group, and the reefal buildups of the Swan Hills Formation (Beaverhill Lake Group) and Leduc Formation.

3D GEOLOGICAL MODELING STUDY
A 3D geological model (Figure 2) is developed based on 2D seismic data and stratigraphic information from well logs from the AGS database.

Lithostratigraphic model
The stratigraphic horizons are mainly modelled based on stratigraphic tops from about 1000 wells. A few stratigraphic tops were identified as outliers and have been removed from the dataset. The model consists of 15 different geological units, of which 8 are from the Paleozoic succession. Figure 2 shows a preliminary 3D lithostratigraphic model.

The 3D lithostratigraphic model enables the analysis of geometry, spatial distribution and thickness of the deep formations.
Thickness of the Granite Wash unit

The distribution of thickness of the Granite Wash unit was mapped using stratigraphic tops from 368 wells using the Sequential Gaussian Simulation (SGS) algorithm (Figure 3). SGS is a widely used algorithm for modeling reservoir properties. It involves estimating conditional distributions for a set of points and conditioning data. For Gaussian random fields, conditional distributions are given by simple kriging and used to generate Gaussian random models. SGS is typically used to generate a set of realizations that reproduce input distribution functions, heterogeneity, and the variogram (Deutsch 2002; Manchuk and Deutsch 2012).

The average thickness of the Granite Wash unit in the study area is 9.4 m. In the eastern part the thickness of the Granite Wash unit ranges from 1 m to 10 m, with a zone of higher thickness up to 15 m in the central east. Towards the west and southwest the thickness increases and ranges from 10 m to 25 m. A positive anomaly zone exists in the northwestern part of the study area where thickness ranges up to 29 m. However, this positive anomaly is based on data from only 2 wells. Earlier studies described no occurrence of the Granite Wash unit in the northwestern part of the study area.

Structural information from seismic data

Knowledge of geological structures is important in geothermal exploration, as faults and fractures are potential fluid pathways. In this study structures are interpreted from 7 seismic lines with a total length of 177 km and will be integrated into the 3D model. Figure 4 shows an overview of the seismic data and highlights the E-W trending line 6-A7H61 in the southwest. This line crosses the NW-SE trending Carboniferous “Tangent” normal fault (Richards et al. 1994). Brittle faulting of basement and Paleozoic units is observed.
**Porosity and Permeability Analysis of Paleozoic Formations**

The parameterization of reservoir rocks plays a major role in EGS exploration. Porosity is the main parameter to detect zones within a rock formation that potentially contain warm fluids in quantities large enough to be utilized for geothermal heat production. Permeability of the formation controls the flow in the reservoir and hence directly influences well positioning and production rate of a geothermal system.

**Data set**

For this study, porosity and permeability of the Paleozoic formations is investigated by utilizing core analysis data from the Alberta general well data file. In total, information from about 10,000 Paleozoic rock samples (plugs) from more than 245 wells is used in this study. Porosity and maximum (horizontal) permeability ($K_{\text{max}}$) were assessed for each of the formations that appeared to have favourable geothermal conditions. The porosity and permeability values obtained from core analyses represent volume-averaged values corresponding to the sample size. In general, they represent matrix properties and not larger scale features such as fractures or vugs.

**Upscaling of core analysis data**

Individual results from core analyses are only representative on the cm-scale and porosity and permeability of rocks may vary within short distances both vertically and laterally. Given the variations at a small scale and the inherent heterogeneity of sedimentary rocks, data trends can still be identified at a larger scale. To investigate regional-scale (km-scale) trends in the data, a scaling-up process must be applied to the small-scale core analysis data (Bachu and Underschultz 1992). Since there are several orders of magnitude between the plug scale and the regional scale, a sequential approach should be used by which the values of the parameter of interest are successively scaled up (Cushman 1984). Therefore, the plug-scale values were scaled up first to well scale, and then the well scale values were scaled up to average values representing the regional scale. As variation of permeability of consolidated sediments is best characterized by a lognormal frequency distribution (Dagan 1989), the geometric average of the plug-scale maximum permeability values was calculated to estimate a representative value at the well scale, following an approach of Bachu and Underschultz (1992). Local-scale porosity may be described by a normal probability density function and has a much smaller variance (Dagan 1989). The porosity value at the well scale in each formation is given by the arithmetic average of the plug-scale values of the sampled interval. Up-scaling to regional-scale values was conducted by calculation of the geometric average of the well-scale values (Table 1).

**Porosity and permeability variation**

The highest regional scale porosity is found in the Swan Hills Formation at 10.1% (based on only two regional scale values; Table 1). Regional scale porosity of the other Paleozoic formations in the study area can be classified as negligible (0% - 5%; classification after Levorsen 1967; Wabamun, Nisku, Leduc and Swan Hills formations) to poor (5% - 10%; Granite Wash unit). However, maximum well – scale porosities of the latter two units (Slave Point Formation and Granite Wash unit) are good (15% - 20%).

Regional scale permeabilities range from fair ($1 \times 10^{-15} \text{ m}^2$) to $10 \times 10^{-15} \text{ m}^2$; Leduc and Slave Point formations, Granite Wash unit) to good ($10 \times 10^{-15} \text{ m}^2$ to $100 \times 10^{-15} \text{ m}^2$; Swan Hills and Nisku formations, both based on only few well scale values). Maximum well scale permeabilities of all formations (except for Swan Hills Formation) exceed $100 \times 10^{-15} \text{ m}^2$ and are classified as very good.

**Table 1:** Well-scale porosity and permeability of Paleozoic formations from core analysis data

<table>
<thead>
<tr>
<th>Formation</th>
<th>No. of well scale values</th>
<th>Porosity</th>
<th>Max. horizontal permeability (x $10^{-15} \text{ m}^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Average (geometric)</td>
<td>Minimum</td>
</tr>
<tr>
<td>Wabamun</td>
<td>105</td>
<td>1.9%</td>
<td>0.4%</td>
</tr>
<tr>
<td>Nisku</td>
<td>3</td>
<td>4.0%</td>
<td>1.5%</td>
</tr>
<tr>
<td>Leduc</td>
<td>14</td>
<td>3.4%</td>
<td>1.2%</td>
</tr>
<tr>
<td>Swan Hills</td>
<td>2</td>
<td>10.1%</td>
<td>9.4%</td>
</tr>
<tr>
<td>Slave Point</td>
<td>63</td>
<td>4.6%</td>
<td>0.3%</td>
</tr>
<tr>
<td>Granite Wash unit</td>
<td>34</td>
<td>7.8%</td>
<td>1.5%</td>
</tr>
</tbody>
</table>
For the Gilwood Sandstone member no data is available for the study area.

**Regional distribution of porosity and permeability**

Positive porosity and permeability domains in sediments are controlled by facies, diagenesis and structural inventory. With geostatistical methods it is possible to analyze the distribution porosity and permeability and detect zones where these properties are elevated. In this study porosity and permeability are mapped with upscaled core analysis data (i.e. well-scale) values using the Sequential Gaussian Simulation algorithm. Figure 5 shows the distribution of well-scale porosity in the Granite Wash unit. In the southeast and southwest two regions with porosities larger 10% exist. Porosity in the northeastern part of the study area is rather low, ranging from 3% to 7% on average. For the central and northwestern part of the study area not data is available.

The distribution of maximum horizontal permeability ($K_{max}$) is shown in Figure 6. The highest permeability is found in the southeastern part of the study area. A zone of elevated permeability exists in the southwest. In the northeast the permeability is low.

**SUBSURFACE TEMPERATURES**

Knowledge of subsurface fluid temperatures is important in geothermal exploration. Recent work on the thermal field in Alberta was done by Gray et al. (2012) and Majorowicz et al. (2012 a,b) and covered most of central and northern Alberta. The thermal field studies are based on an extensive data base, which included data from bottom hole temperature measurements (BHT), temperatures taken during drill stem tests (DST) and data from annual pressure and temperature (P/T) tests. A paleoclimatic correction was applied to the data (see Majorowicz et al. 2012a). 576 temperature values from this data base were extracted for this study and statistically approximated resulting in a geothermal gradient of 33.0 °C/km (Figure 7; standard deviation is 4 °C/km). This rather high geothermal gradient considering we are in the basin formed on top of old Precambrian craton is largely due to thermal blanketing effect of very low effective thermal conductivity of the Phanerozoic sediments (from the surface to the Precambrian basement) which is assessed to be 1.6 W/m K - 1.8 W/m K (+/- 0.2 W/m K). This is low in the context of thermal conductivity spatial variations in the Alberta basin which are (1.5 W/m K - 2.3 W/m K). Heat flow in the study area is generally within the bounds of 50 mW/m² to 60 mW/m².

As mean ground temperature, which is needed to calculate temperature at depth from the known geothermal gradient, we estimate 0 °C.

**Figure 5**: Porosity distribution in the Granite Wash unit. Porosity is estimated based on upscaled core analysis data and mapped using Sequential Gaussian Simulation method. For the Central and Northwestern part no data was available. The map shows an average of 100 realizations.

**Figure 6**: Distribution of maximum horizontal permeability ($K_{max}$) in the Granite Wash unit. Estimates of $K_{max}$ are based on upscaled core analysis data and mapped using Sequential Gaussian Simulation method. For the Central and Northwestern part no data was available. The map shows an average of 100 realizations.

**Figure 7**: Variation of corrected temperature data vs. depth for wells in the study area.
Figure 8: Estimated temperature at the bottom of the Granite Wash unit. Temperature was calculated using an average geothermal gradient for the Phanerozoic succession of 33 °C/km.

While present surface temperature is some 4 °C higher we know that that deep sediments thermal field is still in equilibrium with sub-glacial temperature of 0 °C +/- 1 °C (see Majorowicz et al. 2012a for the discussion of equilibrium conditions in the postglacial environment this study area is in).

With these values - the mean ground temperature and the average geothermal gradient – in combination with depth of stratigraphic units from well data, the temperatures at the top of the units can be calculated. Figure 8 shows the estimated temperature at the bottom of the Granite Wash unit.

**CONCLUSION**

Due to its depth and its distribution throughout the whole study area, the Granite Wash unit appears to be the best suitable horizon for a geothermal development north western Alberta. Temperatures above 70 °C are found in the south western corner of the study area. Here, thickness of the Granite Wash unit is ranging from 15 m to 30 m, and porosity is estimated 10 % to 15 %.

A standard geothermal doublet system that produces a 50 °C temperature gain at a flow rate of 10 l/sec would have a thermal energy of 2.1 MWth and save about 3700 tons of CO₂ emissions compared to burning of natural gas.

Potentially existing non-productive wells could be used for production of geothermal fluids.

To economically exploit hydrothermal systems EGS technologies like massive stimulation would be necessary to increase flow rates.

**OUTLOOK**

Information on faults and structures from the 2D seismic will be integrated into the regional model. Stress state and reactivation potential of faults will be analysed with the slip tendency method. The fault reactivation potential is an important measure for the likelihood of induced seismicity which could occur during massive stimulation.

Porosity and permeability of other potential geothermal formations will be analysed using geostatistical methods.

For a more detailed assessment of the geothermal potential of the Granite Wash unit further exploration is necessary, including thin section analysis and geomechanical testing on available drill cores.

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**REFERENCES**


