# Geothermal assessment of the Upper Devonian carbonate aquifer systems in the Alberta Basin, Canada

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## Summary

Alberta's energy demand is predominantly covered by coal, oil, and gas. Recently, there has been an increased interest in transitioning to a greener energy mix by substituting at least some fossil fuels with geothermal energy to reduce $CO_2$ emissions. Based on temperature data from several tens of thousands of oil and gas wells, the Upper Devonian carbonate aquifer systems within the Alberta Basin are promising target formations for geothermal heat production and in some locations also for power production (Weides and Majorowicz, 2014, Nieuwenhuis et al., 2015). The Upper Devonian reef complexes are well known oil and gas reservoirs and have been extensively investigated by the oil and gas industry with more than 200000 drill holes over the past seven decades (Machel, 2010). However, relatively little is known about their potential for geothermal energy utilization in the Alberta Basin. For a profound reservoir assessment, detailed knowledge of the thermo- and petrophysical rock properties is needed as well as the analysis of available reservoir data retrieved from drill holes.

This paper briefly reports the results obtained in the first phase of the MalVonian project (Sass et al., 2021), which forms the basis for a more reliable geothermal assessment and reservoir modeling. Specific targets selected for this study are the Leduc Formation from the Southesk-Cairn Carbonate Complex (SCCC) and the Rimbey-Meadowbrook Reef Trend (RMRT) as well as the overlying Nisku Formation. The Leduc Formation in the Alberta Basin comprises up to 260 m thick, intensively dolomitized reef buildups developed on the approximately 75 m thick Cooking-Lake platform and is separated by basin-filling shales from the overlying, much thinner Nisku Formation (~ 80 m thick; Switzer et al., 1994). Wellbore core samples from the Leduc and Nisku Formations were analyzed for thermal conductivity, thermal diffusivity, and heat capacity as well as density, porosity, and permeability (Weydt et al., 2018, 2021). Our dataset is complemented by open-file core and reservoir data retrieved from the AccuMap database for the mapping of reservoir temperature, TDS, sour gases and petrophysical core data (density, porosity and permeability) in the deepest and hottest parts of the southwestern RMRT. A preliminary 3D geological model of the Nisku and Leduc aquifers was created for a volumetric heat analysis to enable estimations of the potential for heat supply or power production.

## Workflow and Methods

To create a comprehensive database of thermo- and petrophysical rock properties, ten wellbore cores of the target reservoir formations were investigated in the Calgary Research Centre (CRC) and at the University of Alberta core lab in Edmonton. The wells, which were selected for investigating the Leduc Formation, are located in the central portion of the Alberta Basin between 1800 and 2700 m below ground level (bgl) and at about 4 km depth close to the Rocky Mountains representing the deepest sections of the reservoir. Additionally, three cores of the Nisku Formation were examined, which comprise the Lobstick, Bigoray, Zeta Lake and Dismal Creek

Member. These cores represent the reef, bank-edge reef, and bank of the Nisku Reef Trend (Brazeau area) located in the central part of the Alberta Basin. More than 400 core samples with a sample length ranging between 5 cm and 70 cm have been analyzed for apparent permeability, thermal conductivity, and thermal diffusivity. For closer examination, thin sections made from representative samples were prepared and petrographically analyzed. Additional sample material was analyzed for particle and bulk density, porosity, intrinsic matrix permeability as well as specific heat capacity at the Technische Universität Darmstadt.

Particle density, bulk density, and porosity were determined using an AccuPyc 1330 helium pycnometer and a GeoPyc 1360 powder pycnometer after Micromeritmics (1997 and 1998). Apparent and intrinsic matrix permeability were obtained by using a combined mini and column permeameter after Hornung and Aigner (2004). For the determination of thermal conductivity and thermal diffusivity a thermal conductivity scanner after Popov et al. (2016) was used. Specific heat capacity was determined using a heat-flux differential scanning calorimeter (Setaram Instrumentation, 2009), whereby samples were heated at a steady rate from 20 up to 200 °C within a period of 24 h.

For assessing the reservoir and constructing a preliminary 3D geological model of the western part of the RMRT (Fig. 1a), selected input parameters like petrophysical core data (particle density, permeability, and porosity), reservoir temperature, TDS, and data on sour gases ($H_2S$, $N_2$, $CO_2$) from the AccuMap database were used. Furthermore, well information such as measured depth (MD), true vertical depth subsea (TVDSS), coordinates, and elevation of the kelly bushing (KB) was used for importing well locations and paths into GOCAD/SKUA. The original database for this specific part of the basin included 813 petroleum well logs from 1950-2015 with more than 42,000 data entries of interest in this study - only considering the Leduc and Nisku formations. As this data set was compiled from various operations over many decades resulting in inconsistent quality of the data, several quality control steps and comprehensive data filtering was required. As a first quantification of the geothermal potential of the Leduc and Nisku formations, a volumetric heat-in-place calculation after Muffler and Cataldi (1978) was carried out using the results of the petrophysical characterization. Afterwards, a typical recovery factor of low-enthalpy hydrothermal systems operated by binary power plants was applied to determine the usable amount of energy for different production methods as described in Paschen et al. (2003).

## Results

The investigated core samples of the Leduc Formation mainly comprise intensively dolomitized stromatoporoid- and coral-rich reefs and reef margin lithologies with dissolution enlarged vugs and molds. They consist of dark grey to light grey, medium- to coarse-crystalline skeletal wackestones to floatstones and rudstones as well as to a lesser extend Amphipora grainstones. Within the deepest sections of the RMRT close to the fold and thrust belt (at ca.4300 m bgl), partially dolomitized to completely dolomitized permeable zones occur with interbedded nonporous limestones. The investigated Nisku cores show a high geological heterogeneity including dark grey fine-crystalline argillaceous limestones (Lobstick Member), coarse-crystalline dolomitized mud with limestone breccias (Bigoray Member), fully dolomitized reef lithologies with moldic floatstones and rudstones (Zeta Lake Member) as well as fine-crystalline dolomudstones (Zeta Lake and Dismal Creek Member). Particle density of the dolostones ranges from 2.80 to 2.87 g $cm^{-3}$, while the limestones show particle densities between 2.65 and 2.75 g $cm^{-3}$. Matrix porosity and permeability are quite variable ranging from less than 1% up to 23% and from $10^{-17}$ up to $10^{-12}$ $m^2$, respectively. Even though originating from greater depth (approx. 4100 m bgl), the rocks of the western Leduc Formation exhibit a significantly higher porosity in comparison to samples of the Leduc Formation from the central basin (at 2700 m bgl). Thermal conductivity of the reservoir samples varies between 2.4 W m$^{-1}$K$^{-1}$ and 5.5 W m$^{-1}$K$^{-1}$ with no significant difference between the Leduc Formation of the RMRT and the SCCC. Within the Nisku Formation, the argillaceous limestones of the Lobstick Member show the lowest thermal conductivity, while the thermal conductivity of the dolomitized Zeta Lake Member is within the range of the Leduc Formation.

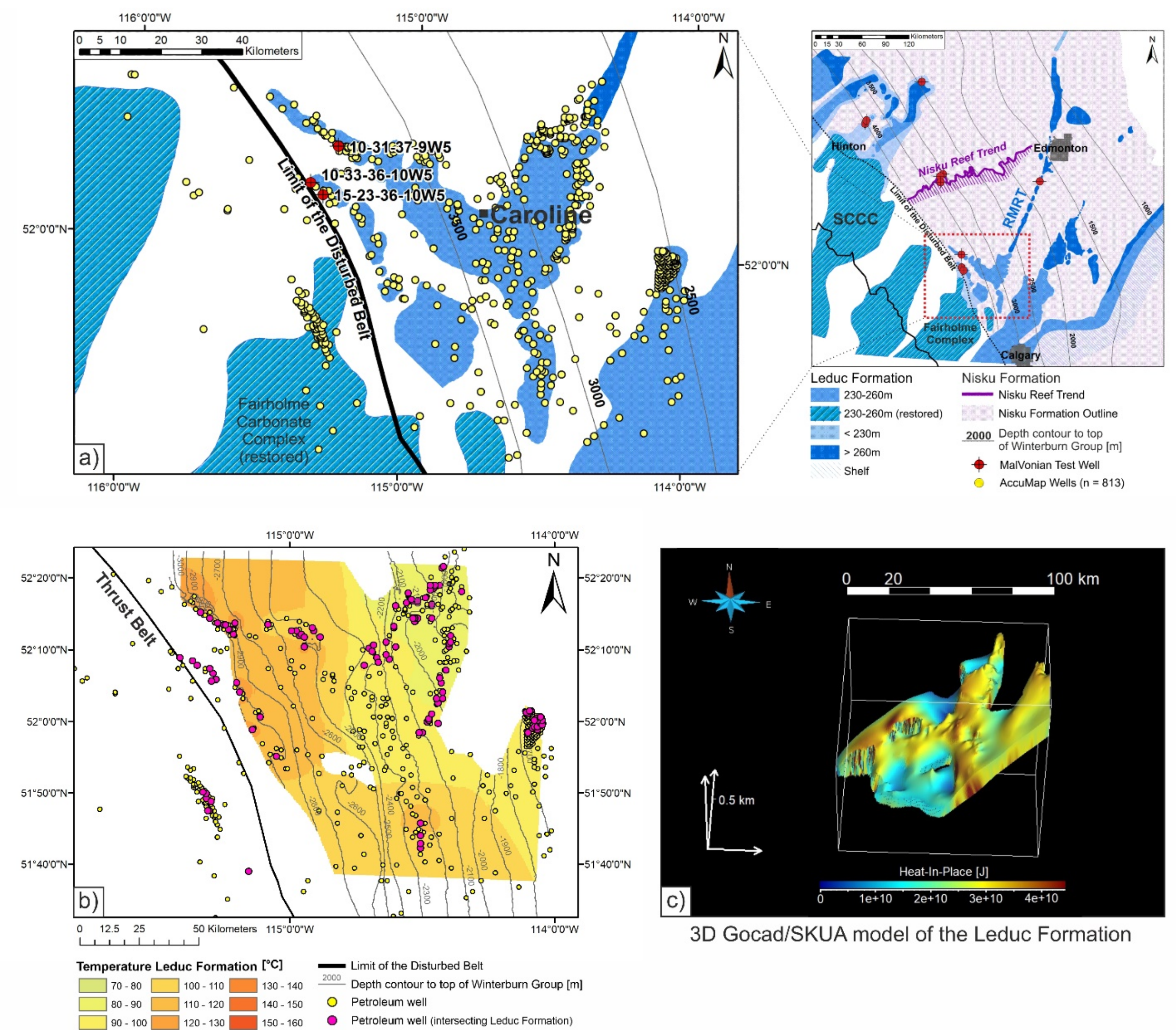


*Figure 1: a) Spatial distribution of the wells (yellow dots) used for reservoir assessment and modeling of the southwestern part of the RMRT. Formation outline (blue) after Switzer et al. (1994). b) Temperature distribution and c) volumetric heat-in-place calculation of the Leduc Formation.*

Assessing the reservoir data of the western part of the RMRT retrieved from the AccuMap database revealed reservoir temperatures of the Nisku and Leduc formations ranging from ~70 °C in the north-eastern part to ~130 °C close to the thrust belt (Fig. 1b). Similar to the results of the core analysis, particle density is mainly constant with values of approximately 2.83 g $cm^{-3}$. Locally, a lower particle density of approximately 2.7 g $cm^{-3}$ was observed, which most likely represents less dolomitized reef sections. Porosity and permeability in both formations showed a large amount of variation ranging from 0.1% to up to ~ 29% and from $10^{-17}$ up to $10^{-10}$ m², respectively. Average porosity ranges from 4.4% up to 5.5% depending on the formation. Generally, porosity appears independent of reservoir depth confirming the observations of the analysed reservoir cores. Both porosity and permeability of the Leduc Formation follow the same trend and increase with depth in the north-western portion towards the disturbed belt.

The Heat-In-Place calculation (Fig. 1c) is based on the volume of the stratigraphic grids of the 3D geological model and results in ~27.59 PJ ($E_{th}$) for the evaluated part of the Leduc Formation and 10.61 PJ for the Nisku Formation (whose surface area is equivalent to approximately 1% of Alberta). In 2016, the residential space and water heating demand of Alberta was estimated as ~148 PJ (Natural Resources Canada, 2019). Taking recovery factors for different production types into account (Paschen et al., 2003), the useable amount of energy is much lower, but still covers up to 6.7% of Alberta's residential heating demand depending on the production type. However, the target formations contain sour gases and saline brines with TDS contents of up to 300 g $L^{-1}$, which could be a limiting factor for geothermal utilization and need to be considered during risk assessment.

## Conclusions and Outlook

The petrophysical characterization of well cores and a preliminary 2D and 3D assessment of selected formation properties of the western part of the RMRT confirm the findings from previous studies (Weides and Majorowicz, 2014), suggesting that the Upper Devonian carbonates are worth investigating as geothermal reservoirs. The obtained reservoir temperatures range between 70 °C and 130 °C and thus indicate application for heat production or combined heat and power production with binary power plants. Porosity and permeability show a wide range and are quite variable throughout the study area. The most promising target reservoirs for geothermal utilization are the completely dolomitized reef sections with a matrix permeability of up to $10^{-10}$ m² and a thermal conductivity of up to 5 W $m^{-1}K^{-1}$. According to Sass and Götz (2012), permeabilities ranging from $10^{-15}$ to $10^{-10}$ m² are categorized as low permeable to permeable 'transitional systems'. It implies that stimulation is needed for economic and technical reasons and hence, the carbonates can be categorized as Enhanced Geothermal System. Therefore, upcoming studies will focus on the rock mechanical properties of the Upper Devonian carbonates.

Reservoir data retrieved from the AccuMap database require time intensive processing and several quality control steps. However, the data yield low cost and practicable results providing an initial overview of the formations' properties and their heterogeneity in the study area. To improve the preliminary 3D geological model and the reservoir assessment, future work should focus on improving these data sets (through close cooperation with the oil and gas industry) and digitizing further (old) data sheets, e.g., geophysical logs. Furthermore, the analysis of hydraulic test data of these wells might provide a better evaluation of the actual hydraulic properties compared to the matrix permeability measured on core samples. Likewise, temperature logs would be helpful to validate the observed reservoir temperatures. Finally, a fundamental knowledge of the fluid chemistry, fluid-rock interactions and the possible economic impact during geothermal production is required.

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