Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Geothermal Assessment of Two Regionally Extensive Upper Devonian Carbonate Aquifers in Alberta, Canada

Leandra M. Weydt[1], Gillian Wilson[1], Kristian Bär[1], Claus-Dieter J. Heldmann[1], Hans G. Machel[2], Ingo Sass[1,3]

[1]Department of Geothermal Science and Technology, Technische Universität Darmstadt, Schnittspahnstraße 9, 64287 Darmstadt, Germany

[2]Earth and Atmospheric Sciences, University of Alberta, Edmonton, AB T6G 2E3, Canada

[3]Darmstadt Graduate School of Excellence Energy Science and Engineering, Otto-Berndt-Straße 3, 64287 Darmstadt, Germany

weydt@geo.tu-darmstadt.de

Keywords: petrophysical rock properties, reservoir characterization, reservoir modeling, EGS, Nisku Formation, Leduc Formation

ABSTRACT

The Canadian province of Alberta has the highest per capita CO_2-equivalent emissions in Canada, predominantly due to the industrial burning of coal for the generation of electricity and mining operations in the oil sand deposits. The use of Alberta's geothermal potential could reduce CO_2 emissions significantly by substituting at least some fossil fuels.

Relatively little is known about the potential for geothermal energy utilization in Alberta despite of a number of geothermal studies conducted over several decades. To assess the geothermal reservoir potential, detailed knowledge of the thermo- and petrophysical rock properties is needed. We conducted an analogue study that compared a number of rock properties from the Devonian Southesk-Cairn Carbonate Complex and of the Rimbey-Meadowbrook Reef Trend with selected outcrop samples from stratigraphically correlative outcrops in the Rocky Mountains. Samples from the Leduc and Nisku formations were analyzed for thermal conductivity, thermal diffusivity and heat capacity, as well as density, porosity and permeability. Our data suggest that the extensively dolomitized and highly fractured reef zones with permeabilities of up to 10^{-12} m^2 and thermal conductivities of higher than 4 W m^{-1} K^{-1} are promising reservoirs for geothermal utilization.

Our dataset is complemented by open-file core and reservoir data retrieved from the AccuMap data base for mapping of reservoir temperature, TDS, sour gases (H_2S, CO_2, N_2) and petrophysical core data (density, porosity and permeability). A preliminary 3D geological model of the Nisku and Leduc aquifers in the western part of the Rimbey-Meadowbrook reef trend was created with GOCAD/SKUA to determine the potential for geothermal utilization on a local scale (e g. on the scale of a few townships). Preliminary findings confirm those from previous studies that the Upper Devonian carbonate aquifers are worth investigating as geothermal reservoirs.

1. INTRODUCTION

Canada currently emits approximately 715 Mt a^{-1} CO_2-equivalent, of which the Province of Alberta emits nearly 270 Mt a^{-1} (Environment Canada, 2019, last reliable numbers for 2017). Thus, Alberta has the highest emission rates. The main reason for this situation is the industrial generation of energy (electricity and heat) from coal and gas, along with the huge mining operations of the oil sands deposits. However, the amounts and trend of increasing CO_2-emissions could be significantly reduced if alternative and/or renewable energy sources were implemented to a larger degree. For Canada to approach the targets of the Paris Accord from 2015 regarding the reduction of CO_2-emissions, geothermal energy should become part of the energy mix, especially in Alberta. Although this province is characterized as a 'low enthalpy region' (Grasby et al., 2012; Jones et al., 1985, Lam and Jones, 1985 and 1986) with a moderate average geothermal gradient of 33.2 °C km^{-1} and an average heat flow of 60.4 W m^{-2} in the Western Canadian Sedimentary Basin (WCSB), recent studies using data from several tens of thousands of oil and gas wells suggest that at least some of the Upper Devonian carbonate aquifers are suitable for geothermal utilization (Weides and Majorowicz, 2014; Hofmann et al., 2014).

The area around the town site of Hinton in the western region of the Alberta Basin (Fig. 1) is of particular interest because well data analysis indicates flow rates of more than 400 m³ h^{-1} and temperatures up to 150 °C at depths of approximately 5 km (Lam and Jones, 1985). While such conditions suggest a reasonable to good potential for geothermal utilization, previous studies provided very few hard data on the geothermal reservoir properties of the rocks in this area (e.g. Weides and Majorowicz, 2014; Weides et al., 2013; Nieuwenhuis et al., 2015; Ardakani and Schmitt, 2016). However, an extensive data base on parameters such as porosity, permeability, thermal conductivity, and others, is necessary for a geothermal assessment, especially with complete parameter sets for every single sample (Clauser, 2006; Bär et al., 2011; Sass and Götz, 2012; Homuth et al., 2015).

This paper represents parts of "Project MalVonian", which attempts to compare the potential for geothermal utilization of the Malm aquifer in the German Molasse Basin with that of the Devonian aquifers in the Rocky Mountain foreland basin in Alberta, in collaboration of the University of Darmstadt and the University of Alberta. Our study is focused on the assessment of the geothermal potential of three Upper Devonian Carbonate aquifer systems within the Alberta Basin, which are the Southesk-Cairn Carbonate Complex (SCCC), the Rimbey-Meadowbrook Reef Trend (RMRT), both comprised of rocks from the Leduc and Nisku formations, and the overlying Nisku Reef Trend (Nisku Formation) (Fig. 1). These carbonates form platforms and reefs have been exploited for oil and gas for several decades. They have formed the backbone of the Canadian petroleum industry until the oil sands in east-central Alberta came on stream on a large scale in the 1990s (Switzer et al., 1994; Machel, 2010). In the same decade some of these Devonian carbonates became the focus of interest for repurposing abandoned oil and gas wells for acid gas sequestration (e.g. Machel 2005), and more recently also for geothermal utilization (Weydt et al., 2018). Furthermore, the SCCC, RMRT, and Nisku Reef Trend were selected for this study, because the two largest cities of the province, Calgary and Edmonton, as well as several smaller cities are located very near and/or almost on top of them. Hence, geothermal facilities in these carbonates could serve well over half of the population of Alberta (approximately 2.2 million people).

Within the first phase of the MalVonian project, an outcrop analogue study was performed (Weydt et al., 2018). The working concept entails that properties of rock units in the target subsurface reservoir are compared to stratigraphically equivalent rock units in outcrops, which are considered as analogue to the subsurface target. Such analogue studies offer a cost-effective opportunity on early exploration stages and/or in areas with a low density of drill holes, in order to investigate and correlate facies, diagenetic, petrophysical and thermophysical properties from outcrops to the subsurface. Using such a data base, a thermofacies classification (Sass and Götz, 2012) enables the identification of heterogeneities and production zones and also includes detailed analyses of the lithologies and their thermophysical properties on different scales (1. macroscale = outcrops, 2. mesoscale = samples, 3. microscale = thin sections). This working concept has already been applied successfully to the Malm Formation in the German Molasse Basin (Homuth et al., 2015) or the Permocarboniferous in the German northern Upper Rhine Graben (Aretz et al. 2015). It allows an extrapolation of the results into the deep subsurface (within a conceptual model) and thus enables more precise reservoir modeling and rock property prediction.

Considering that rock property measurements provide only matrix properties, further assessment of well core and reservoir data provided in the AccuMap or geoScout data base (IHS Markit, 2019; GEOSCOUT, 2019) is mandatory for a reliable geothermal assessment. These data bases contain an enormous amount of data from about 600.000 drilled wells in the Alberta Basin, which was compiled by various companies during the last seven decades. However, the quality of the data was found as very variable. In particular, much of the temperature data were identified as inaccurate (Weides and Majorowicz, 2014; Nieuwenhuis et al., 2015).

In a first test phase of the Leduc and Nisku formations, reservoir temperature and petrophysical core data (particle density, porosity and permeability) were evaluated, processed and mapped for the western (and thus deepest and hottest) part of the RMRT. Additionally, risk maps were created for sour gases (CO_2, N_2, H_2S) and total dissolved solids (TDS). Based on this analysis, a preliminary 3D geological model was created with GOCAD/SKUA (Emerson, 2019), serving as a tool in assessing the geothermal potential on a local scale, i.e., the scale of a few townships (Fig. 3). Moreover, a work flow was established for processing well data for future modeling projects within the study area.

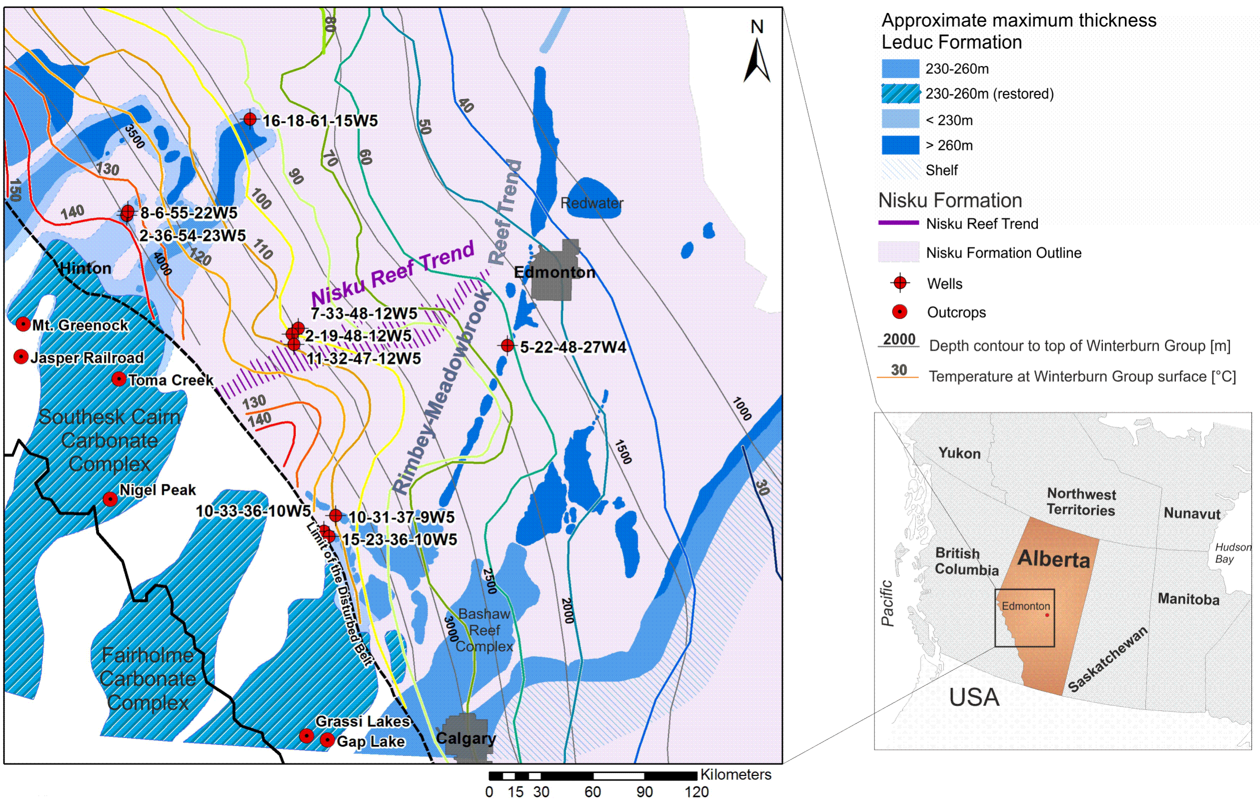

Figure 1: Spatial distribution and approximate thickness distribution of the Leduc (blue) and Nisku formations (purple) in Alberta and neighboring British Columbia. The outlines of the carbonate platforms are based on seismic (map modified from Switzer et al., 1994). The wavy colored contours indicate temperatures ranging between 40 °C (dark blue lines) and 140 °C (red lines) on top of the Winterburn Group, as calculated from data derived from more than 26400 wells (Majorowicz and Weides, 2014). The flat grey lines are depth contours marking the top of the Winterburn Group (see Fig. 2). The red points west of the limit of the disturbed belts mark the analyzed outcrops, where rock samples have been collected (see further explanation in chapter 3). The red points with a black cross represent the boreholes within the deep subsurface.

2. GEOLOGICAL FRAMEWORK

The WCSB is a large geological feature that is located mainly in Alberta east of the Rocky Mountains and in the adjacent provinces of Saskatchewan and Manitoba, as well as in the northern United States and in northeastern British Columbia (Grasby et al., 2012). The WCSB basin is divided into the Alberta Basin and the Williston Basin, the border of which roughly coincides with the Alberta-Saskatchewan border. The sedimentary evolution of the WCSB throughout the Phanerozoic was intimately related to the tectonic evolution of the region, which eventually resulted in the formation of the Rocky Mountains (Wendte, 1992; Price, 1994; Switzer et al., 1994). The size, depth, subsidence, accommodation space and uplift of the WCSB were largely caused by four orogenies, the most significant of which being the Antler orogeny during the Devonian to Carboniferous and the Laramide orogeny that lasted from the Mid-Late Cretaceous to Early Tertiary (Machel, 2010). East of the limit of the disturbed belt (Fig 1) the sedimentary layers now form a structural homocline that dips westward, whereby the Devonian strata increase in depth from zero in the east to more than 6 km near the limit of the disturbed belt in the west.

The Devonian succession was deposited on the passive margin of the ancestral North American continent under mostly subtropical, open-marine conditions. Stratigraphically the Devonian succession is subdivided into four groups, each containing a carbonate platform (hydrologically acting as aquifers), and are separated from one another by marls and shales (acting as aquitards). From top to bottom they have been numbered and named by the oil industry as D1 (Wabamun Group), D2 (Winterburn Group, with the Nisku Formation as the main carbonate platform and associated reefs), D3 (Woodbend Group, with Leduc reefs and the underlying Cooking Lake carbonate platform), and the D4 (Beaverhill Lake Group; Fig. 2). According to Rostron et al. (1997) the four aquifers form the Upper Devonian Hydrogeological Group (UDHG), which is underlain by shales and marls of the Waterways Formation and overlain by Carboniferous shales. Within the SCCC, the aquitards within the UDHG thin towards the Rocky Mountains and/or are absent in some areas, thus allowing for hydrologic connection between the four aquifers of the UDHG.

The D3 Cooking Lake Formation forms the regionally most extensive and thickest carbonate platforms of the UDHG and thus comparable to the Malm carbonate aquifer in the Bavarian Molasse Basin, and potentially the most promising candidate for geothermal exploitation in Alberta. Although somewhat variable regionally, on average the Cooling Lake Formation is about 75 m in thickness and forms the foundation for Leduc-aged reefal buildups, which are approximately 100 to 260 m thick and contain(ed) the bulk of the conventional oil in the Devonian carbonates of Alberta. These carbonates are surrounded by basin-filling shales of the Duvernay, Majeau Lake and Ireton Formations (Amthor et al., 1993 and 1994). The overlying D2 Nisku platforms are laterally much smaller than the underlying D3 platforms, and also much thinner with max. thickness of approximately 80 m. The reefal facies in the Nisku Formation is called the Zeta Lake Member (Chevron, 1979).

As is the case with most deeply buried carbonate sequences, the Devonian carbonates in Alberta underwent extensive diagenesis. Both the SCCC and the RMRT were affected by more than 20 recognizable diagenetic processes, including multiple phases of dissolution and cementation (mainly by calcite, dolomite, and anhydrite), pervasive dolomitization, and in the deeper part of the basin also by thermochemical sulfate reduction and injection of metamorphic fluids via squeegee-type fluid flow (Amthor et al., 1993 and 1994; Mountjoy et al., 1999 and 2001; Machel and Buschkuehle, 2008, Machel, 2010; Kuflevskyi, 2015).

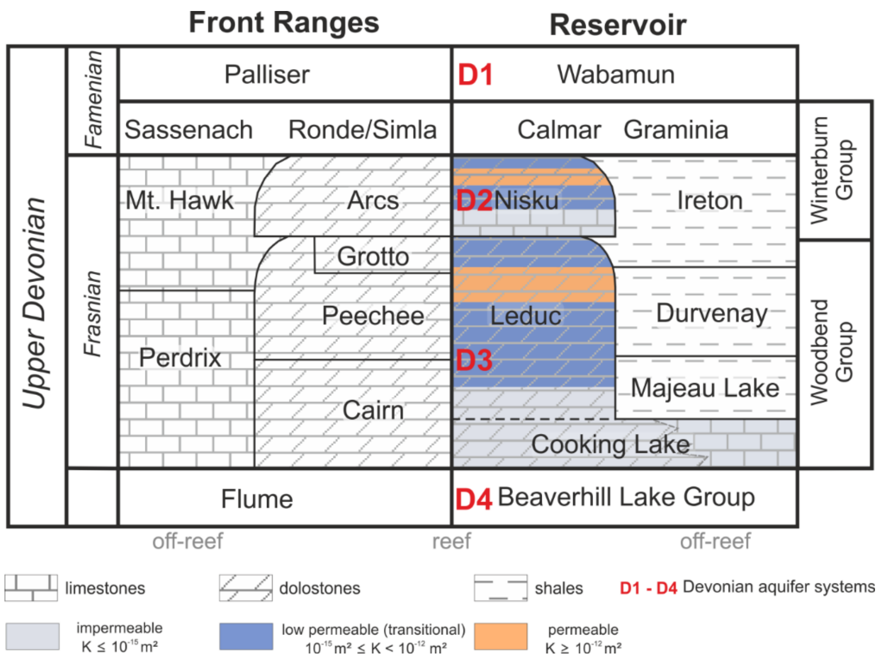

Figure 2: Simplified lithostratigraphy for the Alberta Basin and the adjacent Rocky Mountains, and schematic classification of permeability zones (based on Switzer et al., 1994). D1 to D4 marks the four Upper Devonian aquifer systems within the Alberta Basin.

The regional distribution of the D3 aquifers in the subsurface of Alberta is delineated by seismic (Switzer et al., 1994; Fig. 1). Parts of the Upper Devonian succession are exposed in the Rocky Mountain Front Ranges (west of the limit of the disturbed belt), where they are exposed in a series of imbricated thrust sheets. At the time of deposition, these strata extended much farther westward as an expansive platform into what is now British Columbia (as reconstructed in Fig. 1). Of particular interest for the current study is the SCCC in an area west and southwest of the town of Hinton (as marked in Fig. 1), and also the southern part of the Fairholme

Carbonate Complex, where strata stratigraphically equivalent to the Leduc and Nisku Formations are accessible at or near several roadcuts in the Front Ranges. The stratigraphic outcrop-subsurface correlation is shown in Figure 2.

3. MATERIAL AND METHODS

Sampling and determination of thermo- and petrophysical rock properties

A data base of thermo- and petrophysical rock properties was furnished for the outcrop and reservoir samples from Alberta at the laboratory of the Technische Universität Darmstadt (Germany).

As no outcrops of the Upper Devonian exist within the Alberta Basin and the RMRT is not exposed anywhere (see Fig. 1), analogue samples were taken from three outcrops each of the SCCC and from the adjacent Fairholme Complex in the Rocky Mountain Front Ranges. The outcrops Toma Creek, Jasper Railroad and Mt. Greenock belong to the SCCC (Fig. 1), while the outcrops Nigel Peak, Grassi Lakes and Gap Lake were related to the Fairholme Complex. In total 141 plugs with diameters ranging from 25 mm to 64 mm were drilled from 38 outcrop samples. Petrophysical parameters, i.e., density, porosity, and permeability, as well as thermophysical parameters, i.e., thermal conductivity, thermal diffusivity and specific heat capacity, were measured on these samples. All parameters were measured on each plug for direct correlation whenever possible. To ensure reproducibility the plugs were measured in oven dry conditions and cooled down to room temperature in a desiccator (20 °C).

Furthermore, ten 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 associated wells 5-22 (RMRT, ranging between1800 and 2000 m b.g.l.) and 16-18 (SCCC, ~2700 m b.g.l.) are located in the central portion of the Alberta Basin, whereby the wells 10-31, 10-33, 15-23 (RMRT), 08-06 and 2-36 (SCCC) represent areas close to the Rocky Mountains at about 4 km depth b.g.l. (see Fig. 1). To analyze differences between the D3 and the overlying D2 Devonian aquifer systems, three representative cores of the D2 Nisku Formation were examined (located at about 3100 m b.g.l.). These wells are located within the Nisku Reef Trend (Brazeau area, Fig. 1) and represent the reef (7-33), the bank-edge reef (2-19) and the bank (11-32), respectively (bank = platform in this context). The cores of the reef (7-33) and the bank-edge reef (2-19) comprise the Lobstick, Bigoray and Zeta Lake Member, while the bank (11-32) contains core samples of the Dismal Creek Member. More than 400 core samples with a sample length ranging between 5 cm to 70 cm have been analyzed for apparent permeability, thermal conductivity and thermal diffusivity. Additionally, about 45 samples from the Leduc Formation were taken to analyze specific heat capacity.

Additional data was retrieved from the AccuMap data base for validation and correlation with the lab measurements obtained in the course of this study. These core analyses include particle density, permeability and porosity. For closer examination, thin sections made from representative plugs of the analogue- and reservoir samples were prepared and petrographically analyzed.

Particle and bulk density measurements were accomplished by using an AccuPyc 1330 helium pycnometer and a GeoPyc 1360 powder pycnometer, thereby measuring the particle and bulk volume, respectively. Porosities were calculated from the resulting differences in volume. The accuracy of the method is 1.1 % (Micromeritmics, 1997 and 1998).

Matrix permeability (intrinsic permeability K_i) of the outcrop samples was determined with a column permeameter after Hornung and Aigner (2004) at the TU Darmstadt laboratory. The plugs were measured using at least five air pressure levels ranging from 1 to 3 bar. Measurement accuracy varies from 5 % for high permeable rocks ($K > 10^{-14}$ m²) to 400 % for impermeable rocks ($K < 10^{-16}$ m²) (Bär, 2012; Filomena et al., 2014). Permeability measurements of the reservoir core samples were determined at the CRC and at the UofA core lab using a mini permeameter (Hornung and Aigner, 2004), a portable variation of the column permeameter, which allows point measurements on the planar or mantle surface of each core sample. The device allows measurements only at one air pressure level; therefore, the measured values represent apparent permeability (K_a). After Jaritz (1999) the difference between apparent and intrinsic permeability is smaller than 13 % for values greater than 50 mD (~ 10^{-15} m²).

For the determination of thermal conductivity and thermal diffusivity a thermal conductivity scanner after Popov et al. (1999, 2016) was used, allowing non-destructive as well as contactless measurements by using infrared sensors. The measurement accuracy is 3 % (Lippman and Rauen, 2009).

Specific heat capacity was determined using a heat-flux differential scanning calorimeter (Setaram Instrumentation, 2009), where samples were heated at a steady rate from 20 up to 200 °C within a period of 24 h. Specific heat capacities were derived from the resulting temperature curves through heat flow differences. The measurement accuracy is 1 % (Setaram Instrumentation, 2009).

Selected results of the thermo- and petrophysical measurements are presented in Figure 4.

Reservoir data assessment and processing

For mapping selected input parameters applicable to geothermal suitability and the construction of a preliminary 3D geological model of the western part of the RMRT, drill core and reservoir data from the AccuMap data base was used. The original data base for this specific part of the basin included about 813 petroleum well logs from 1950-2015 with more than 42,000 data values of interest to this study - only considering the Leduc and Nisku formations (Fig. 3). Thereby, the following parameters were acquired for further assessment: petrophysical core data like permeability, porosity and particle density, reservoir temperature, TDS and sour gas analysis (H_2S, N_2, CO_2). Furthermore, well information such as measured depth (MD) of the well, true vertical depth of the well subsea (TVDSS), coordinates of the well and elevation of the kelly bushing (KB) was used for importing well locations and paths into GOCAD/SKUA.

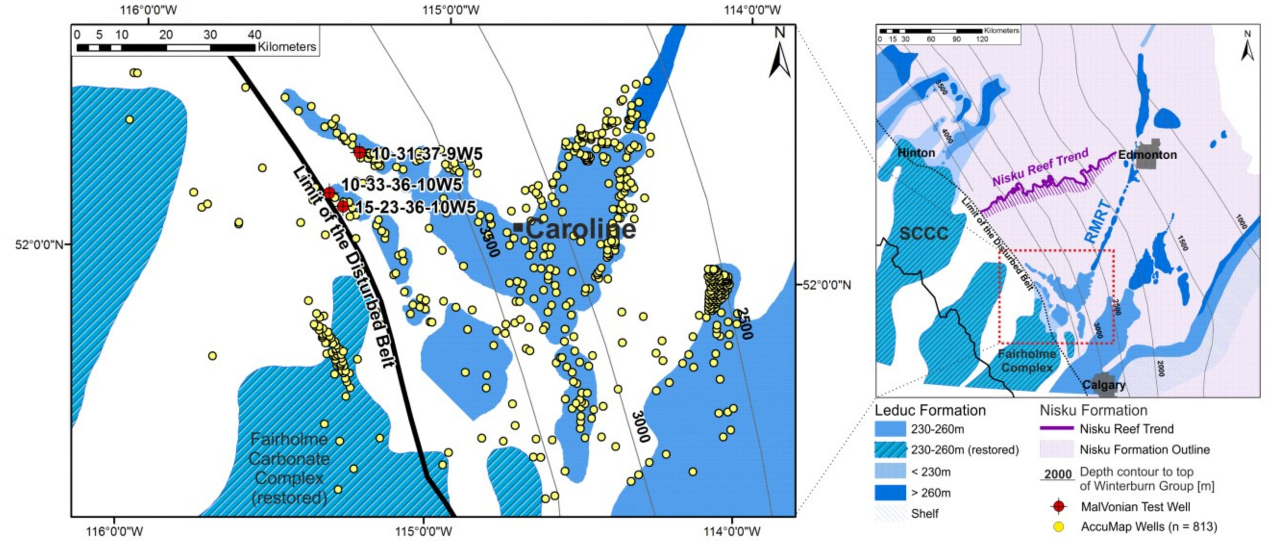

Figure 3: Spatial distribution of the wells (yellow dots) showing clustering around the reef buildups of the southwestern part of the RMRT. Formation outline (blue) after Switzer et al. (1994).

As this data set was compiled from various operations over many decades resulting in inconsistent quality of the data, quality control steps such as removing blank/error values, correcting causes of calculation errors, converting to SI units; and reformatting for conversions and software compatibility were required. In contrast to previous studies (Weides and Majorowicz, 2014; Nieuwenhuis et al., 2015), no DST temperatures nor BHT's were included in this data set. Therefore, reservoir temperature was only retrieved from well pressure surveys (WPS) as described by Lengyel (2013). The temperatures were filtered using a minimum shut-in time of 24 hours (Lengyel, 2013; Nieuwenhuis et al., 2015) and compared against the geothermal gradient range (22 – 35 °C km^{-1}) for the WCSB proposed by Ardakani and Schmitt (2016). Error-prone measurements not fitting the geothermal gradient were removed. Depth measurements are not uniform in the log files and can differ extremely between individual analyses (e.g. core analysis, water and gas analysis or oil and gas pressure analysis). In this study 'depths in m KB' (= depth measured below the Kelly bushing) was the most consistent data set and therefore used for further processing. Likewise, inclination-azimuth data was not available for all wells. After filtering, 352 wells had qualifiable property data (representing about 43 % of all wells in the data set), while only 167 wells (approximate 20 % of all wells) had qualifiable temperature data.

In order to display the individual parameters in 2D, weighted means were calculated for each parameter per hole using core length or run depth length as the weight. Afterwards, they were spatially interpolated across the top of each formation using the Inverse Distance Weighting (IDW) tool in ArcGIS. Additionally, all previously listed parameters were imported into GOCAD/SKUA as log files and subsequently interpolated through stratigraphic grids. As literature provides little to no information about the geological structures in the deep subsurface which could be useful to constrain formation boundaries in a 3D model, e.g. there exist only a few cross sections in proximity of the thrust belt (Price, 1994; Switzer et al., 1994; Wright et al., 1994), the regional structure surface files or isopach files from the Geological Atlas of Alberta (Mossop and Shetsen, 1994) were used in combination with the well data to build the stratigraphic grids. As a simplification measure for this preliminary model, only the reef sections east of the thrust belt were mapped and modeled. Therefore, all wells situated further westward were not considered at this stage of the project.

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. 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). Selected results are displayed in Figure 5.

4. RESULTS

Thermo- and petrophysical properties

The investigated Leduc Formation mainly represents intensively dolomitized stromatoporoid- and coral-rich reefs and reef margin lithologies with dissolution enlarged vugs and molds. The formation consists of dark grey to light grey, medium- to coarse-crystalline skeletal wackestones to float-stones and rudstones and to a lesser content Amphipora grainstones (well 5-22). Within the deepest sections of the RMRT close to the fold and thrust belt (at ca.4300 m b.g.l.), partially dolomitized to completely dolomitized permeable zones occur with interbedded nonporous limestones (e.g. well 10-31; Mountjoy and Marquez, 1997). The investigated Nisku cores comprise four members, which are Lobstick, Bigoray, Zeta Lake and Dismal Creek. The Lobstick Member mainly contains dark grey to black, fine-crystalline, nonporous argillaceous limestones with a lenticular fabric. The Bigoray Member constitutes of fine-bedded, coarse-crystalline dolomitized mud with interbedded dark grey and fine-crystalline limestone breccia. Well-preserved corals, mollusks, or small-sized vugs filled with anhydrite or calcite are present at some depth intervals. The Zeta Lake Member represents the reef and comprises light grey, fine-crystalline, nearly nonporous dolomudstones to bioclastic floatstones and rudstones with molds of a variety of corals, brachiopods, and stromatoporoids. Finally, the Dismal Creek Member (which represents the platform) comprises light grey, nonporous, fine-crystalline dolomudstones with abundant dissolution seams and argillaceous dolomudstone breccia with anhydrite nodules.

In contrast, the investigated outcrops in the Front Ranges consist mainly of dark grey to mouse grey reefal carbonates adjacent to or with interfingering dark grey argillaceous off-reef sections. Most of the outcrops expose nonporous, massive carbonate rocks equivalent to the Leduc Formation, while only two outcrops revealed rocks equivalent to the Nisku Formation (Toma Creek and Nigel Peak). In general, the investigated parts of the Fairholme Complex are partially to pervasively dolomitized, while the stratigraphically equivalent parts of the SCCC are largely present as limestones. Due to the fact, that almost all found/investigated outcrops are situated in close proximity to major thrust faults, the exposed strata are pervasively foliated, jointed, and fractured, with the faults dipping mostly west to southwest ward, resulting in different sets of fractures that have not been observed in the subsurface core samples. Summarizing, dolomitization, metamorphism, and tectonism affected the rocks in all outcrops, but to a different degree. Consequently, this leads to vast differences in the formation's appearance and rock properties of the outcrop samples.

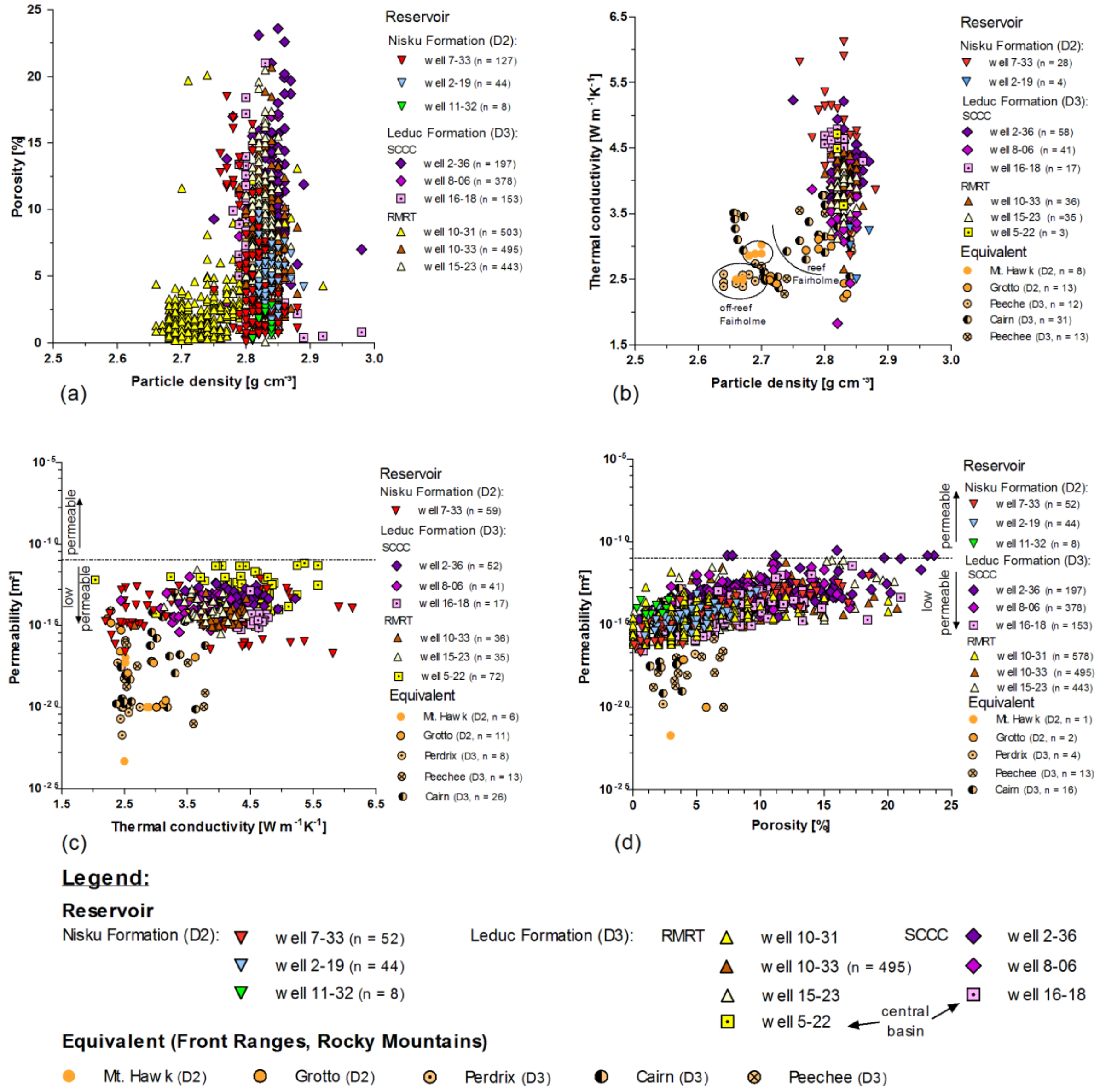

Figure 4: Correlation of petro- and thermophysical rock properties of the outcrop and reservoir samples analyzed at dry conditions.

Except for the deepest parts of the RMRT, almost all investigated cores have a constant rock density ranging from 2.80 to 2.85 g cm^{-3}. In contrast, matrix porosity and permeability are quite variable ranging from less than 1 % to 23 % and 10^{-17} up to 10^{-10} m², respectively. Even though originating from greater depth (approx. 4100 m b.g.l.), the rocks of the western Leduc Formation (well 2-36, SCCC) indicate the highest discovered porosity in comparison to more central basin samples of the Leduc Formation (well 16-18, SCCC at 2700 m of depth). Thermal conductivity of the reservoir samples varies between 2.4 W m^{-1}K^{-1} and 5.5 W m^{-1}K^{-1}. There is 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. Thermophysical properties seem to be density controlled and increase with decreasing clay content and increasing dolomite content. In general, thermal conductivity and density of the analogue outcrop samples is significantly lower. The Fairholme Complex analogue samples indicate a difference between off-reef (argillaceous limestones from the Perdrix and Mt. Hawk Formation) and dolomitized reef areas. However, results for the analogue samples taken from SCCC do not follow this trend and do not show any facies dependencies. Furthermore, matrix porosity and permeability are lower compared to the reservoir samples, most likely due to the low-grade metamorphosis during the orogeny of the Rocky Mountains. Core analyses of the Nisku Formation taken from the AccuMap data base, including particle density, porosity, and permeability, predominantly represent the dolomitized upper sections of the analyzed cores (this accounts especially for the selected wells 7-33, 2-19 and 11-32). Thus, the data is not representative of the whole formation. Furthermore, not all parameters were available for every well.

Assessment of the AccuMap data base

The assessment of the well core and reservoir data of the western part of the RMRT revealed reservoir temperatures of the Nisku and Leduc formations ranging between ~70 °C in the north eastern part and ~130 °C close to the thrust belt. As the temperature data is derived from WPS, the results can be regarded as conservative. As in the results of the core analysis, particle density is mainly constant with values ranging approximately 2.83 g cm^{-3}. Particle density values of approximately 2.7 g cm^{-3} were observed locally, most likely due to less intensive dolomitization of these specific reef sections. Porosity and permeability values in both formations show very large ranges with 0.1 to up to ~ 29 % and 10^{-17} to 10^{-10} m², respectively (Fig. 5b and c). Average porosity ranges between 4.4 and 5.5 % depending on the formation. Generally, porosity appears independent of reservoir depth confirming the observations of the analysed reservoir cores, e.g. well 2-36 originating from greater depth (4100 m b.g.l.) shows much higher porosity values in comparison to well 16-18 (2700 m b.g.l.) situated in the central part of the basin (Fig. 4). 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.

Within the GOCAD/SKUA model, both formations dip steeply towards the thrust zone. As the Leduc Formation comprises several reefs sitting on top of the Cooking Lake platform, the modeled surface shows a greatly varying relief (Fig. 5d). This Leduc Formation surface is constructed from well measurements and differs in formation geometry compared to the reef outlines based on seismic as presented in Switzer et al. (1994). In Switzer et al. (1994) the Leduc Formation is represented as separate reef structures (Fig. 3), whereas the well data implies rather one large unit (Fig. 5). There are several possible reasons for the differences: i) the seismic used in the published study could have inaccuracies as they are from old investigations; ii) the points where wells intersect Leduc Formation are incorrectly spatially displayed due to error-prone data or absence of inclination-azimuth data; iii) the Cooking Lake Platform carbonates that underlie the Leduc Formation have been incorrectly logged as Leduc due to the intensive dolomitization of the aquifer systems.

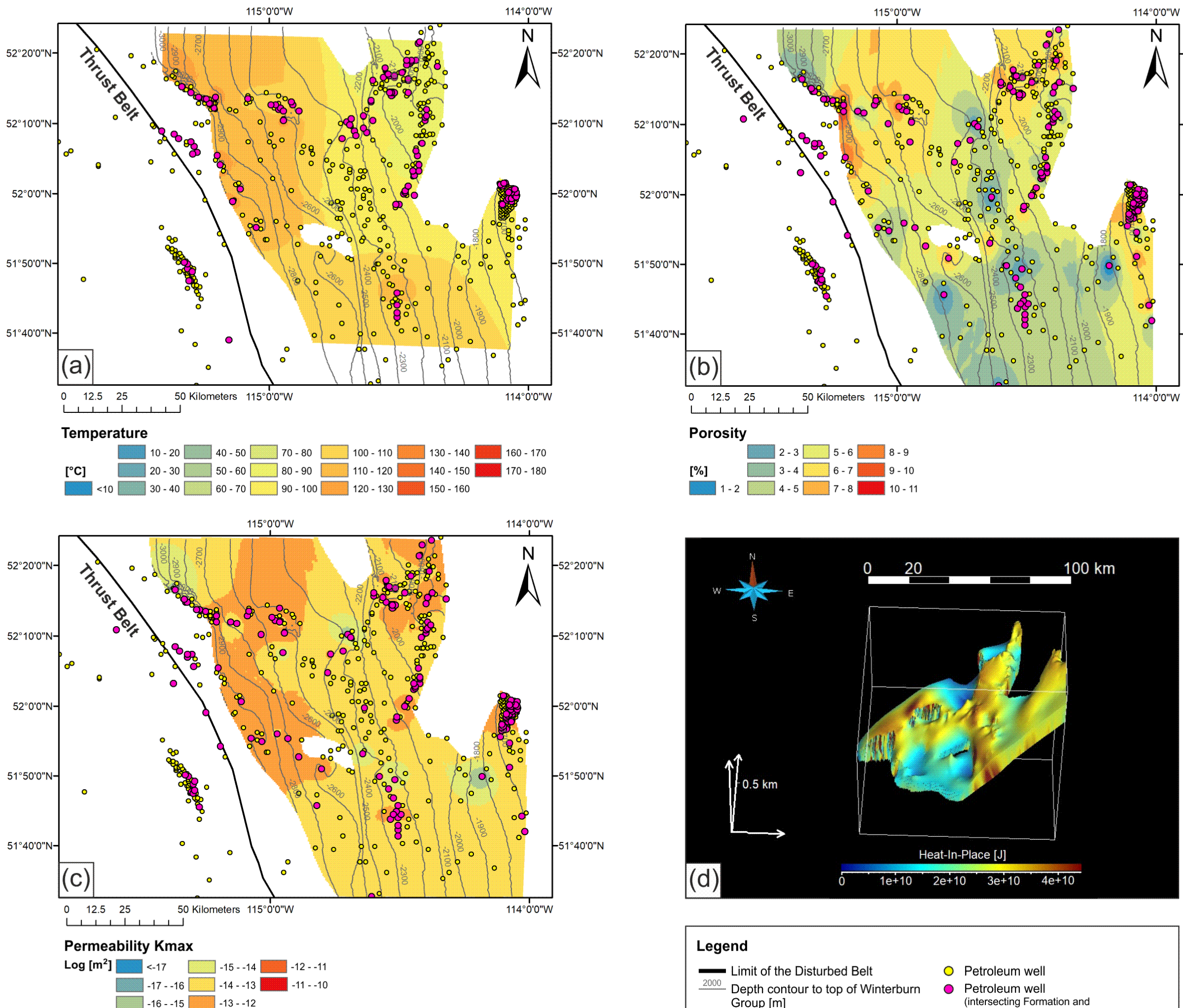

Figure 5: Spatial distribution of selected core and reservoir properties of the Leduc Formation: (a) formation temperature, (b) porosity and (c) maximal permeability. Volumetric heat-in-place calculation (d) carried out with GOCAD/SKUA.

The Heat-In-Place calculation (Fig. 5d) is based on the volume of the stratigraphic grids 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 energy is much lower, but still covers up to 6.7 % of Alberta's residential heating demand depending on the production type. Analyses of the sour gases are not presented in this study but should be considered for future investigations.

5. CONCLUSIONS AND OUTLOOK

The results from Leduc and Nisku well cores indicate good reservoir conditions regarding geothermal utilization with an average reservoir porosity of about 8 %, average reservoir permeability between 10^{-12} and 10^{-15} m², and relatively high thermal conductivities ranging from 3 to 5 W m^{-1} K^{-1}. Thereby, the most promising target reservoirs for geothermal utilisation are the completely dolomitized reef sections. The measured rock properties of the Leduc Formation in the subsurface show no significant differences between the Rimbey-Meadowbrook reef trend and the Southesk-Cairn Carbonate Complex. Differences between the dolomitized reef sections of the examined Leduc and Nisku Formation are also minor to insignificant, whereas the deeper basinal facies of the Nisku Formation differs significantly. In contrast, the outcrop analogue samples have lower porosity and permeability, and indicate different diagenetic processes compared to the reservoir samples. As such, the outcrop analogues are no valid proxies for the buried reservoirs in the Alberta Basin.

The preliminary 2D and 3D assessment of selected formation properties of the western part of the RMRT confirm the findings, 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 (Bär, 2012). Porosity and permeability show a wide range and are quite variable throughout the study area. Average porosity is lower than the average porosity of the analysed cores, while permeability and particle density are in the same range. 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 EGS. Upcoming studies will focus on the rock mechanical properties of the Upper Devonian carbonates.

The quality of the data set retrieved for this study from the AccuMap data base is rather poor and requires time intensive processing and quality control. Most important is the quality of the reservoir temperature (Nieuwenhuis et al., 2015), but also errors in the directional survey logs of the wells to constrain the formation geometry. Future work should focus on further 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 all kind of hydraulic test data of these wells might provide a better evaluation of the actual hydraulic properties compared to the matrix permeabilities measured on core samples. However, the evaluation of the AccuMap data set provides an initial overview of the formations' properties and their heterogeneity throughout the study area. It yields low cost and practicable results, especially in comparison to alternative field-based exploration methods such as drilling new wells.

This paper reports briefly the results of a pilot study that forms the first phase of the 'MalVonian' project. It provides the basis for future projects with respect to modeling and serves to improve the geological understanding of the Upper Devonian carbonates within the Alberta Basin, allowing a more precise and reliable geothermal assessment.

ACKNOWLEDGEMENT

This study has received funding from the DAAD – German Academic Exchange Service in the framework of the 'MalVonian' project. We thank David Gärtner for his contribution to this project.

REFERENCES

Amthor, J. E., Mountjoy, E. W., and Machel, H. G.: Regional-scale porosity and permeability variations in Upper Devonian Leduc buildups: implications for reservoir development and prediction in carbonates, *AAPG Bulletin*, **78**, (1994), 1541–1559.

Amthor, J. E., Mountjoy, E. W., and Machel, H. G.: Subsurface dolomites in Upper Devonian Leduc Formation buildups, central part of Rimbey-Meadowbrook reef trend, Alberta, Canada, *Bulletin of Canadian Petroleum Geology*, **41**, (1993), 164–185.

Ardakani, E. P. and Schmitt, D. R.: Geothermal energy potential of sedimentary formations in the Athabasca region, northeast Alberta, Canada, *Interpretation*, **4**, doi: 10.1190/INT-2016-0031.1, (2016), 19–33.

Aretz, A., Bär, K., Götz, A. E., and Sass, I.: Outcrop analogue study of Permocarboniferous geothermal sandstone reservoir formations (northern Upper Rhine Graben, Germany): impact of mineral content, depositional environment and diagenesis on petrophysical properties, *International Journal of Earth Sciences*, doi: 10.1007/s00531-015-1263-2, **105 (5)**, (2015), 1431-1452.

Bär, K.: Untersuchung der tiefengeothermischen Potenziale von Hessen, Dissertation, *Technische Universität Darmstadt*, (2012), 111 Fig., 28 Tab., 6 App., XXVI and p. 265.

Bär, K., Arndt, D., Fritsche, J.-G., Kracht, M., Hoppe, A., and Sass, I.: 3D-Modellierung der tiefengeothermischen Potenziale von Hessen – Eingangsdaten und Potenzialausweisung, *Z. dt. Ges. Geowiss.*, **162**, (2011), 371–388.

Chevron Exploration Staff: The geology, geophysics, and significance of the Nisku reef discoveries, West Pembina area, Alberta, Canada, *Bulletin of Canadian Petroleum Geology*, **27**, (1979), 326-359.

Clauser, C.: Geothermal Energy, in: Landolt-Börnstein, Group VIII: Advanced Materials and Technologies, **3**, Energy Technologies, Subvol. C, Heinloth, K. (Ed.), *Renewable Energies*, Springer, Heidelberg, Berlin, doi 10.1007/b83039, (2006), 493–604.

Emerson: SKUA-GOCAD software, Emerson Paradigm Holding LLC., https://www.pdgm.com/products/skua-gocad/#, last access July 2019, (2019).

Environment Canada: Canadian Environmental Sustainability Indicators – Greenhouse Gas Emissions report, Environment and Climate Change Canada, report available at https://www.canada.ca/en/environment-climate-change/services/environmental-indicators/greenhouse-gas-emissions.html, last access 25 July 2019, **1**, (2019), p. 24.

Filomena, C. M., Hornung, J., and Stollhofen, H.: Assessing accuracy of gas-driven permeability measurements: a comparative study of diverse Hassler-cell and probe permeameter devices, *Solid Earth*, **5**, doi: 10.5194/se-5-1-2014, (2014), 1–11.

GEOSCOUT: geoScout – Visualize, Analyze, and Forecast, geologic Systems, https://www.geologic.com/products/geoscout/, last access July 2019, (2019).

Grasby, S. E., Allen, D. M., Chen, Z., Ferguson, G. J., Kelman, M., Majorowicz, J., and Therrien, R.: Geothermal Energy Resource Potential of Canada, *Geological Survey of Canada*, Calgary, AB, Canada, (2012), p. 322.

Hofmann, H., Weides, S., Babadagli, T., Zimmermann, G., Moeck, I., Majorowicz, J., and Unsworth, M.: Potential for enhanced geothermal systems in Alberta, Canada, *Energy*, **69**, http://dx.doi.org/10.1016/j.energy.2014.03.053, (2014), 578-591.

Homuth, S., Götz, A. E., and Sass, I.: Reservoir characterization of the Upper Jurassic geothermal target formations (Molasse Basin, Germany): role of thermofacies as exploration tool, *Geoth. Energ. Sci*, **3**, doi: 10.5194/gtes-3-41-2015, (2015), 41–49.

Hornung, J. and Aigner, T.: Sedimentäre Architektur und Poroperm-Analyse fluviatiler Sandsteine: Fallbeispiel Coburger Sandstein, Franken, *Hallesches Jahrb. Geowiss*, Reihe B, Beiheft **18**, (2004), 121–138.

IHS Markit: AccuLogs, IHS Markit, https://ihsmarkit.com/products/oil-gas-tools-accumap.html, last access July 2019, (2019).

Jaritz, R.: Quantifizierung der Heterogenität einer Sandsteinmatrix am Beispiel des Stubensandstein (Mittlerer Keuper, Württemberg), Tübinger Geol. Abhandlungen, C, 48, 104 pp., 1999.

Jones, F. W., Kushigbor,C., Lam, H. L., Majorowicz, J.A, and Rahman,M.: Estimates of terrestrial thermal gradients and heat flow variations with depth in the Hinton-Edson area of the Alberta basin derived from petroleum bottom-hole temperature data, *Geophysical Prospecting*, **32**, (1984), 1111-1130.

Jones, F., Lam, H., and Majorowicz, J.: Temperature distributions at the Paleozoic and Precambrian surfaces and their implications for geothermal energy recovery in Alberta, *Can. J. Earth. Sci.*, **22**, (1985), 1774–1780.

Klinkenberg, L. J.: The permeability of porous media to liquids and gases, Drilling Production Practice, *API*, (1941), 200-213.

Kuflevskiy, S.: Dolomite Recrystallization Along the Rimbey-Meadowbrook Reef Trend, Western Canada Sedimentary Basin, Alberta, Canada, M. Sc. thesis, Department of Earth and Atmospheric Sciences, *University of Alberta*, Edmonton, Canada, (2015), p. 263.

Lam, H., and Jones, F.: Geothermal energy potential in the Hinton-Edson area of west-central Alberta, *Canadian Journal of Earth Sciences*, **22**, https://doi.org/10.1139/e85-036, (1985), 369–383.

Lengyel, T.: Geothermics of the Phanerozoic strata of Saskatchewan. M. Sc. Thesis. Department of Earth and Atmospheric Sciences, *University of Alberta*, Edmonton, Alberta, (2013), p. 263.

Lippmann, E. and Rauen, A.: Measurements of Thermal Conductivity (TC) and Thermal Diffusivity (TD) by the Optical Scanning Technology, *Lippmann and Rauen GbR*, Schaufling, Germany, (2009), p. 49.

Machel, H. G. and Buschkuehle, B. E.: Diagenesis of the Devonian Southesk-Cairn Carbonate Complex, Alberta, Canada: marine cementation, burial dolomitization, thermochemical sulfate reduction, anhydritization, and squeegee fluid flow, *Journal of Sedimentary Research*, **78**, doi: 10.2110/jsr.2008.037, (2008), 366-389.

Machel, H. G.: Geological and hydrogeological evaluation of the Nisku Q-Pool in Alberta, Canada, for H2S and/or CO2 storage, *Oil & Gas and Technology - Rev. IFP*, **60**, (2005), 51-65.

Machel, H. G.: The Devonian Petroleum Systems of the Western Canada Sedimentary Basin–with implications for Heavy-oil Reservoir Geology, in: Heavy oils: Reservoir characterization and and production monitoring, Chopra, S., Lines, L.R., Schmitt, D.R. and Batzle, M.L. (Eds.), *SEG Geophysical Developments*, **Series No. 13**, Chapter 9, https://doi.org/10.1190/1.9781560802235.ch9, (2010), 131–154.

Micromeritics: AccuPyc 1330 Pycnometer, V2.02, Part No. 133-42808-01, Micromeritics GmbH, Munich, Germany, (1997), p. 67.

Micromeritics: GeoPyc 1360, V3., Part 136-42801-01, Micromeritics GmbH, Munich, Germany, (1998), p. 69.

Mielke, P., Bär, K., and Sass, I.: Determining the relationship of thermal conductivity and compressional wave velocity of common rock types as a basis for reservoir characterization. – *J. Appl. Geophys*., **140**, doi:10.1016/j.jappgeo.2017.04.002, (2017), 135-144.

Mountjoy, E. W. and Marquez, X. M.: Predicting reservoir properties in dolomites: Upper Devonian Leduc buildups, Deep Alberta Basin, in: Reservoir quality prediction in sandstones and carbonates, Kupecz, J.A., Gluyas, J., and Bloch, S. (Eds.), *AAPG*, **Memoir 69**, (1997), 267-306.

Mountjoy, E. W., Drivet, E,. and Marquez, X. M.: Porosity Modification During Progressive Burial in Upper Devonian Leduc Reservoirs, Rimbey-Meadowbrook Reef Trend, Alberta, Rock of the Foundation Convention, *Canadian Society of Petroleum*, 18-22 June 2001, Calgary, Alberta, Canada, (2001), 241-252.

Mountjoy, E. W., Machel, H. G., Green, D., Duggan, J., and William-Jones, A.: Devonian matrix dolomites and deep burial carbonate cements: a comparison between the Rimbey-Meadowbrook reef trend and the deep basin of west-central Alberta. *Bulletin Canadian Petroleum Geology*, **47**, (1999), 487-509.

Natural Resources Canada: National Energy Use Database Publications. Government of Canada, available online at http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/data_e/publications.cfm, checked on 6/30/2019, (2019).

Nieuwenhuis, G., Lengyel, T., Majorowicz, J., Grobe, M., Rostron, B., Unsworth, M. J. and Weides, S.: Regional-Scale Geothermal Exploration Using Heterogeneous Industrial Temperature Data; a Case Study from the Western Canadian Sedimentary Basin, *Proceedings of the World Geothermal Congress*,19-25 April 2015, Melbourne, Australia, (2015), p. 5.

Paschen, H.; Oertel, D.; and Grünwald, R.: Möglichkeiten geothermischer Stromerzeugung in Deutschland – Sachstandbericht, TAB Arbeitsbericht 84,Büro für Technikfolgen – Abschätzung beim Deutschen Bundestag, (2003), p. 124.

Popov, Y. A., Sass, P. D., Williams, C. F., and Burkhardt, H.: Characterization of rock thermal conductivity by high resolution optical scanning, *Geothermics*, **28**, https://doi.org/10.1016/S0375-6505(99)00007-3, (1999), 253–276.

Popov, Y., Beardsmore, G, Clauser, C. and Roy, S.: ISRM Suggested Methods for Determining Thermal Properties of Rocks from Laboratory Tests at Atmospheric Pressure, *Rock Mech Rock Eng*, **49**, https://doi.org/10.1007/s00603-016-1070-5, (2016), 4179-4207.

Price, R. N.: Cordilleran tectonics and the evolution of the Western Canada Sedimentary Basin, in: Geologic atlas of the Western Canada Sedimentary Basin, Mossop, G. D. and Shetsen, I. (Eds.), *CSPG and Alberta Research Council*, Calgary, Alberta, Canada, (1994), 13-24.

Rostron, B. J., Toth, J., and Machel, H. G.: Fluid flow, hydrochemistry, and petroleum entrapment in Devonian reef complexes, south-central Alberta, Canada, in: Basin-wide diagenetic patterns: integrated petrologic, geochemical, and hydrologic considerations, Montanez, I. P., Gregg, J. M., and Shelton, K. L. (Eds.), *Society for Sedimentary Geology Special Publication*, **57**, (1997), 139–155.

Sass, I. and Götz, A.: Geothermal reservoir characterization: a thermofacies concept, *Terra Nova*, **24**, doi: 10.1111/j.1365-3121.2011.01048.x, (2012), 142–147.

Setaram Instrumentation: K/C80-1A C80 Commissioning, *Setaram Instrumentation KEP Technologies*, Caluire, France, (2009), p. 52.

Switzer, S. B., Holland, W. G., Christie, D. S., Graf, G. C., Hedinger, A. S., McAuley, R. J., and Packard, J. J.: Devonian Woodbend-Winterburn strata of the Western Canada Sedimentary Basin, in: Geologic atlas of the Western Canada Sedimentary Basin, Mossop, G . D. and Shetsen, I. (Eds.), *CSPG and Alberta Research Council*, Calgary, Alberta, Canda, (1994), 165–195.

Weides, S. and Majorowicz, J.: Implications of Spatial Variability in Heat Flow for Geothermal Resource Evaluation in Large Foreland Basins: The Case of the Western Canada Sedimentary Basin, *Energies*, **7**, doi: 10.3390/en7042573, (2014), 2573–2594.

Weides, S., Moeck, I., Majorowicz, J., Palombi, D., and Grobe, M.: Geothermal exploration of Paleozoic formations in Central Alberta, *Can. J. Earth Sci*., **50**, https://doi.org/10.1139/cjes-2012-0137, (2013), 519–534.

Wendte, J.C.: Overview of the Devonian of the Western Canada Sedimentary Basin, in: Devonian–Early Mississippian Carbonates of the Western Canada Sedimentary Basin: A Sequence Stratigraphic Framework, Wendte, J.C., Stoakes, F.A., Campbell, C.V. (Eds.), *Soc. Econ. Paleontol. Mineral*., Short Course 28, doi:10.2110/scn.92.28.0001, (1992), 1-24.

Weydt, L. M., Heldmann, C.-D. J., Machel, H. G., and Sass, I.: From oil field to geothermal reservoir: assessment for geothermal utilization of two regionally extensive Devonian carbonate aquifers in Alberta, Canada, *Solid Earth*, **9**, https://doi.org/10.5194/se-9-953-2018, (2018), 953-983.

Wright, G. N.; McMechan, M. E.; and Potter, D. E. G.: Structure and Architecture of the Western Canada Sedimentary Basin, in G. D. Mossop, I. Shetsen (Eds.): Geological atlas of the Western Canada Sedimentary Basin, https://ags.aer.ca/publications/chapter-3-structure-andarchitecture.htm, last access 6th April 2019, (2019).