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

Geothermal Reservoir Analogues on a Continental Scale: Western Canadian Sedimentary Basin versus Northern Alpine Molasse Basin

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Keywords: Continental analogue study, carbonate aquifers, Devonian, Jurassic, Canada, Germany, deep geothermal systems

ABSTRACT

The public utility company of the city of Munich, Germany (Stadtwerke München, SWM) develops geothermal heat usage for district heating from geothermal sources. The municipality of Munich, which is a major shareholder of SWM, decided to terminate heat generation from fossil fuels and to supply all remote heat from geothermal sources, notably from the Jurassic Malm carbonate aquifer in the Northern Alpine Molasse Basin (NAMB). This study intends to qualify, whether thermo-physical, thermo-facial, and structural knowledge from the Malm aquifer can be transferred to and/or interchanged with similar data from Devonian carbonate aquifers in Alberta, Canada, and to which extent this is useful.

In Alberta, a vast number of oil and gas wells drilled in the Western Canadian Sedimentary Basin (WCSB) are available to be evaluated for geothermal utilization, yet there is no utilization of deep geothermal resources at this time. In contrast, few wells have been drilled in the German Molasse Basin, containing the Malm aquifer. Thus, Germany is in need of much more detailed reservoir assessment to intensify the ongoing geothermal utilization. This circumstance forms the basis for our study, in that ample core material from the Upper Devonian carbonate aquifers, which are promising target formations for geothermal energy utilization, is investigated and compared to cores from the Malm aquifer. Samples from prominent carbonate formations were analyzed for thermal conductivity, thermal diffusivity and heat capacity, as well as density, porosity and permeability. Furthermore, open-file petrophysical core data retrieved from the AccuMap database were used for correlation.

Structural and thermal similarities between the German Molasse Basin and the Canadian Rocky Mountain Foreland Basin are obvious. The question is: can exploration data and experience from research in these two regions be exchanged and utilized for mutual benefit? The worldwide trend of increasing CO_2-emissions could be significantly reduced if alternative and/or renewable energy sources were implemented to a larger degree.

1. INTRODUCTION

So far, there is no utilization of deep geothermal resources in Alberta. To meet or at least 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 in Alberta. This appears feasible because, although this province is characterized as a 'low enthalpy region' (Grasby et al., 2012), 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). The town site of Hinton in the western region of the Western Canadian Sedimentary Basin is of particular interest, since data analyses indicate flow rates of more than 400 $m^3 h^{-1}$ and temperatures up to 150 °C at depths of approximately 5 km (Lam and Jones, 1985). Being one of the largest oil and gas reservoirs in Alberta, the Upper Devonian carbonate aquifers have been investigated extensively by the oil and gas industry, which drilled more than 600.000 wells in the Alberta Basin over the past seven decades. In Alberta, the Core Research Centre in Calgary provides a giant storage of core meters which are publicly accessible. Furthermore, an extensive data set of downhole well logs, results of drill stem tests, and petrophysical data (mainly porosity and permeability data from plugs) is available in the AccuMap or geoScout database (IHS Markit, 2019; GEOSCOUT, 2019). However, while facies, diagenesis, and structure are well characterized and found to be highly variable across the basin (e.g., Switzer et al., 1994; Machel, 2010), the potential of the Devonian strata as geothermal reservoirs has not been assessed or only in a very superficial manner. Previous studies provided little data on the geothermal reservoir properties of the rocks (e.g. Weides and Majorowicz, 2014; Weides et al., 2013; Nieuwenhuis et al., 2015; Ardakani and Schmitt, 2016). However, an extensive database of parameters such as porosity, permeability, thermal conductivity, amongst others, is necessary for geothermal assessment (Clauser, 2006; Sass and Götz, 2012; Homuth et al., 2015).

In contrast, the Upper Jurassic Malm-Aquifer in Southern Germany has already been proven to be suitable as a geothermal reservoir (Birner et al., 2012; Homuth et al., 2015; Wolfgramm et al., 2017). Today, the public utility company of the city of Munich, Germany (Stadtwerke München, SWM) develops geothermal heat usage for district heating from geothermal sources and the municipality of Munich, which is a major shareholder of SWM, decided to terminate heat generation from fossil fuels and to supply all remote heat from geothermal sources. Up to now, there are 34 active geothermal wells around Munich (Böhm et al., 2013; geothermie.de), and several more are spread out over a greater distance in Southern Germany. However, the overall subsurface database is relatively scarce because it is mainly based on drill cores from exploration wells, of which there are few in areas without extensive hydrocarbon reservoirs. In order to obtain a representative database for upscaling and correlation of geothermal reservoir characterization, Homuth et al. (2015) and Mraz et al. (2018) used samples not only from wells within the reservoir, but also performed outcrop analogue studies as a key exploration tool in the shallow parts of the structural homocline.

Both, the Upper Devonian aquifer systems in the Alberta Basin and the Upper Jurassic Malm-Aquifer in Southern Germany show many similarities regarding rock types, thicknesses, depth and deformation (they form structural homoclines in the subsurface), and hydrogeological properties. The MalVonian project intends to identify and characterize the suitability of both carbonate aquifer systems for geothermal utilization. Another objective is to analyze to which extent it is possible to use and transfer exploration data and knowledge amongst both systems and other sedimentary basins showing similar geological settings as proposed by the play type concept in Moeck (2014). To implement the utilization of geothermal energy on a larger scale in the next few years, it is important to analyze sister play types to increase the learning curve. This concept includes knowledge about the geological setting and the resulting conditions for geothermal energy production, concept development for geophysical exploration, drilling and exploitation technologies as well as ecological and economical aspects. At this stage of the project, we focus on reservoir parameters determined in wellbores or on drill core and outcrop samples.

To gain a similar data set as presented in Homuth et al. (2015) and Mraz et al. (2018), an outcrop analogue study was conducted in the Alberta Basin (Weydt et al., 2018). The aim of outcrop analogue studies is to investigate facies, diagenesis and petrophysical properties of rock units, which are stratigraphically equivalent to the target subsurface and whenever possible to compare these units with borehole samples of the reservoir. The concept includes detailed analyses on different scales: macroscale = outcrops, mesoscale = samples, microscale = thin sections. Using such a database, a thermofacies classification (Sass and Götz, 2012) enables the identification of heterogeneities and production zones and allows an extrapolation of the results into the deep subsurface and a more precise reservoir modeling and rock property prediction.

Here, we present a comparison of two potential basin settings, the Upper Jurassic Malm aquifer of the Northern Alpine Molasse Basin (Germany) and the Upper Devonian aquifer systems of the Alberta Basin (Canada), following the geothermal play type concept (Fig. 1) of Moeck (2014). This comparison is crucial for future knowledge transfer and a key aspect for sustainable geothermal energy utilization from deep sedimentary basins worldwide.

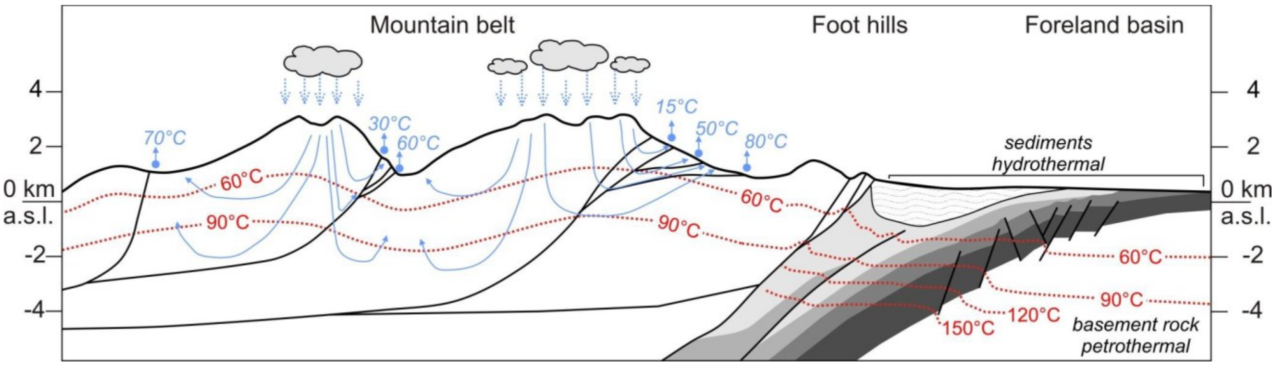

Figure 1: Sketch of the Foreland Basin play type modified from Moeck (2014).

1.1 Geological setting

The North Alpine Foreland Basin, the so called "Molasse Basin", is a wedge-shaped basin with a length of about 1000 km that extends from the Rhône Basin in the west via Switzerland and Bavaria to Austria (Rasser et al., 2008). It was formed during the Oligocene and Miocene as a result of the flexure of the European plate under the weight of the orogenic wedge of the Alps. It is part of the Alpine-Carpathian Foredeep and subdivided into a western (Switzerland and Germany) and an eastern (Austria) part (Rasser et al., 2008; Reicherter et al., 2008). Here, we focus on the Upper Jurassic (Malm) of the Bavarian part of the basin (Fig. 2 d). Within the Bavarian Molasse Basin, the Malm aquifer system occurs in depths between ca. 1 km and 5 km, with outcrop analogues located in the North in the Swabian and Franconian Alb (Fig. 2d).

The Western Canada Sedimentary Basin (WCSB) 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 is divided into the Alberta Basin and the Williston Basin, the border of which roughly coincides with the Alberta-Saskatchewan border (Fig. 2c). The sedimentary evolution throughout the Phanerozoic was intimately related to the tectonic evolution of the region and the formation of the Rocky Mountains (Wendte, 1992; Price, 1994; Switzer et al., 1994). The size, depth, subsidence, accommodation space and uplift were largely caused by four orogenies, the most significant of which being the Antler orogeny in the Devonian to Carboniferous and the Laramide from Mid-Late Cretaceous to Tertiary (Machel, 2010). East of the limit of the disturbed mountain belt, the sedimentary layers form a structural homocline that dips westward (Fig. 2a), whereas the Devonian strata increase in depth from zero in the east to more than 6 km near the limit of the disturbed mountain belt in the west and are exposed in the Front Ranges of the Rocky Mountains.

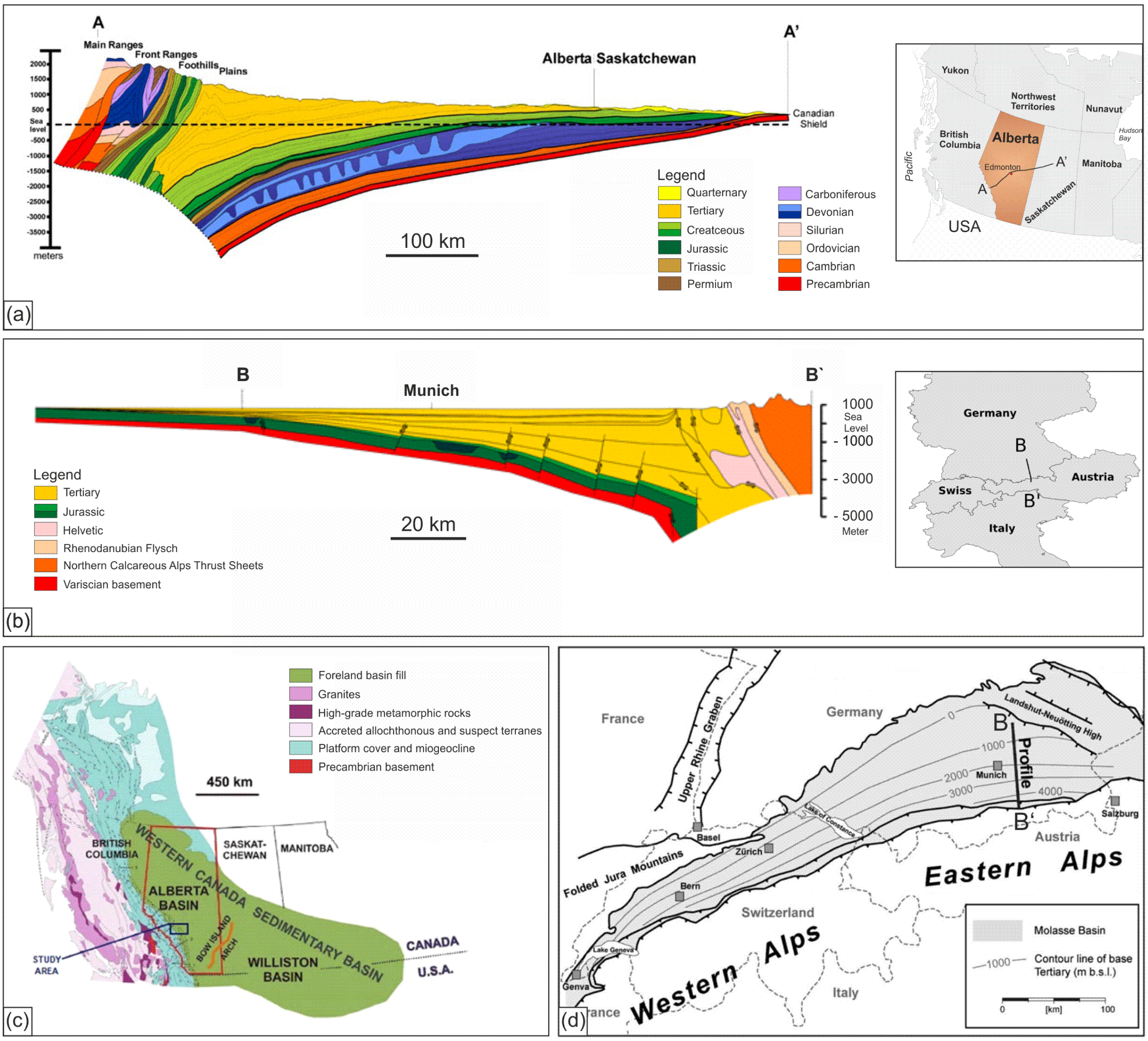

Figure 2: Schematic cross section of the Alberta Basin in Canada (a, modified and simplified from Wright et al., 1994) and of the Molasse Basin in Germany (b, modified and simplified from Reinecker et al., 2010 and Birner, 2013). (c) Overview map of the Alberta Basin (modified from Machel, 2010) and (d) the Molasse Basin (modified from Reinecker et al., 2010).

2. HISTORY OF GEOTHERMAL EXPLORATION

2.1 Western Canada (Alberta)

Geothermal research in Alberta started back in the 60's (Grasby et al., 2012), mainly focusing on the determination of heat flow, geothermal gradients and reservoir temperature in the basin (e.g., Garland and Lennox, 1962; Majorowicz and Jessop, 1981; Lam et al., 1982; more recently Majorowicz et al., 2012, and others described in Weides et al., 2013), while only a few studies considered water chemistry and recovery (e.g., Lam and Jones, 1985, 1986). Reservoir temperatures retrieved from the AccuMap database were identified as error-prone (Majorowicz et al., 2014) and controlling factors were proposed by Niewenhuis et al. (2015). Reservoir modeling was conducted within the Helmholtz-Initiative by Weides et al. (2013), Reiter and Heidbach (2014) and Hofmann et al. (2014), considering parameters such as porosity and permeability followed by studies of Ardakani and Schmitt (2016). Thermal properties measured on core samples exist for the Hinton–Edson area (Beach et al., 1987). However, these authors provide only mean values of different Palaeo-, Meso-, and Cenozoic rock types. In 2015, the MalVonian project was initiated as a joint research of TU Darmstadt and University of Alberta with a focus on outcrop analogue studies, including detailed analysis of reservoir core samples (Weydt et al., 2018). Parallel studies by Ferguson and Ufondu (2017) used injection and production rates in combination of reservoir temperatures as a tool for geothermal reservoir characterization. A first heat-in-place assessment was published by Banks (2018).

2.2 Southern Germany (Bavaria)

The Alpine Foreland Basin in Bavaria is a minor oil and moderate gas province, with over 1200 hydrocarbon exploration wells documented (Dill et al., 2008). On the other hand, balneological applications have a long tradition in the Molasse Basin (Stober, 2014). Between 1977 and 1985, the first shallow hydrogeothermal wells have been drilled in the central Upper Jurassic aquifer of the SW German Molasse Basin. Two of the eight wells failed, but the others were successful and are in operation until today. In 1983 an unsuccessful hydrocarbon exploration well was drilled close to the city of Erding in Bavaria. However, thermal fluids of about 65 °C were produced. Several years later in 1998, the city of Erding built the first geothermal power plant within the Molasse Basin. Since 1998, 28 deep geothermal projects have been realized (Bundesverband Geothermie (BVG), 2019). According to BVG (2019), the total installed deep geothermal energy in Bavaria is about 322 MWth (total Germany: 336 MWth) and about 35 MWel (total Germany: 37 MWel). Research on the geothermal energy utilization in the Molasse Basin started in 2006 with the Geotis project. Within the framework of this project an extensive open access database (Agemar et al., 2014a) and geological and temperature 3D models (Agemar et al., 2012 and 2014b) were produced, and is continued (Mraz et al., 2018, Agmear and Tribbensee, 2018).

3. WCSB VS. NAMB

3.1 Spatial distribution

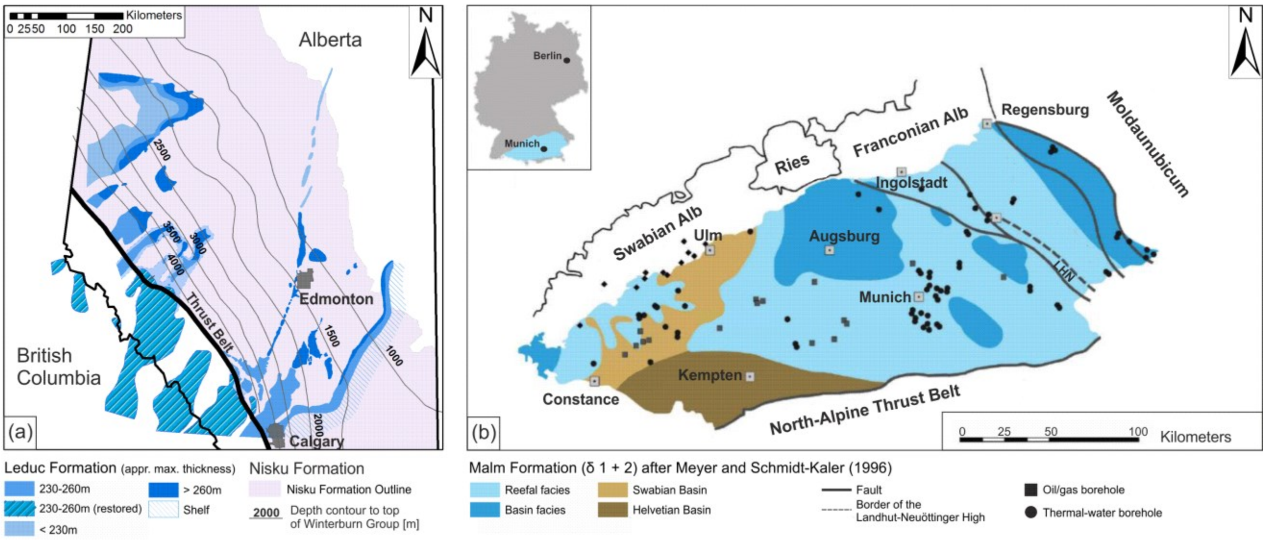

Figure 3: (a) Spatial distribution and approximate thickness distribution of the Leduc (blue) and Nisku formations (purple) in Alberta and neighbouring British Columbia (WCSB, Canada) on the left. The outlines of the carbonate platforms are based on seismic profiles (map modified from Switzer et al., 1994). The grey lines are depth contours marking the top of the Winterburn Group. (b) Spatial distribution of the Jurassic Malm Formation (blue to brown, NAMB, Germany) on the right modified and simplified from Birner et al. (2012) after Meyer-Schmidt-Kaler (1996).

The Devonian succession in Alberta was deposited on the passive margin of the ancestral North American continent under mostly subtropical, open-marine conditions. Stratigraphically, the Devonian is subdivided into four groups, each containing a carbonate platform (hydrologically acting as aquifers), and 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 the Leduc reefs and the underlying Cooking Lake carbonate platform), and the D4 (Beaverhill Lake Group). The focus of geothermal exploration is the Leduc (D3) and Nisku (D2) Formation, which are former or still productive oil and gas plays in the Alberta Basin. The Leduc Formation comprises 100 to 260 m thick reef buildups which sit on a large, ca. 75 m thick carbonate platform called 'Cooking Lake Platform'. These reef build-ups are surrounded by basin-filling shales (Amthor et al., 1993 and 1994). The overlying Nisku platforms are laterally much smaller than the underlying Leduc Formation, and much thinner with a maximum thickness of approximately 80 m. The carbonates dip steeply towards the Rocky Mountain thrust belt at a depth of ca. 4 to 5 km. They underwent extensive diagenesis including several processes such as pervasive dolomitization, multiple phases of dissolution and cementation (mainly by calcite, dolomite, and anhydrite) 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).

The Upper Jurassic (Malm) of the Molasse Basin in Bavaria (Germany) is composed of a 400 to 600 m thick carbonate succession (Pieńkowski et al., 2008) and two major facies are distinguished (Geyer and Gwinner, 1979; Pawellek and Aigner, 2003): the basin facies, consisting of well-bedded limestones and calcareous marls and the reefal or massive facies where bedding is absent, indistinct or very irregular. The massive reefal limestones are built by microbial crusts (stromatolites and thrombolites) and siliceous sponges (Pawellek and Aigner, 2003). The basin facies may either interfinger with the reefs or onlap onto the reefs (Gwinner, 1976; Pawellek, 2001). In the upper parts of the Upper Jurassic, a coral facies developed locally upon the microbial crust-sponge reefs. Variations in hydraulic conductivity, particularly within the Upper Jurassic aquifer, are related to lateral changes in lithofacies and degree of karstification (Birner et al., 2012). These carbonates are characterized by a karst-fractured, partially dolomitized aquifer system (Schulz et al., 2012) located 3500 to 5500 m below the surface in the southern part of the Molasse Basin.

3.2 Reservoir temperature, geothermal gradient and heat flow

The WCSB in Alberta is a low-enthalpy region (Grasby et al., 2012; Jones et al., 1985; Lam and Jones, 1985 and 1986) with a moderate average geothermal gradient between 25 and 30 °C km^{-1} (Ardakani and Schmitt, 2016) and an average heat flow of 60.4 Wm^{-2} (Weides et al., 2013). Reservoir temperatures of the Upper Devonian carbonates range from 30 °C in the central part up to 160 °C (Fig. 4a; Majorowicz and Weides, 2014). The area around the town site of Hinton in the western region of the Alberta Basin 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).

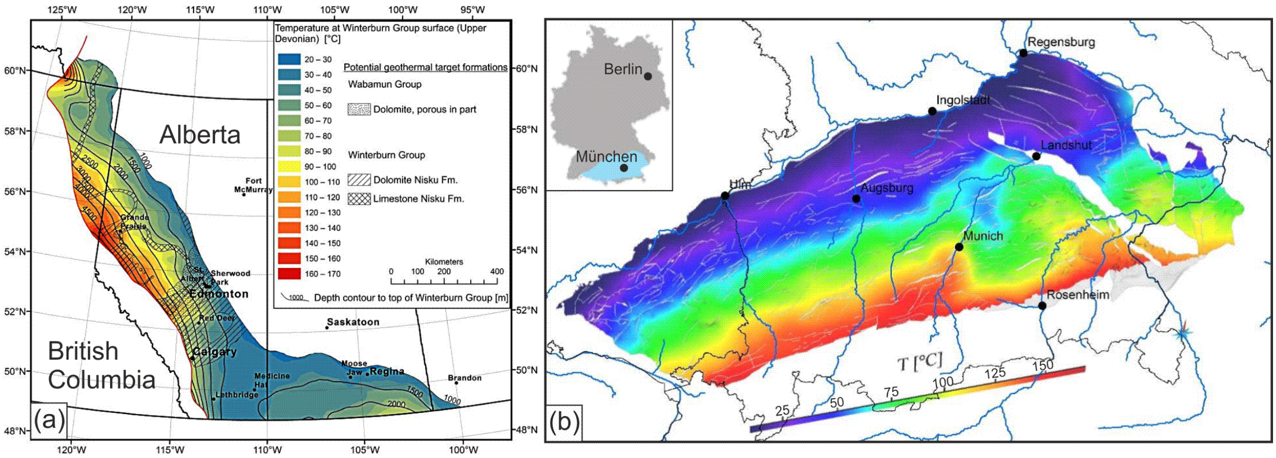

Figure 4: Temperature distribution at top of the Winterburn Group surface (Upper Devonian, Canada) on the left (a) after Majorowicz and Weides (2014) and 3D subsurface temperature model of the Upper Jurassic Malm Formation (Southern Germany) on the right (b) modified after Agemar and Tribbensee (2018) and Agemar et al. (2012).

Likewise, the Molasse Basin in Bavaria is a low-enthalpy region (Schultz et al, 2012) with a geothermal gradient ranging between 25 and 30 °C km^{-1} (Agemar et al., 2012). Reservoir temperatures of the Upper Jurassic (Malm) carbonates range from 30 °C in the northern part up to 150 °C in the southern part (Agemar and Tribbensee, 2018; Agemar et al., 2012); the heat flow ranges between 40 and 100 Wm^{-2} (Haenel et al., 1980). A thermal anomaly occurs northeast of Munich (Fig. 4b). According to BVG (2019) flow rates are highly variable within the reservoir and range between 160 m³ h^{-1} (= 45 l s^{-1} in Straubing) and 540 m³ h^{-1} (= 150 l s^{-1} in Dürnharr).

3.3 Petro- and thermophysical characterization

Petro- and thermophysical parameters studied include particle density, porosity, permeability and thermal conductivity. Both, Upper Devonian carbonates of the WCSB (Alberta, Canada) and Upper Jurassic (Malm) carbonates of the Molasse Basin (Bavaria, Germany) are grouped into four lithotypes: marly limestones, limestones, partly dolomitized limestones and dolomites (Fig. 5). Particle density increases with increasing degree of dolomitization (Fig. 5a). The same applies for the thermal conductivity (Fig. 5d). Porosity within the Malm Formation ranges between <1 % and 20 %, while Upper Devonian dolomites show porosities between <1 % and 30 % (Fig. 5b). Permeability shows a wide range as well (10^{-10} to < 10^{-18} m²; Fig. 5c). However, permeability of Upper Jurassic carbonates is low (below 10^{-15} m²), while Upper Devonian carbonates feature a range of 10^{-10} to 10^{-17} m². It has to be emphasized, that the data taken from Homuth et al. (2015) are values derived from core samples of two boreholes ca. 50 m and ca. 1 km deep, respectively. By contrast, the Upper Devonian samples analyzed by Weydt et al. (2018) come from seven deep boreholes between 2 and more than 4 km depths. In general, porosity slightly decreases with depth. However, on a local scale a very high variation of < 1 % up to 30 % is observed at about 4 km depth close to the Rocky Mountains. Thus, it can be stated that porosity is independent from reservoir depth (Amthor et al., 1993; 1994; Weydt et al., 2018).

4. CONCLUSIONS AND OUTLOOK

In this study we summarized and reviewed exploration work carried out in the WCSB (Alberta) and in the NAMB (Bavaria). Both systems show similarities with respect to rock type, reservoir temperature, heat flow, geothermal gradient and rock properties. Geothermal exploration in the WCSB has a long history and already started in the 60's. However, the geothermal industry in Alberta is still at the beginning. Regarding the results from bore core measurements and well data analysis, the Upper Devonian carbonates are suitable targets for developing enhanced geothermal systems. Especially diagenetic processes such as dolomitization play an important role. Direct hydrothermal utilization will be an additional option but is limited to some areas with enhanced permeabilities of the reservoir systems.

Knowledge gained from recent research on the Upper Jurassic Malm carbonates of the NAMB can be applied to the development of the WCSB target formations. There is strong evidence that the development of some hundreds of MW capacity under conditions of a carbon tax complementation will justify a larger investment in geothermal in Alberta. Operations in the WCSB have the potential to become economical operations earlier in time than it was the case for the NAMB. However, economical operation is strongly dependent on the entire drilling design.

Usually, a hydrothermal reservoir is opened through a production wellbore and an injection well. The distance between doublet or triplet wellbores in the reservoir has to be chosen in such a way that the cold, re-injected water does not lead to cooling of the water in the area of the delivery bore. In addition to the flow and feed rates, the flow direction in the reservoir must be observed. Since at this time there is insufficient in situ data on a possible hydrothermal reservoir in the WCSB, the important parameters temperature and flow rate cannot be determined off situ. These data will be transferred from similar properties of reservoirs in the NAMB.

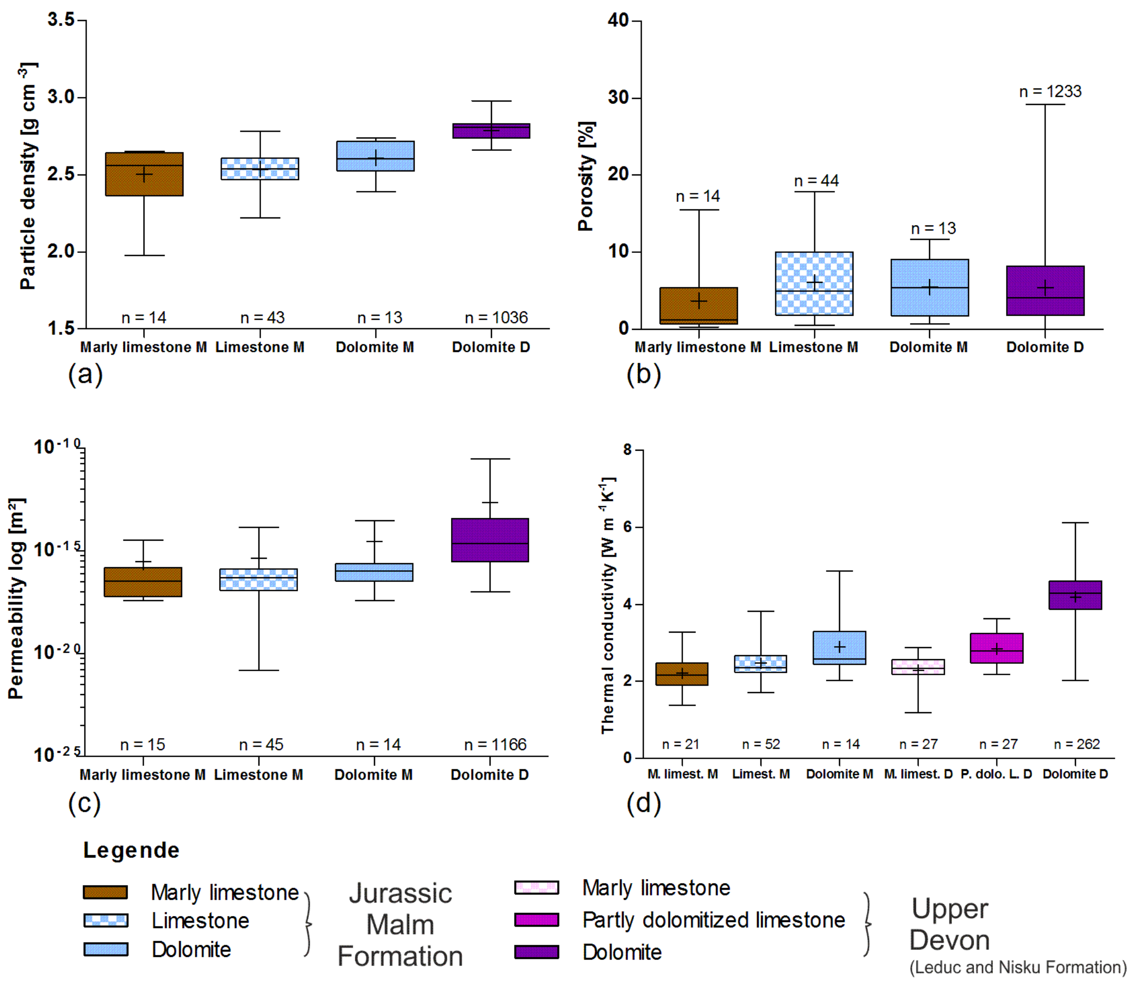

Figure 5: Box plots of selected thermo- and petrophysical rock properties of the Leduc and Nisku formations (Upper Devonian, Alberta; Weydt et al., 2018) and the Malm Formation (Upper Jurassic, Bavaria; Homuth et al., 2015).

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