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Geothermal Assessment of Paleozoic Aquifers in the Central Alberta Basin, Canada

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ABSTRACT

The Alberta Basin 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 containing hot fluids and structurally or facies controlled high permeability domains. Two focus regions are studied by well data analysis, 2D seismic sections, stress field analysis and temperature modeling. The study areas are located around the city of Edmonton in central Alberta (basin depth 1.8 – 3.5km) and in northeastern Alberta around the town of Peace River (basin depth 1.7 – 2.4 km). Extension and thickness of potential geothermal target formations is investigated by 3D structural geological modeling, and geostatistical methods are applied to analyze the distribution of porosity, permeability and temperature within these formations. For central Alberta, the medium to coarse grained Cambrian Basal Sandstone Unit is the most promising formation for deep geothermal applications. This potential hydrothermal resource could be used for district heating in the Edmonton metropolitan area, where the Cambrian Sandstone is located at a depth of 2.2 – 2.7km with a temperature of 78 – 93°C. Fluids from overlying Upper Devonian porous carbonates host fluids up to 63°C. In northeastern Alberta, warm fluids (51-75°C) from the siliciclastic Granite Wash Unit could be used for heating of greenhouses. Considering the climatic conditions in Alberta with its long and cold winter season, the temperature range between 60-90°C of hydrothermal resources seems to be efficient in highly populated areas with high heat demand as the metropolitan region of Edmonton, remote areas on northern Canada where fuel for heating needs to be transported by helicopters, or generally in Canada to grow local food in greenhouses.

1. INTRODUCTION

The Western Canada Sedimentary Basin (WCSB) is known for its resources of oil, gas and coal. Although traditional exploration in the WCSB is focused on hydrocarbons, recently renewed interest in the geothermal energy potential of the WCSB has risen as renewable energy technologies are regarded to play a larger role in future energy production (Majorowicz and Moore 2008; Bell and Weis 2009; Grasby et al. 2011; Weides et al. 2013). Alberta, located in the central WCSB, has been characterized as a low enthalpy region with an average geothermal gradient of 25–35 °C/km and a heat flow of 50–70 mW/m^2 (Majorowicz and Grasby 2010a; Grasby et al. 2011; Weides and Majorowicz 2014). Due to the cold climatic conditions (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), large amounts of energy are needed simply for heating and warm water provision in Alberta. Geothermal energy could serve as an energy source for domestic heating and warm water provision, and reduce fossil-fuel generated heat energy used within industrial processes, e.g. in the heating of greenhouses.

1.1 Geological Setting

The Alberta Basin is the central part of the Western Canada Sedimentary Basin (WCSB), which sits on a stable Precambrian platform and elongates along the eastern edge of the Rocky Mountains from British Columbia through Alberta and Saskatchewan into Manitoba (Porter et al. 1982, Bachu 1995) (Fig. 1). Basically, the WCSB comprises a wedge of sedimentary rocks increasing in thickness from zero at the Canadian Shield in the northeast to more than 6 km in the southwest (Porter et al. 1982, Bachu 1995) (Fig. 1). The WCSB was initiated during the late Proterozoic by rifting of the North American Craton (Bachu 1995). Two major basin stages can be distinguished in the evolution of the WCSB: a passive margin period, which ranged from Late Proterozoic to Middle Jurassic, and foreland basin period beginning in the Middle Jurassic (Porter et al. 1982). During the passive margin phase, thermal contraction led to transgressive onlap of the cratonic platform (Bachu 1995). Deposition of shallow water carbonates, evaporites and shales characterize this period. In the Middle Jurassic the second basin period was initiated. During the Columbian and Laramide orogenies allochtonous terranes were subsequently accreted to the western margin of North America, resulting in isostatic flexure of the lithosphere which formed the foreland basin. From the Middle Jurassic to early Cretaceous, westward dipping of the passive-margin succession led to extensive erosion of eastwardly progressively older strata, which subcrop along the pre-Cretaceous unconformity (Bachu 1995). During the active margin phase in the Cretaceous and early Tertiary, synorogenic clastics (mainly shales) from the emerging Cordillera filled the basin. From Tertiary to recent, erosion has removed from up to 3800 m of sediments in the southwest to only 1000 m in the north (Bachu 1995). Present day topography of the basin ranges from close to 1200 m elevation in the southwest at the edge of the thrust and fold belt to slightly less than 200 m in the northeastern corner of the basin near the Canadian Shield (Bachu 1995).

1.2 Previous work

Investigation of the geothermal state of the WCSB started with the study by Garland and Lennox (1962) who performed the first measurements of heat flow in two wells near Edmonton. With the sudden rise in the price of oil in 1973, and the popular perception that the supply of oil was approaching a decline, the Government of Canada initiated a geothermal energy research program which ran from 1974 to 1986 with a total budget of 6 million CAD. In the beginning of the program geological knowledge was accumulated to delineate the Canadian resources. After a feasibility study a well was drilled into the depth of 2214 m at the Campus of the University of Regina (Vigrass 1979; Jessop and Vigrass 1989). Tests showed an excellent geothermal potential, but unfortunately the large sports building that was intended to be the load for the well was not built, so the well has only been used as a research facility (Jessop 2005).

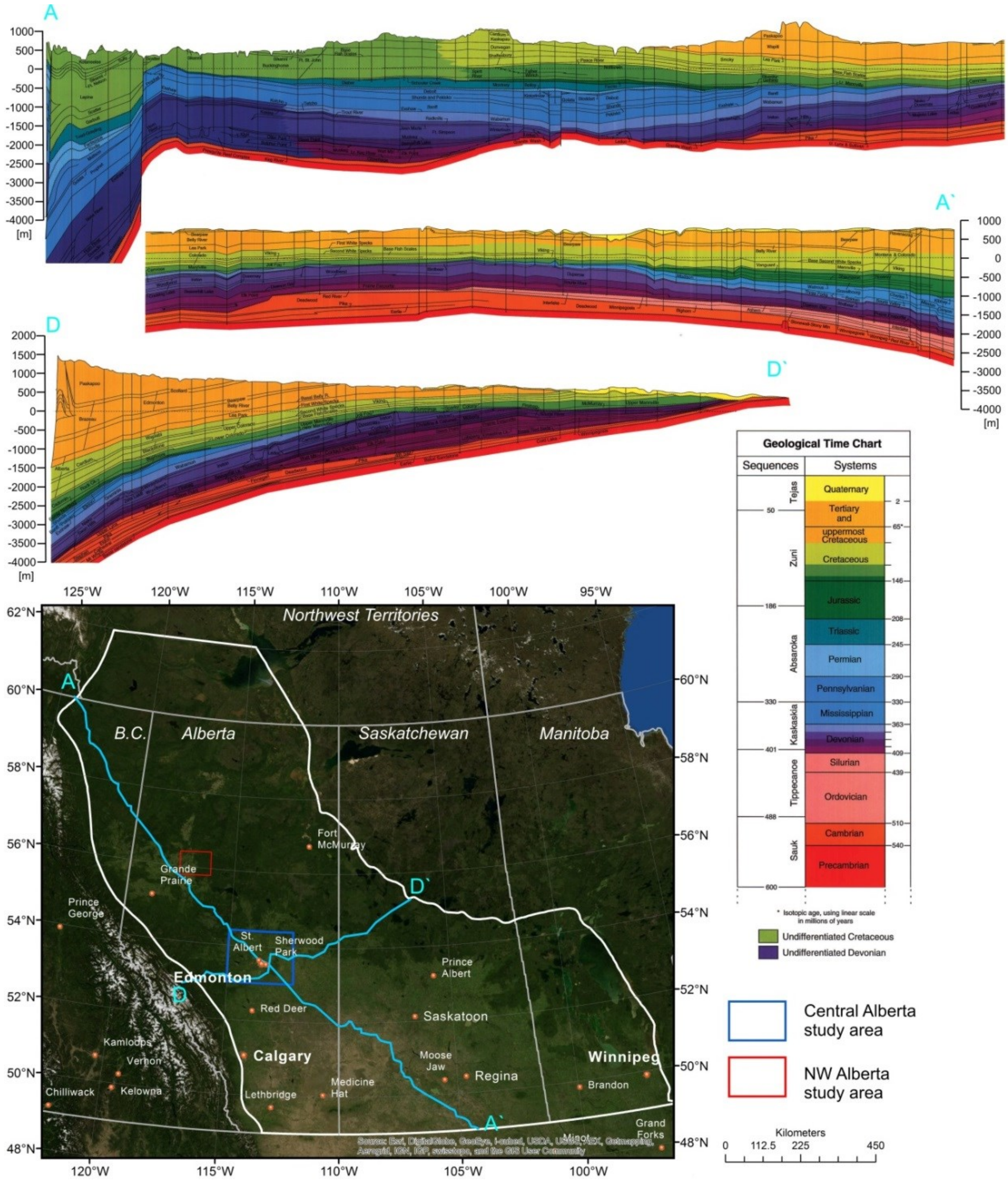

Fig. 1: ***Upper part*****: Two cross sections cutting through the Western Canada Sedimentary Basin; A–A` strikes perpendicular and D–D` parallel to the main dip direction of the basin.** ***Lower part*****: Location of the cross sections and the two study areas. Cross sections are modified from Wright et al. (1994).**

The first regional scale geothermal study in the WCSB was published by Jones et al. (1985) who predicted and mapped the temperature at the depth of the Paleozoic erosional surface and the Precambrian surface for the whole Alberta basin. After the discovery of a geothermal anomaly around the towns of Hinton and Edson in western Alberta, Lam and Jones (1985) investigated the geothermal potential of the area. Due to the combination of the relatively high gradient of approx. 36 °C/km and the thick sedimentary succession (4–6 km), the Hinton-Edson area was seen as a possible geothermal energy source. Aquifer porosity, aquifer thickness, water chemistry and water recovery were examined with petroleum exploration data. The authors concluded that the Mississippian and Upper Devonian carbonate rocks appear to present aquifers with good geothermal potential because of their depth, thickness, wide spatial extent and good water recovery (Lam and Jones 1985). In a second study Lam and Jones investigated the potential for geothermal energy recovery in the Calgary area in southern Alberta (Lam and Jones 1986). In this area the geothermal gradient is rather low (24 °C/km). However, due to the relatively thick sedimentary succession (4 km) and the substantial population of the city, the authors concluded that the Calgary area is an attractive location for geothermal recovery and use. Following their approach of the Hinton-Edson study (Lam and Jones 1985), different aquifer properties were examined with petroleum exploration data. The largest potential for geothermal purposes again was found in Upper Devonian and Mississippian carbonate rocks.

Since the end of the geothermal energy program in 1986 only little research on geothermal questions was conducted, with the exception of the studies published by Bachu and Burwash in the early 1990`s, who investigated and mapped heat flow, geothermal gradient and temperature at Precambrian surface for the whole WCSB (Bachu and Burwash 1991; Bachu 1993; Bachu and Burwash 1994).

In the beginning of the millennium the hydrocarbon industry came up with a new potential application for geothermal utilization. In 2007 the industry consortium GeoPos (Geopowering the oil sands) began to investigate the technical and economic feasibility of using geothermal sources to supply the heat for energy and greenhouse-gas intensive oil sands extraction and processing. However, due to the economic crisis in 2008, the consortium stopped its work. In 2010 the Helmholtz Alberta Initiative, a research collaboration between the University of Alberta and the German Helmholtz Association of Research Centres, took up the idea of providing geothermal energy for oil sands in northeastern Alberta and, beyond that, focused also on the exploration of the geothermal potential of the deeper Alberta basin (as presented in this study). In 2011 the Geological Survey of Canada published a report (Grasby et al. 2011), which synthesizes previous geothermal studies and delineates the potential of the different geothermal resource types in Canada. A major finding of the report is that the highest geothermal potential (for electricity production) exists in the volcanic belts of the Cordillera and in parts of the WCSB (northeastern British Columbia, northern Alberta and southern Northwest Territories). The report describes the other deeper parts of the WCSB as very large resource for direct heat use. In 2013 the British Columbia Ministry of Energy and Mines assessed the geothermal resource at the geothermal anomaly of the Clarke Lake gas field in northeastern British Columbia (Walsh 2013) by using the volume method. Ferguson and Grasby (2014) studied the geothermal potential of the Basal Clastics in eastern Saskatchewan. Numerous studies have investigated heat flow and temperature at depth of the WCSB (Majorowicz and Jessop 1981; Jessop et al. 1984; Majorowicz et al. 1985; Majorowicz 1996; Majorowicz et al. 1999; Jessop et al. 2005; Grasby et al. 2009; Majorowicz and Grasby 2010a,b;) and North America (Blackwell and Richards 2004). The heat flow in the southern and central part of the WCSB generally ranges from 30–80 mW/m^2, while values up to 100 mW/m^2 and higher were measured in the northern part. The geothermal gradient in the southern and central parts of the WCSB ranges from 20–40 °C/km. In the northern part of the WCSB gradients > 50 °C/km were measured.

1.3 Focus of the study

This study focuses on two areas in the deeper Alberta Basin- The first study area is located in central Alberta around the city of Edmonton, while the second study area is located in northwestern Alberta around the town of Peace River (Fig. 1). Both areas differ from each other not only in respect to their geology and their geographic location, but also in respect to the heat demand and the potential application of geothermal heat production. In central Alberta the application for geothermal heat would be the provision of heat for district heating and for warm water supply in the densely populated Edmonton metropolitan area. In northwestern Alberta a huge heat demand exists for industrial (in-situ oil sands exploitation) and agricultural processes (heating of greenhouses).

The key questions addressed in this study are:

- What is the extension and thickness of potential geothermal target formations in the Alberta basin and in the two study areas?

- What is the porosity and permeability of the potential geothermal target formations, and how are these rock properties distributed?

- How are heat flow and geothermal gradient distributed in the Alberta Basin, and what temperatures can be expected in the potential geothermal target formations?

- Which are, according to the previous points, the best spots for a geothermal development?

- What kind of geological structures exist in the subsurface, and how are the structures oriented in the current stress field? What is reactivation potential of existing faults during production or injection of geothermal fluids?

To answer these questions, a wide range of different methods was applied, including 3D structural geological modeling based on well log data and 2D seismic data, geostatistical mapping of hydraulic parameters and temperature data, hydraulic and geomechanical testing and thin section analysis. Application of data intensive methods like 3D modeling and geostatistical mapping was only possible due to the extensive well data base which is publically available in Alberta. Thanks to the long tradition of hydrocarbon exploration and production in Alberta, more than 300,000 wells were drilled in the Alberta Basin until today. Temperature data from more than 26,000 of these wells were used to investigate the thermal state of the WCSB. Geological modeling and analysis of hydraulic parameters in the two study areas were conducted with stratigraphic information and core test results from more than 10,000 wells. In the Peace River study, the in-situ stress field was estimated from literature data, and the reactivation potential of faults was assessed using the slip tendency method (Morris et al. 1996). The most suitable geothermal aquifer in central Alberta—the Cambrian Basal Sandstone Unit (BSU)—was investigated by thin section analysis, core analysis and geomechanical testing.

2. METHODS

2.1 3D structural geological modeling

For both areas, 3D structural geological models were developed to analyze thickness and spatial distribution of the potential geothermal reservoir units and for investigation of geological structures (Fig. 2). The 3D structural geological model can be subdivided into two separate models: a lithostratigraphic model and a fault model.

The lithostratigraphic models were developed by using stratigraphic tops of thousands of wells from the IHS AccuMap database (IHS Energy 2012). These tops were originally interpreted from geophysical well logs. Despite being a large dataset, it is also biased towards hydrocarbon-rich strata and areas, since most data come from hydrocarbon exploration and production wells. The dataset was checked for outliers by using the inverse distance weighted interpolation method in ArcGIS, where outliers can be easily identified as they appear as a bulls eye. Few stratigraphic tops were identified as outliers as their z-value differed markedly in relation to tops from other wells in the vicinity (in some cases the difference in depth to other tops in the direct surrounding of less than 5 km was more than 100 m). These obvious data errors, probably resulting from erroneous kelly bushing elevations, were removed from the dataset. The development of the 3D geological model used EarthVision® modelling software (Dynamic Graphics Inc.). Formation top surface grids were calculated using minimum tension gridding, an interpolation algorithm based on the nearest neighbour weighted average method (Dynamic Graphics Inc. 2009). The large scale of the models allowed only modelling of regionally extensive formations.

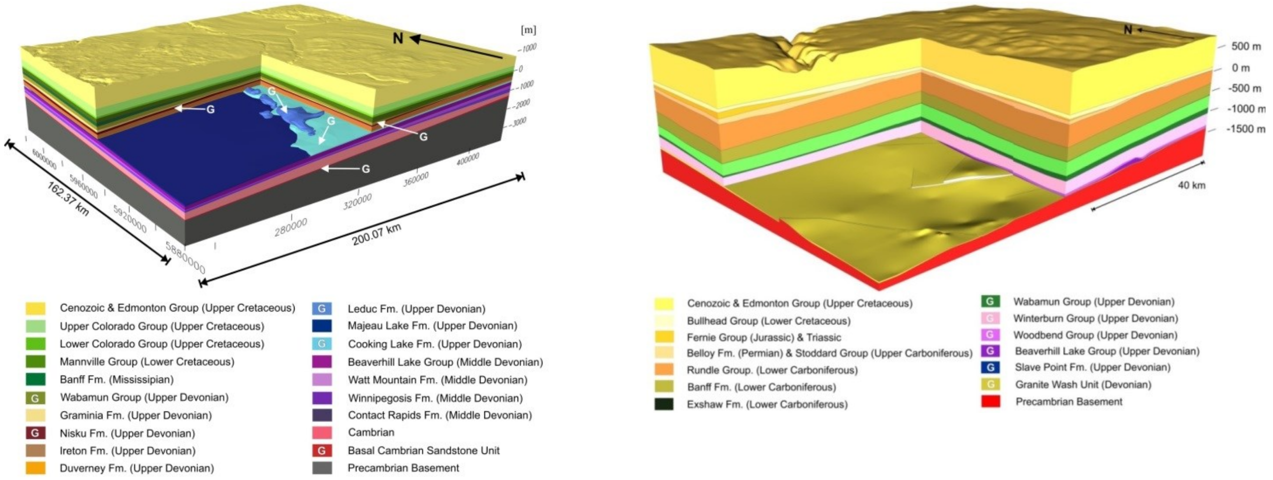

Fig. 2: 3D structural geological model of the central Alberta (left) and northwestern Alberta (right) study areas based on seismic data and well log data from more than 1000 wells. Potential geothermal target formations are marked with the letter "G" in the legend (from Weides et al. 2013, 2014a).

2.2 3D fault modelling

For the northwestern Alberta study area, existing 2D seismic data from hydrocarbon exploration (eight seismic lines with a total length of 177 km) were re-interpreted for the development of a 3D fault model (Fig. 3). The strike direction of the faults was interpreted in consideration of lineaments from the literature (Mei 2006, 2009b), and by identification of lineaments in the dataset by applying the refined trend surface analysis method by Mei (2009a) (Fig. 3, Fig. 5). Using this approach, small-scale formation-top offsets were extracted from the database of formation-top picks by using geostatistical analysis and trend surface analysis (Mei 2009a). After removal of a geologist-controlled trend (Mei 2009a) from the data, a residual map for selected formation tops was generated. Linear trends were identified on this residual map which could be caused by faults, or by a change in slope. Using this approach from Mei (2009a), residual maps for the Permian Belloy Fm., the Carboniferous Banff Fm. and the Devonian Wabamun Fm. were generated and lineaments were mapped. Fig. 3 shows the residual map for the Belloy Fm., with the newly identified lineaments of Belloy, Banff and Wabamun formations. Also included are lineaments from Mei (2006), the seismic lines, and the identified faults with the interpreted fault strike. Based on the seismic interpretation of the 2D seismic data and the interpreted lineaments, the 3D fault model was developed using EarthVision® modelling software (Dynamic Graphics Inc.).

2.3 Stress regime and stress state of faults

The stress state of the Granite Wash reservoirs was determined by an integrated approach of 3D fault modelling, stress ratio definition based on frictional constraints, and slip tendency analysis (Fig. 4, Fig. 5). With the slip-tendency analysis (Morris et al. 1996) critically stressed and dilational segments along the faults in the Granite Wash reservoirs of northwestern Alberta were identified. Fault segments are regarded as being critically stressed when the ratio of shear to normal stress acting on the fault plane exceeds the frictional strength of reservoir rock. The pore pressure reduces the total stress, and is therefore reconsidered in the stress ratio calculation. The effective stresses at the reservoir depth of 2262 m are S_{veff} = 29.8 MPa, $S_{Hmaxeff}$ = 35.7 MPa and $S_{Hmineff}$ = 14.7 MPa (see Weides et al. 2014a) (Fig.4). The azimuth of S_{Hmax} is assumed to be 20°, as data from the World Stress Map (Heidbach et al. 2008) measured approximately 70 km east of the study area indicate.

2.4 Porosity and Permability analysis

Porosity and permeability of the potential geothermal target formations were investigated by conduction of core tests (in case of the BSU in central Alberta) and using core analysis data from IHS AccuMap (IHS Energy 2012) for the Granite Wash Unit in northwestern Alberta. Core analysis data represent volume-averaged values corresponding to the sample size, which means they represent matrix properties and not larger scale features such as fractures or vugs. As porosity and permeability of rocks may vary within short distances both vertically and laterally, the individual results from core analyses are only representative on the cm-scale. To investigate regional-scale (km-scale) trends in the data, the small-scale core analysis data were scaled up to well scale by calculating average values for each well. Following the approach of Bachu and Underschultz (1992), the arithmetic average was used for porosity values (which show a normal distribution) and the geometric average was used for permeability values (which show a lognormal distribution). Up-scaling to average regional-scale values was conducted by calculation of the geometric average of the well-scale values. For the calculation, only datasets from wells which contain at least 5 single core tests where used.

The upscaled porosity and permeability data (i.e. well-scale) were mapped using kriging ore inverse distance weighting, to detect zones where these properties are elevated (Fig. 7b,c).

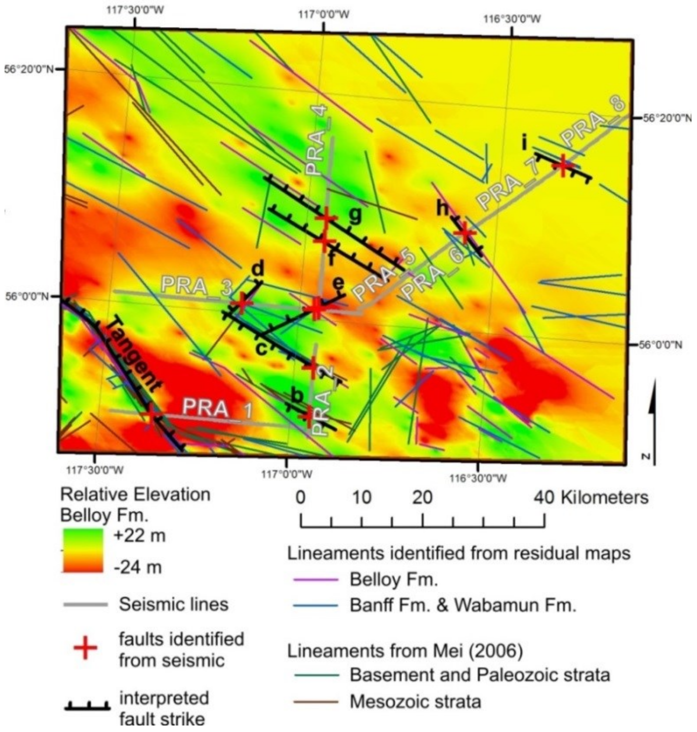

Fig. 3: Residual map for the Belloy Fm (calculated with the approach of Mei, 2009a). Superimposed are newly identified lineaments of Belloy, Banff and Wabamun formations, the lineaments from Mei (2006) and the location of the 2D seismic lines with the identified faults. The strike of the faults was interpreted in consideration of the lineaments (from Weides et al. 2014a).

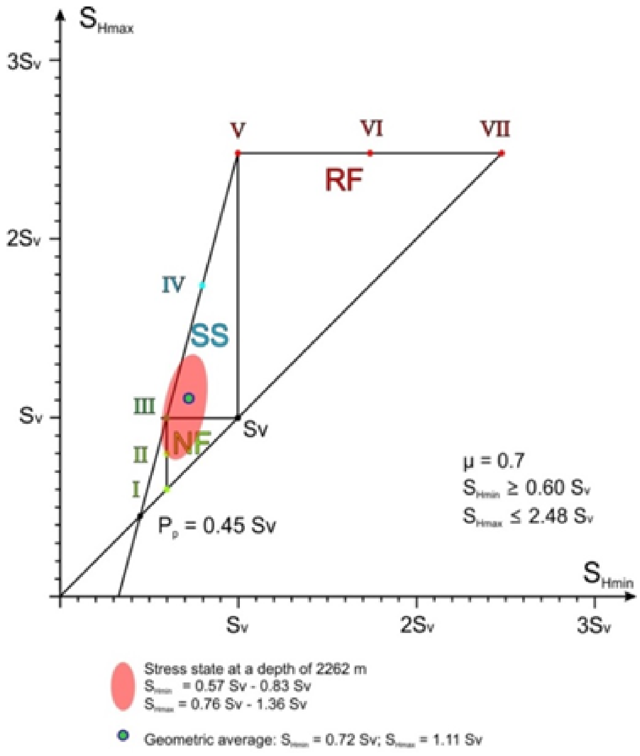

Fig. 4: Allowable horizontal stresses S_{Hmax} and S_{Hmin} in the crust based on the frictional equilibrium (after Peška and Zoback 1995 and Moeck 2009b). The stress polygon is normalized to S_v at the depth of 2262 m (53.8 MPa). The friction coefficient is assumed to be μ = 0.7. The pore pressure of 24.3 MPa was calculated for a Granite Wash brine with a density of 1162 kg/m^3 (from Michael and Buschkühle, 2008) assuming a constant increase of brine salinity with depth. NF normal faulting, SS strike slip, RF reverse faulting. I–VII cases of stress regimes defined by certain stress ratios. I radial extension, II normal faulting, III transition normal–strike slip faulting (hybrid case), IV strike slip faulting, V transition strike slip–reverse faulting, VI reverse faulting, VII radial compression (from Weides et al. 2014a).

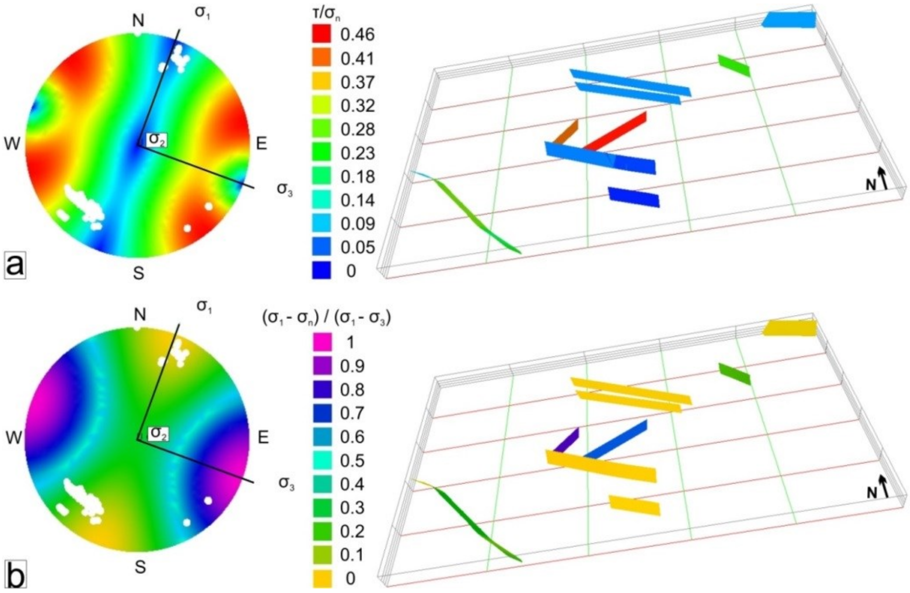

Fig. 5: Slip and dilation tendency plots for the fault planes from the 3D structural model *a: (left side)* the slip tendency and fault poles are displayed in the lower hemisphere projection; *(right side)* the spatial extension of the fault system and slip tendency along the faults are visualized in the 3D fault model. The slip tendency for a given fault is indicated on the color scale. Red indicates a relatively high slip tendency and blue indicates a relatively low slip tendency. b: (left side): the dilation tendency and fault poles are displayed in the lower hemisphere projection; *(right side)*: dilation tendency along the faults is visualized in the 3D fault model. The dilation tendency for a given fault is indicated on the color scale where purple indicates a relatively high dilation tendency and yellow indicates a relatively low dilation tendency (from Weides et al. 2014a).

2.5 Mapping of thermal gradient and temperature

The geothermal gradient in the formations was calculated from temperature values from thousands of wells. The temperature data were derived from bottom hole temperature measurements (BHTs), temperature measurements from drill stem tests (DSTs) and annual pressure and temperature tests in shut in wells. This data set was compiled from data published in Majorowicz and Moore (2008), Majorowicz and Grasby (2010), Gray et al. (2012), Majorowicz et al. (2012) and Weides and Majorowicz (2014). Where information about circulation times was available, the data from BHTs were corrected using the Horner method (Lachenbruch and Brewer 1959). The rest were corrected using the standard AAPG Harrison correction (Harrison et al. 1983). The distribution of the thermal gradient in the sedimentary succession was mapped using the simple kriging method. With kriging, unbiased estimates of regionalized variables at unsampled locations are made using the structural properties of the semivariogram and the initial set of data values (David 1977). The raster of the thermal gradient map was then multiplied with the raster of a Precambrian depth map, resulting in a temperature map for the top of the Precambrian (i.e., the base of the BSU).

3. RESULTS

3.1 Potential geothermal target formations in Alberta

Central Alberta

In central Alberta five Paleozoic formations were identified as potentially usable for geothermal applications: The Cambrian Basal Sandstone Unit (BSU), the Devonian Cooking Lake, Leduc, and Nisku formations, and the Devonian Wabamun Group.

Due to its depth related high temperature and its extension throughout central Alberta, the BSU is the most favorable formation for further geothermal prospection in central Alberta. The unit is distributed throughout the entire study area at a depth of 1785–3490 m (Fig. 6a), and has a thickness of 28–45 m (Fig. 6b). The temperature of the BSU in the study area ranges from 65–120 °C (Fig. 6d). Beneath the Edmonton metropolitan area the BSU is located at a depth of 2.4–2.6 km and has a temperature of 79–93 °C. Porosity (measured from core samples) is between 5.3–19.6 %. A general trend of increasing porosity with decreasing depth is identified for the BSU in central Alberta and is interpreted as typical diagenetic effect in sandstones exhibiting a linear relationship of porosity-permeability ratio versus depth (Moeck 2014). Permeability of the BSU (measured with probe permeametry) is generally low, with values less than 10×10^{-15} m^2. However, in one well a highly permeable (> 100×10^{-15} m^2) section was identified. Geomechanical tests showed that the BSU has relatively high unconfined compressive strength (up to 97.7 MPa), high cohesion (up to 69.8 MPa) and remarkably high values for the friction coefficient (up to 1.22), while the tensile strength is rather low (less than 5 MPa). Due to the low thickness and the relatively low matrix porosity and permeability horizontal drilling and hydraulic stimulation treatments would be required to achieve sufficient flow rates for geothermal heat production (see also results from numerical reservoir simulations from Hofmann et al. 2014).

In all four Devonian carbonate formations positive porosity- and permeability anomalies exist, with values exceeding 20 % and 100×10^{-15} m^2, respectively. In combination with the large average thickness of the units, which ranges from 60 m (Cooking Lake) to more than 300 m (Leduc), high flow rates can be expected for parts of Devonian formation. The temperature in the Devonian units ranges from 22–88 °C at a depth of 0.6–2.5 km for the whole central Alberta study area, and from 38 °C (Wabamun) to 63 °C (Cooking Lake) in the Edmonton metropolitan area.

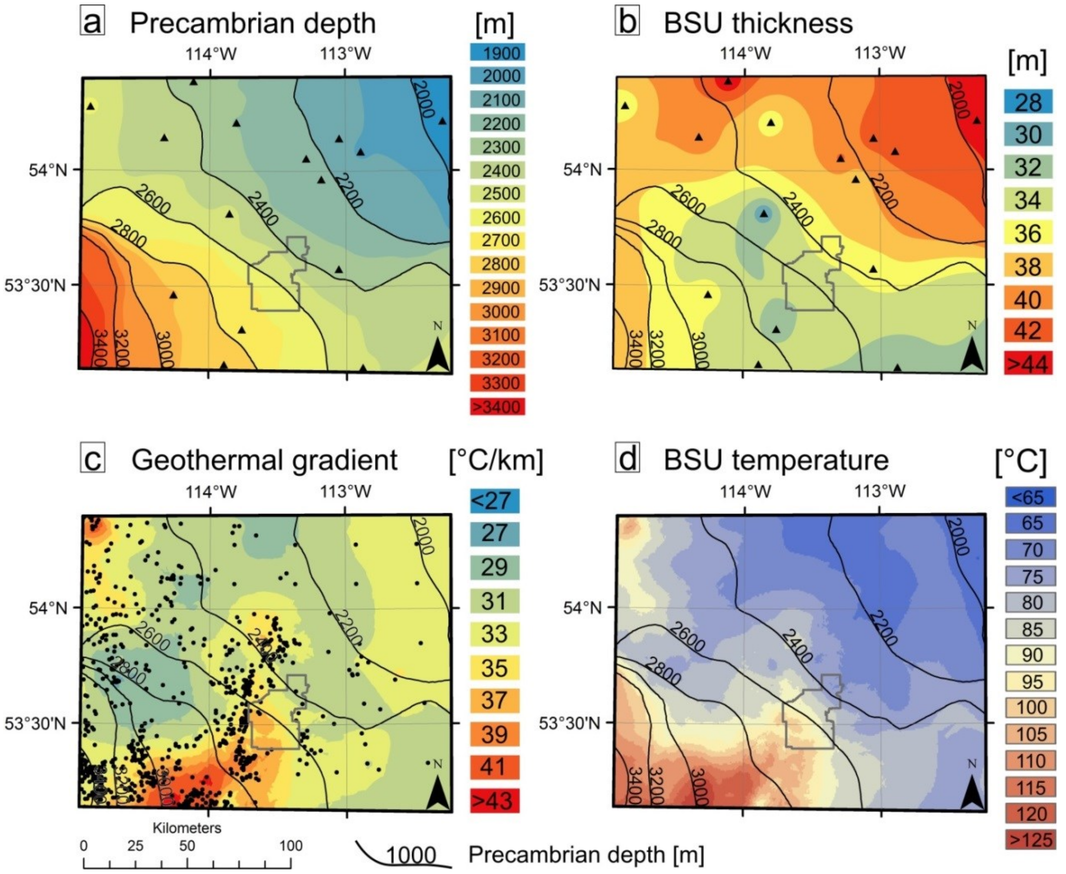

Fig. 6: a: Map showing the depth from ground surface to the top of the Precambrian basement (i.e., the base of the BSU), based on 15 wells; inverse distance weighting method (IDW) was used for interpolation; b: Thickness map of the BSU, based on 15 wells, calculated with IDW; c: Geothermal gradient map of the Phanerozoic succession, based on approximately 2000 temperature values from 615 wells; map was calculated using the simple kriging method; d: Map of the temperature distribution at the base of the BSU; map was calculated by multiplication of raster maps a and b, assuming a surface temperature of 0°C to be in equilibrium with the deeper Basin (see Majorowicz et al. 2012) (from Weides et al. 2014b).

Northwestern Alberta

In the northwestern Alberta study area the Devonian Granite Wash Unit is a potential geothermal target formation. The unit is located at a depth of 1.6–2.4 km and has a temperature ranging from 51–75 °C (Fig. 7d). The thickness of the unit is generally low, ranging from few meters to 38 m (Fig. 7a). The average porosity and permeability of the Granite Wash Unit are quite low (7.4 % porosity and less than 5×10^{-15} m^2 permeability), but positive anomalies exist in the southwestern and southeastern part of the study area. The most promising zone for geothermal applications is located in the southwestern part of the study area, where elevated porosity (10–12 %) and permeability ($1–4 \times 10^{-14}$ m^2) coincide with temperatures of more than 75 °C. Due to the low thickness of the unit, horizontal drilling would be needed to achieve economic flow rates from the Granite Wash Unit.

3.2 Stress state of faults

The stress state of faults was analyzed for the stress conditions at 2262 m depth in a Granite Wash reservoir in northwestern Alberta using an integrated approach of 3D structural geological mapping, stress ratio definition based on frictional constraints, and slip tendency analysis under consideration of existing stress magnitude data from literature. The in-situ stress state at the depth of the Granite Wash Unit is a strike-slip regime with $S_{Hmax} = 1.11\ S_v$ ($\pm 0.19\ S_v$) and $S_{Hmin} = 0.72\ S_v$ ($\pm 0.06\ S_v$). The vertical stress S_v in the reservoir depth of 2262 m is 53.8 MPa. The results from the slip tendency analysis indicate that under these stress conditions none of the interpreted faults is critically stressed. The highest slip tendency exists for the NE–SW striking faults (0.4–0.46). Faults striking in this direction also have the highest dilation tendency (0.7–0.9).

3.3 Thermal state of the Alberta Basin and temperature distribution of potential geothermal target formations in Alberta

The heat flow and thermal state of the sedimentary succession of the Western Canada Sedimentary Basin (WCSB)—of which the Alberta Basin represents the largest central part—were mapped based on a large thermal database consisting of more than 68,000 temperature values from more than 26,000 wells.

The heat flow in the Alberta Basin generally ranges from 30–90 mW/m^2, and is approximately 60 mW/m^2 on average (Fig. 8). Generally a northerly trend of increasing heat flow exists, with the highest heat flow being found in the northwesternmost part of Alberta. Positive heat flow anomalies exist in the western central Alberta Basin (west and southwest of Edmonton), while negative heat flow anomalies are found in northeastern Alberta (south of Fort McMurray) and in southern Alberta in the area of Calgary. The distribution of the thermal gradient follows the same trend of increasing values towards the northern Alberta Basin.

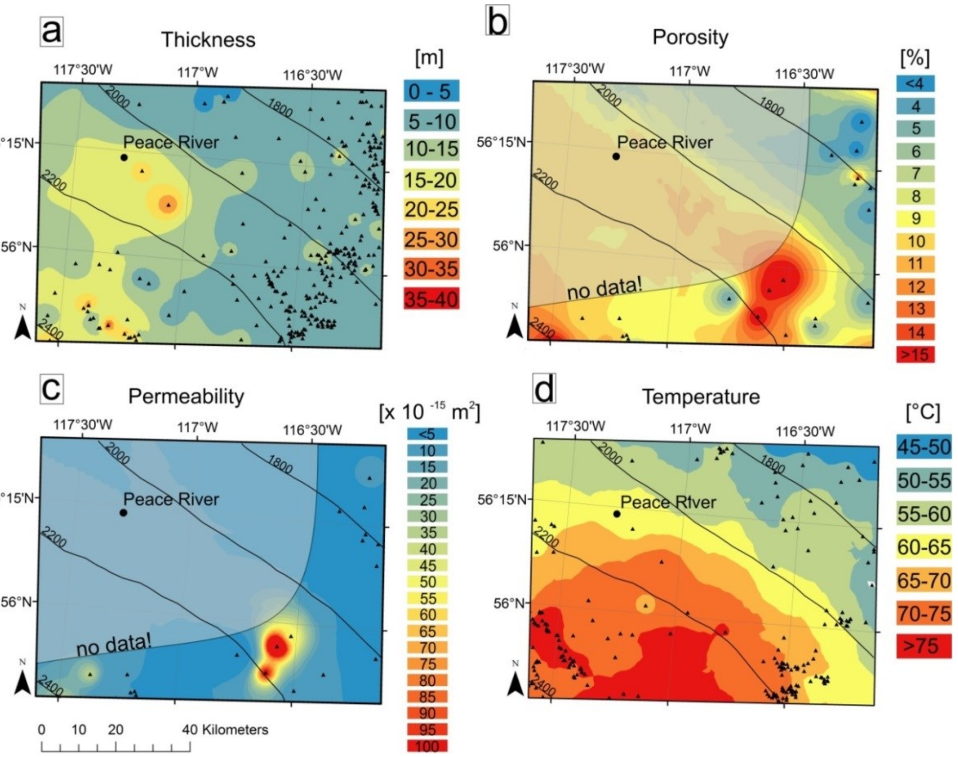

Fig. 7: Properties of the Granite Wash Unit. *a*: thickness distribution based on well log data and mapped with inverse distance weighting (IDW) *b*: porosity distribution based on upscaled core analysis data and mapped with IDW; for the northwestern part of the study area no core analysis data was available *c*: distribution of maximum horizontal permeability (Kmax) based on upscaled core analysis data and mapped with IDW; for the northwestern part of the study area no core analysis data was available. *d*: temperature map based on the geothermal gradient from 265 wells and on depth distribution (from well log data); contours are in metres below ground surface; black triangles represent wells with well log data (*a*), wells with core analysis data (*b* & *c*) or wells with temperature measurements (*d*) (from Weides et al. 2014a).

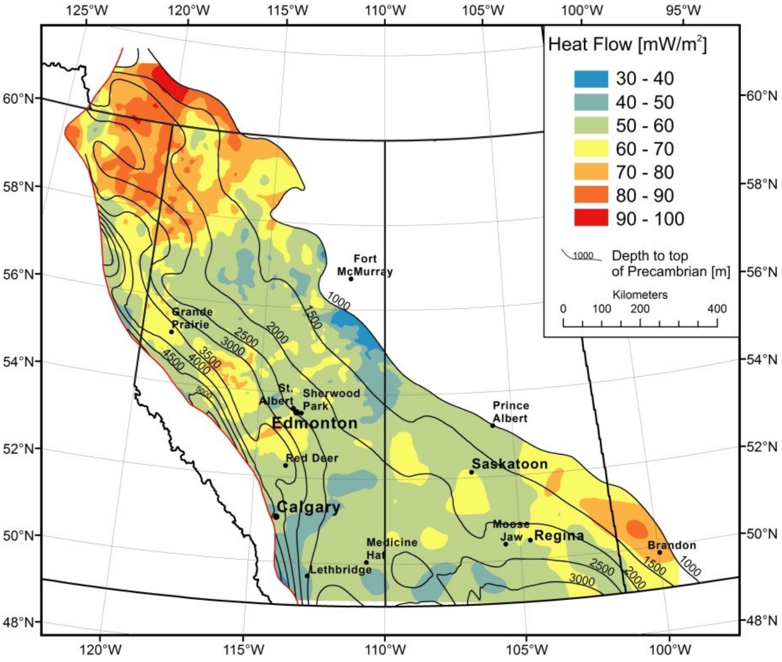

Fig. 8: Heat flow of the WCSB; map was calculated using the simple kriging algorithm (from Weides & Majorowicz 2014).

The geothermal gradient in the Alberta Basin ranges from 20–55 °C/km, with an average value of about 33 °C/km.

Temperatures at the base of the Phanerozoic succession in Alberta are > 180 °C in the vicinity to the Cordillera in western Alberta. In the most urbanized area of Alberta, the Calgary-Edmonton corridor, temperatures at the base of the Phanerozoic are between

80–140 °C at a depth of 2.5–4 km. At the top of the Devonian Winterburn Group, temperatures from 51–75 °C are found in this area at a depth of 1.3–3.1 km.

3.4 Potential applications for geothermal energy in Alberta

The low (< 90 °C) to intermediate enthalpy (< 150 °C) geothermal resources of the Alberta Basin offer a good potential for different direct heat use applications (categorization from Muffler and Cataldi 1978).

In the Calgary–Edmonton corridor fluid temperatures at the base of the Phanerozoic are high enough to be used for district heating purposes. If economic flow rates can be achieved, geothermal heat production from the BSU appears as a feasible option for domestic heat provision and warm water provision in the area. Hereby fluids from overlying Devonian carbonates could be co-produced to increase the total flow rate of a geothermal well. Provision of heat for industrial applications, e.g. in the refineries of the Edmonton metropolitan area could also be an application for direct-use of geothermal resources. In the Peace River region of northwestern Alberta geothermal heat could be used to feed the large heat demand of the greenhouses farming industry.

Electrical power production from geothermal heat is generally possible if temperatures exceed 100 °C. As the efficiency of geothermal power plants is better at higher fluid temperatures, electricity production is only possible in the warmest (and deepest) part of the Alberta basin in vicinity to the Cordillera in westernmost Alberta. A good location for a geothermal power plant would be the area near Hinton in western Alberta, where temperatures in the Leduc Formation at a depth of 5 km are above 150 °C. Another favorable location is found at the western margin of the Calgary-Edmonton corridor at the geothermal anomaly around the hamlet of Winfield, located 100 km southwest of Edmonton and in direct vicinity to the Altalink transmission line, where temperatures above 150 °C are found in the BSU at a depth of 3.7 km. Geothermal power production could also be an option for remote communities in northern Alberta, which are currently dependent on expensive diesel fuel transports. Here, even electricity production from resources < 150 °C could be economically competitive.

4. DISCUSSION

This assessment study benefitted from the large number of well log data and core analysis data which enabled the development of 3D geological models and the mapping of rock properties. With help of these models and maps it was possible to describe the depth, thickness and extension of potential geothermal aquifers and to investigate porosity, permeability and temperature distribution. Based on the results of these investigations it is possible to delineate the best sites for detailed reservoir studies which could then be followed by drilling of a first geothermal well and subsequent development of a geothermal heat (or power) plant. This approach as presented in this study could be applied in other areas of the WCSB, or in other conduction dominated geothermal systems in the world where sufficient pre-existing data are available.

Future assessment studies in these geothermal systems would benefit from using geological well log data and results from Drill Stem Tests (DST), both of which were not available for this study. Using well logs as input data instead of or in combination with core analysis data would strengthen the analysis of porosity distribution within a formation, as well logs provide information over the whole thickness of the formation and not only at the cm-scale of the core sample. Therefore well logs account for larger scale feature such as fractures, while core tests measure matrix porosity only. Beyond this, core samples are often taken preferentially from well sections of interest to the particular study, and are not systematically sampled over the whole thickness of the formation. Well log interpretation would reduce this effect of preferential sampling. With well logs as input parameters the distribution of porosity could also be easier mapped in 3D, which would allow for better identification of vertical and lateral facies changes within a formation. DST`s could be used to investigate flow rates, which could subsequently be compared to the porosity and permeability values. High flow rates are crucial for the success of a geothermal well, and while analyzing porosity and permeability of formations is a relatively good method to delineate favorable locations for a geothermal well, it must be emphasized that high porosities and permeabilities do not necessarily result in high flow rates.

Conduction-dominated geothermal play types such as the Alberta Basin can in most cases only be developed using engineered geothermal systems (EGS), which requires knowledge of geomechanical parameters of the reservoir rock and the in-situ stress field (Moeck and Beardsmore 2014). Investigation of these parameters (and subsequent hydraulic reservoir modeling; see also Hofmann et al. 2014) as it was conducted for the BSU in central Alberta is an important part of a geothermal assessment study in any conduction-dominated geothermal system.

Knowledge of faults and on their stress state (as investigated in the Peace River area) is also an important part of a geothermal assessment study in conduction-dominated geothermal systems for two main reasons. On the one hand it is important to account for possible movement on fault planes and related seismicity that can occur when the in-situ stress field is changed due to production or injection of fluids during geothermal heat production. On the other hand faults can also play an important role as fluid conduit (or barrier) during geothermal production (Moeck and Beardsmore 2014), and can therefore be preferential targets for a geothermal well (as for example in parts of the German Molasse Basin). For the Alberta Basin the influence of faults on the fluid flow has not been investigated as part of this study and remains an important open question for future geothermal assessment.

5. FUTURE STEPS GOR A GEOTHERMAL DEVELOPMENT IN ALBERTA

Depending on the desired end-use a suitable location for a first geothermal development can be determined using the results of this study (see 0 this chapter for potential locations in Alberta). For this site, a small scale (5 km × 5 km) structural geological model of the reservoir should be developed based on 3D seismic data and pre-existing well log data. The distribution of porosity, permeability and temperature should be mapped, and the stress state of faults in the recent stress field should be analyzed to identify faults with high slip- and dilation tendency. With numerical reservoir simulations the perfect combination of well path design and hydraulic stimulation scenario for this site can then be identified. The reservoir model should continuously be updated with parameters from core testing and well logging after the first well has been drilled into the reservoir.

Alberta has a long tradition of hydrocarbon production with more than 300,000 wells drilled until today. Many of these wells penetrate the oil and gas reservoirs of the Upper Devonian carbonates of the Wabamun Group, and Nisku and Leduc formations, which were identified a potential geothermal target formations in this study. With regard to the large number of wells it would be worthwhile to investigate whether it is possible to use some of the „old“ wells from depleted oil- or gas reservoirs to produce geothermal heat.

Beyond this, the utilization of supercritical CO_2 as transport fluid might be an option to increase the efficiency of geothermal heat production from the low temperature and relatively low permeable reservoirs of Alberta. CO_2 is anticipated to be a better geothermal fluid than water with an average heat extraction rate 50% greater than that of water (Eastman and Muir 2013). With this concept, which until today has only been applied in demonstration projects, the geothermal reservoirs of Alberta could be used for both geothermal heat production and CO_2 sequestration. A combined use of CO_2 sequestration and geothermal production could reduce Alberta`s rapidly growing CO_2 emissions and lower the dependency of fossil fuel based energy sources and the related environmental problems that exist in the province. The BSU reservoirs northeast of Edmonton, which are already used for underground CO_2 sequestration (Shell 2010a, 2011) would be an optimal site for the worldwide first combined commercial CO_2-EGS and CO_2-sequestration operation.

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REFERENCES

Bachu, S.: Basement heat flow in the Western Canada sedimentary basin. Tectonophysics 222(1), (1993), 119-133.

Bachu, S.: Synthesis and model of formation-water flow, Alberta Basin, Canada. AAPG Bulletin-American Association of Petroleum Geologists 79(8), (1995), 1159-1178.

Bachu, S. and Burwash, R.A.: Regional-scale analysis of the geothermal regime in the Western Canada Sedimentary Basin. Geothermics 20 (5), (1991), 387-407.

Bachu, S. and Burwash, R.: Geothermal regime in the Western Canada sedimentary basin. Geological Atlas of the Western Canada Sedimentary Basin, G Mossop and I Shetsen, compilers, Canadian Society of Petroleum Geologists and Alberta Research Council, Special Report:447-454, (1994).

Bachu, S. and Underschultz, J.R.: Regional-scale porosity and permeability variations, Peace River Arch area, Alberta, Canada. AAPG Bulletin 76 (4), (1992), 547-562.

Bell, J., and Weis, T.: Greening the Grid: Powering Alberta's Future with Renewable Energy. Pembina Institute for Appropriate Development, Canada, (2009).

Blackwell, D., and Richards, M.: Geothermal Map of North America: American Association of Petroleum Geologists. Tulsa, Oklahoma, scale (1:6,500,000), (2004).

David, M.: Geostatistical ore reserve estimation, Elsevier Scientific Publishing Company, New York (1977).

Dynamic Graphics Inc.: EarthVision 8.1 User´s Guide. Dynamic Graphics, Alameda, CA, (2009).

Eastman, A., and Muir, M.: CO2 EGS and the utilization of highly pressured CO2 for purposes other than power generation. In Transactions of the Thirty-Eighth Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 11-13, (2013).

Ferguson, G., and Grasby, S.E.: The geothermal potential of the basal clastics of Saskatchewan, Canada. Hydrogeology Journal 22 (1), (2014), 143-150.

Ferrill, D.A. and Morris, A.: Dilational Normal Faults. Journal of Structural Geology 25 (2), (2003), 183-196.

Garland, G. and Lennox, D.: Heat Flow in Western Canada. Geophysical Journal International 6, (1962), 245-262.

Grasby, S., Majorowicz, J. and Ko, M.: Geothermal maps of Canada. Geological Survey of Canada, Open File 6167:35, (2009).

Grasby, S.E., Allen, D.M., Chen, Z., Ferguson, G., Jessop, A., Kelman, M., Majorowicz, J., Moore, M., Raymond, J. and Therrien, R.: Geothermal energy resource potential of Canada. Geological Survey of Canada, Calgary, Canada, (2011).

Gray, D.A., Majorowicz, J. and Unsworth, M.: Investigation of the geothermal state of sedimentary basins using oil industry thermal data: case study from Northern Alberta exhibiting the need to systematically remove biased data. Journal of Geophysics and Engineering 9 (5), (2012), 534-548.

Harrison, W., Luza, K., Prater, M., and Chueng, P.: Geothermal resource assessment of Oklahoma, Oklahoma Geological Survey Special Publication SP 83-1, 1983, Oklahoma.

Heidbach, O., Tingay, M., Barth, A., Reinecker, J., Kurfeß, D., and Müller, B.: The World Stress Map database release 2008, (2008), doi:10.1594/GFZ.WSM.Rel2008.

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, (2014), 578–591.

IHS Energy: IHS Accumap. Commercial database IHS Energy, Englewood, CO, (2012).

Jaeger, J., Cook, N., and Zimmerman, R.: Fundamentals of Rock Mechanics, 4th edn. Blackwell, Malden, Massachusetts, (2007).

Jessop, A.M., and Vigrass, L.W.: Geothermal measurements in a deep well at Regina, Saskatchewan. Journal of Volcanology and Geothermal Research 37 (2), (1989), 151-166.

Jessop, A., Lewis, T., Judge, A., Taylor, A., and Drury, M.: Terrestrial heat flow in Canada. Tectonophysics 103 (1), (1984), 239-261

Jessop, A.M., Allen, V., Bentkowski, W., Burgess, M., Drury, M., Judge, A.S., Lewis, T., Majorowicz, J., Mareschal, J., and Taylor, A.: The Canadian geothermal data compilation. Geological Survey of Canada, Open File 4887, (2005).

Jones, F., Lam, H.-L., and Majorowicz, J.: Temperature distributions at the Paleozoic and Precambrian surfaces and their implications for geothermal energy recovery in Alberta. Canadian Journal of Earth Sciences 22(12), (1985), 1774-1780.

Lachenbruch, A.H., and Brewer, M.C.: Dissipation of the temperature effect of drilling a well in Arctic Alaska. US Geol. Surv. Bull. 1083, (1959), 73-109.

Lam, H., and Jones, F.: Geothermal energy potential in the Hinton-Edson area of west-central Alberta. Canadian Journal of Earth Sciences 22 (3), (1985), 369-383.

Lam, H., and Jones, F.: An investigation of the potential for geothermal energy recovery in the Calgary area in southern Alberta, Canada, using petroleum exploration data. Geophysics 51 (8), (1986), 1661-1670.

Levorsen, A.: Geology of petroleum. WH Freeman, New York, (1967).

Líndal, B. Industrial and other applications of geothermal energy:(except power production and district heating). *In*: Geothermal Energy: Review of Research and Development. UNESCO, Paris, pp 135-148, (1973).

Majorowicz, J.A.: Anomalous heat flow regime in the western margin of the North American craton, Canada. Journal of geodynamics 21 (2), (1996), 123-140.

Majorowicz, J., and Grasby, S.E.: Heat flow, depth–temperature variations and stored thermal energy for enhanced geothermal systems in Canada. Journal of Geophysics and Engineering 7 (3), (2010a), 232

Majorowicz, J., and Grasby, S.E.: High potential regions for enhanced geothermal systems in Canada. Natural resources research 19 (3), (2010b), 177-188.

Majorowicz, J., and Jessop, A.: Regional heat flow patterns in the western Canadian sedimentary basin. Tectonophysics 74 (3), (1981), 209-238.

Majorowicz, J. and Moore, M.C.: Enhanced Geothermal Systems (EGS) Potential in the Alberta Basin. University of Calgary, Institute for Sustainability, Energy, Environment and Economy, Calgary, (2008).

Majorowicz, J., Jones, F., Lam, H., and Jessop, A.: Terrestrial heat flow and geothermal gradients in relation to hydrodynamics in the Alberta Basin, Canada. Journal of geodynamics 4 (1), (1985), 265-283.

Majorowicz, J.A., Garven, G., Jessop, A., and Jessop, C.: Present heat flow along a profile across the Western Canada Sedimentary Basin: the extent of hydrodynamic influence. In: Geothermics in basin analysis. Springer, pp 61-79, (1999).

Majorowicz, J., Gosnold, W., Gray, A., Safanda, J., Klenner, R., and Unsworth, M.: Implications of Post-Glacial Warming for Northern Alberta heat flow- correcting for the underestimate of the geothermal potential. *In:* GRC Transactions 36:693-698, (2012).

Mei, S.: Structures and Faults in the Peace River Arch Region, Alberta, 2006 (GIS Data, line features). Energy Resources Conservation Board, (2006). http://www.ags.gov.ab.ca/publications/abstracts/DIG_2007_0011.html. Accessed 28 March 2014,

Mei, S.: Geologist-controlled trends versus computer-controlled trends: introducing a high-resolution approach to subsurface structural mapping using well-log data, trend surface analysis, and geospatial analysis. Canadian Journal of Earth Sciences 46 (5), (2009a), 309-329.

Mei, S.: New insights on faults in the Peace River Arch region, northwest Alberta, based on existing well-log data and refined trend surface analysis. Canadian Journal of Earth Sciences 46 (1), (2009b), 41-65.

Michael, K., and Buschkuehle, B.: Subsurface Characterization of Acid-Gas Injection Operations in the Peace River Arch area. Energy Resources Conservation Board ERCB/AGS Special Report (090):186 p. (2008).

Moeck, I.: Catalog of geothermal play types based on geologic controls. Renewable & Sustainable Energy Reviews (in press). 2014.

Moeck IS, Beardsmore G (2014) A new 'geothermal play type' catalog: Streamlining exploration decision making. Thirty-Ninth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 24-26, 2014,SGP-TR-202

Moeck, I., Kwiatek, G., and Zimmermann, G.: Slip tendency analysis, fault reactivation potential and induced seismicity in a deep geothermal reservoir. Journal of Structural Geology 31 (10), (2009a), 1174-1182.

Moeck, I., Schandelmeier, H., and Holl, H.-G.: The stress regime in a Rotliegend reservoir of the Northeast German Basin. International Journal of Earth Sciences 98 (7), (2009b), 1643-1654.

Morris, A., Ferrill, D.A., and Henderson, D.B.: Slip-tendency analysis and fault reactivation. Geology 24 (3), (1996), 275-278.

Muffler, P., and Cataldi, R:. Methods for regional assessment of geothermal resources. Geothermics 7(2), (1978), 53-89.

National Climate Data and Information Archive: Canadian Climate Normals 1971-2000. http://climate.weatheroffice.gc.ca/climate_normals. Accessed 28 February 2012.

Porter, J., Price, R., and McCrossan, R.: The western Canada sedimentary basin. Philosophical Transactions of the Royal Society of London Series A, Mathematical and Physical Sciences 305 (1489), (1982), 169-192.

Schmitt, D.R., Currie, C.A., and Zhang, L.: Crustal stress determination from boreholes and rock cores: Fundamental principles. Tectonophysics 580 (0), (2012),1-26. doi:http://dx.doi.org/10.1016/j.tecto.2012.08.029

Shell: Quest Carbon Capture and Storage Project; Directive 65: Application for a CO2 acid gas storage scheme. Available from http://s05.static-shell.com/content/dam/shell-new/local/country/can/downloads/pdf/aboutshell/our-business/oil-sands/quest/d65-main-report-appai.pdf, (2010), [accessed 6 January 2014].

Shell: Quest Carbon Capture and Storage Project; update to directive 65: Application for a CO2 acid gas storage scheme. Available from http://s08.static-shell.com/content/dam/shell-new/local/country/can/downloads/pdf/aboutshell/our-business/oil-sands/quest/quest-d65-updatejune2011.pdf, (2011), [accessed 6 January 2014].

Vigrass, L.: Final well report U or R Regina 3-8-17-19 (W.2nd.Mer.) Saskatchewan. Earth Physics Branch Open File, vol 79-9. Regina, Saskatchewan, Canada, (1979).

Walsh, W.: Geothermal resource assessment of the Clarke Lake Gas Field, Fort Nelson, British Columbia. Bulletin of canadian petroleum geology 61 (3), (2013), 241-251.

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(4), (2014), 2573-2594.

Weides, S., Moeck, I., Majorowicz, J., Palombi, D., and Grobe, M.: Geothermal exploration of Paleozoic formations in Central Alberta. Canadian Journal of Earth Sciences 50 (5), (2013), 519-534. doi:10.1139/cjes-2012-0137

Weides, S., Moeck, I., Schmitt, D., and Majorowicz, J.: An integrative geothermal resource assessment study for the siliciclastic Granite Wash unit, north western Alberta (Canada). Environmental Earth Sciences (2014a), published online first 10 May 2014, doi: 10.1007/s12665-014-3309-3.

Weides, S., Moeck, I., Majorowicz, J., and Grobe, M.: The Cambrian Basal Sandstone Unit in central Alberta – an investigation of temperature distribution, petrography and hydraulic and geomechanical properties of a deep saline aquifer. Submitted to Canadian Journal of Earth Sciences (2014b), published online first 10 July 2014.

Wright, G., McMechan, M., and Potter, D.: Structure and architecture of the Western Canada sedimentary basin. Geological Atlas of the Western Canada Sedimentary Basin, G Mossop and I Shetsen, compilers, Canadian Society of Petroleum Geologists and Alberta Research Council, Special Report 4:25-40, (1994).