Interactive comment on "From oil field to geothermal reservoir: First assessment for geothermal utilization of two regionally extensive Devonian carbonate aquifers in Alberta, Canada" by Leandra M. Weydt et al.

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Author's comment on "Referee comment 4 – general comment" by Jean Borgomano

Dear Jean Borgomano,

Thank you very much for your very valuable and helpful comments to improve our manuscript. Please see our answers below.

Referee 4 – C1 line 11: *"a missing topic in this interesting chapter is the "upscaling-donwscaling" of the properties (reservoir and geothermal)"*

Answer: We agree that upscaling and downscaling of the rock properties is essential for reservoir modelling. As far as we did not model in this study, we did not elaborate this point in this manuscript. For the upscaling of the rock properties from plug to reservoir scale, further data should be included, which is beyond the scope of this study.

So we agree to give information about "upscaling-downscaling" according to the hint of Referee 4:

- upscaling in porous media: e.g. Renard et al. (1997), Farmer (2002)
- stratigraphy based upscaling permeability and porosity in carbonate platforms: e. g. Leonide et al. (2012), Borgomano et al. (2013), Brigaud et al. (2014)
- upscaling of thermal conductivities: Rühaak et al. (2015).

Reservoir properties of carbonate rocks and their upscaling are related to architecture and facies. Nevertheless, our results show that (pervasive) dolomitization has affected the reservoir parameters of the Western Canadian Sedimentary Basin in an equitable degree.

Referee 4 – C2 line 1: *“Another implicit assumption is that rock properties statistics are not dependent of sample size (no "support effect").”*

Answer: We do not claim that property statistics are independent from sample size. According to the hint of Referee 4 we will consider this point and add it to the section about upscaling and downscaling.

Further comments are included in in the supplementary material: https://www.solid-earth-discuss.net/se-2017-129/se-2017-129-RC4-supplement.pdf

Referee 4 – p. 3 line 21: *“what are precisely these "properties" and at what scale are they considered? Be more precise here“*

Answer: Homuth et al. (2015) analyzed density, porosity, permeability, thermal conductivity, thermal diffusivity and specific heat capacity on plugs from more than 350 samples taken from 19 outcrops in the Swabian and Franconian Alb as well as on core samples and cutting material from wells in the Molasse Basin in order to obtain a large enough data base for upscaling and correlation of the geothermal properties. The rock samples were classified with respect to the dominant reservoir facies types in order to identify facies dependant trends. To transfer the petrophysical properties to reservoir conditions, a Thermo-Triaxial-Cell was used to simulate pressure and temperature conditions of the reservoir. Furthermore, data from previous studies (bio- and lithostratigraphic model of the target formation) and well data were included.

Referee 4 – p.3 line 24: *„if you mean "physical-chemical rock properties" it needs to be demonstrated that outcrop and subsurface rocks are analogues (given different burial, structural, and diagenetic history, including telogenesis); if you mean facies, stratigraphic architecture/diemensions, sedimentrry bodies etc...the analogy is probably ok”*

Answer: The term “analogue” in this manuscript refers to “facies, stratigraphic architecture, and sedimentary bodies”.

Our study results are in agreement with your comment, as described later on in chapter “discussion and conclusions” (p 14, line 25ff).

Referee 4 – p. 3 line 29: *“how do you measure thermophysical properties at all these scales?“*

Answer: The multi-scale method includes analysis on three different scales 1) macro scale (outcrop, well data) 2) meso scale (rock samples/plugs) and 3) micro scale (thin section, chemical analysis etc.). Macro-scale studies include well data (e.g. hydraulic tests, heat flow) as well as outcrop investigation (facies, structures). It is to emphasize, that not every parameter can be “measured” on every scale. In this manuscript we focused on the meso and micro scale (rock samples and thin sections).

Referee 4 – p. 3 line 30: *“it is not because you are doing multi-scale assessment that the properties or charactéristics are automatically upscales and downscaled! It depends also of the intrinsic heterogeneity of the system at all scales”*

Answer: We agree with Referee 4. To make it clear, we will add a short section about upscaling and downscaling in the manuscript.

Referee 4 – p.8 line 9: *"what are the key parameters for this classification? Are they universal or are they dependent of local conditions, basin, etc..."*

Answer: This classification especially considers economic and technological factors for geothermal utilization of the Federal state of Hesse in Germany. To assess the rock and reservoir properties in the 3D structural model of the Federal State of Hesse, a multiple criteria approach was used to incorporate their relevance for geothermal systems (Bär et al., 2011, Bär and Sass, 2014). Based on an extensive data base of rock properties and reservoir data, the threshold values (very low to very high) were defined to specify the geothermal potential. Since there exist no such data base for the Alberta Basin (and also no experience with geothermal power/heat generation), this classification was applied to the rock properties presented in this manuscript for a first evaluation.

Referee 4 – p. 9 line 20: *"Petrography Outcrops" changed to "Outcrop petrography"*

Answer: Accepted.

Referee 4 – p. 11 line 31: *"dry samples? It may change when samples are saturated with water?"*

Answer: Sentence will be changed to: "… The sample set shows no correlation between thermal conductivity and porosity." According to Popov et al. (2016) thermal conductivity of rocks depends on the mineral composition, interstitial porosity and fluids filling pores and fractures as well as mineral grain size and orientation, anisotropy of the rock matrix and the nature of grain contacts. Thermal conductivity of water is ~ 0.6 W m^{-1} K^{-1}, while thermal conductivity of air is approx. 0,025 W m^{-1} K^{-1}. Therefore, bulk thermal conductivity generally increases with increasing water content depending on the porosity of the rock sample. Likewise, bulk thermal conductivity of a rock sample generally decreases with increasing porosity.

Our data set indicates no correlation between thermal conductivity and porosity. It is most likely, that in this case mineral composition, grain size/geometry and grain contacts have a stronger influence on thermal conductivity than the porosity of the samples (plug scale).

Referee 4 – p. 12 line 2: *"that is in contradiction with the statement in the introduction."*

Answer: The "thermo facies concept" was explained in chapter 1 "Introduction" by the example of the Southern German Molasse Basin. This concept was successfully applied in the Southern German Molasse Basin to assess the geothermal potential of the Malm-Aquifer (Homuth et al., 2015). For this reason, we considered it appropriate to apply this methodology to the Upper Devonian carbonates in Alberta. Our results show the limits of this method. Although we could identify several similarities between the outcrops and the reservoir core samples, the outcrops are no valid proxies for the buried reservoirs in the Alberta Basin. This implies that, besides many similarities (rock types, thicknesses, depth and deformation, hydrogeological properties) the term ‘analogue’ needs to be specified.

Referee 4 – p. 12 line 5: *” in outcrop conditions, not necessarlily in subsurface conditions“*

Answer: Yes that is correct, but here we meant it in a different context. According to several transfer models (Allen and Allen, 1990; Pape et al., 1999, etc.) porosity and permeability generally decrease with increasing depth.

Permeability of the outcrop samples is already significantly lower than permeability of the well core samples, even though the results are not corrected for reservoir conditions yet. We will specify this.

Referee 4 – p.12 line 14: *“what type of pore space? intergranular, intercrystalline? microporous, vugs, ????”*

Answer: On p. 12 line 14 it is written “The highly permeable, extensively dolomitized reef zones represent promising reservoirs for hydrothermal utilization with predominantly convective heat and laminar fluid flow.” It is therefore unclear as to what extent this question refers to this sentence.

Referee 4 – p.12 line 14: *“why? this is an important conclusion but there is no real demonstration of the heat transport and flow behaviour”*

Answer: As mentioned in the sentence before, this conclusion was made according to the classification of the thermofacies concept (Sass and Götz, 2012). The application of the thermofacies concept is useful in an early exploration stage or in cases where detailed reservoir information is not available. This concept allows a first characterization (whether it is a petrothermal, transitional or hydrothermal reservoir), but does not replace further investigation. Due to the high number of well data (several thousand wells) that need to be evaluated for a more detailed assessment, this point is not further elaborated in the manuscript and will be part of the next phase of the project.

This conclusion takes also previous studies into account regarding diagenesis (Machel and Buschkuehle, 2008), fluid flow and hydraulically connected areas (Michael et al., 2003; Rostron et al., 1997; Bachu et al., 2008) as well as the well data from the oil industry (production data).

Referee 4 – p. 12 line 19: *“it is not "reservoir scale", it is "plug scale" measurements within reservoir units”*

Answer: Accepted.

Referee 4 – p. 12 line 19: *“ambiguous“*

Answer: Accepted.

Referee 4 – p.12 line 20: *“5 % of porosity variation for 3 orders of K permeability: does it suggest micro- fracture”*

Answer: We identified hairline fractures e.g. in well 5-22 (Leduc Formation, central basin), which has also been observed in the Strachan pool close to the Rocky Mountains (Marquez and Mountjoy, 1996). These fractures form networks throughout the rock matrix and might explain higher permeability values.

Referee 4 – p. 12 line 28: *"what do you mean by "apparent" K?"*

Answer: See answer below.

Referee 4 – p.12 line 31: *" "intrinsic" K ?"*

Answer:

After Languth and Voigt (2004) the permeability describes the hydraulic parameters of an aquifer. When different fluids (oil, gas, water) occur in a reservoir, the specific, absolute or intrinsic permeability becomes important. The intrinsic permeability describes the aquifer matrix only and does not consider fluid specifications.

Permeability was measured with a column permeameter and a mini permeameter, which is a variation of the column permeameter (Hornung and Aigner, 2004). Both devices are gas driven, which allows quick, contaminant-free and non-destructive measurements (Filomena et al., 2014). The column permeameter measures the intrinsic permeability after Klinkenberg (1941). Thereby the intrinsic permeability corresponds to the effective gas permeability of air under infinitely high pressure. The calculation is based on Darcy's law, supplemented by the addition of compressibility and viscosity of gases. As it's not possible to determine the permeability under infinitely high pressure (Jaritz, 1999), the column permeameter measures the apparent gas permeability of air with at least five pressure stages from 1000 to 5000 mbar. Afterwards the intrinsic permeability is calculated from the apparent permeability using the Klinkenberg method (1941).

Referee 4 – p.13 line 7: *"a missing topic in this interesting chapter is the "upscaling-donwscaling" of the properties (reservoir and geothermal).*

Answer: Accepted. See Answer above.

Referee 4 – p.13 line 7: *"there are no measurements or estimation of properties at greater scale than the plugs; so all the extrapolation made from plug measurements to larger scale are implicitely based on averaging and assuming some level of "stationnarity" within stratigraphic units or sedimentary units. Another implicit assumption is that rock properties statistics are not dependent of sample size (no "support effect"). Certainly not the case for permeability in carbonate reservoirs! All these assumptions should be discussed prior to the conclusive statement on the geothermal potential and extrapolation of core plug data."*

Answer: Accepted. Porosity and permeability is highly variable within the reservoir. In our manuscript we focused on the core sample scale. We will consider this point.

Referee 4 – p.13 line 7:*" you might add histograms of diffrent properties for the various stratigraphic units and facies, to help the discussion on upscaling"*

Answer: Thank you very much for this kind advice. We will consider this point during revision of the manuscript. Histograms of the different rock properties might be helpful regarding the upscaling discussion, but they do not replace the plots presented in this manuscript. Figure 7 shows the correlation of the rock properties and Figures 8 to 10 give a first impression how the properties vary within the reservoir, whereby we focused on the latter.

Referee 4 – p.28: *"I would add some histograms, for different geologicl units and facies , etc...that would help to discuss the upscaling issue in the conclusion"*

Answer: Same answer as above.

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