The effect of fluvial architecture in Hot Sedimentary Aquifers on the connectivity and life time of a geothermal doublet.

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Introduction

Fluvial Hot Sedimentary Aquifers (HSA) are composed of permeable sandstone bodies surrounded by impermeable floodplain claystones. In this type of aquifers, the sandstone bodies form the fluid pathways. The aquifer architecture describes the distribution of the sand- and claystone bodies. One of its main parameters is the net-to-gross. This is the ratio of total sandstone body volume and the total aquifer volume including both the permeable and impermeable bodies. If the net-to-gross is high, the sandstone bodies are more likely to form larger and fewer clusters. If in contrast, the net-to-gross is low, more and smaller, isolated clusters are formed. This is reflected by the connectivity of the aquifer which is the ratio of the volume of the largest sandstone body cluster and the total sandstone body volume (Larue & Hovadik, 2006). For example, if the connectivity is 100% all sandstone bodies form one big network. If the connectivity is 20%, the largest sandstone body volume is 20% of the total sandstone volume in the aquifer. Low connectivity is a risk in the development of HSA because isolated clusters do not contribute to the heat production. The connectivity is furthermore influenced by the geometries and paleo flow direction range of the sandstone bodies (Cuevas Gazolo et al., 1997; Larue & Hovadik, 2006). Both the net-to-gross and the connectivity influence the life time of a geothermal doublet. During the production, a cold-water plume develops around the injection well. The moment at which the cold water plume reached the production well is defined as the thermal breakthrough moment. After this moment the production temperature decreases. In heterogeneous fluvial sedimentary aquifers, the cold water 'fingers' through high permeability sandstone bodies. Bypassed low permeability aquifer bodies supply heat to the more permeable bodies through heat diffusion (Salimi et al., 2012, Poulsen et al., 2015). The aquifer architecture therefore influences the thermal breakthrough moment and the following speed of the production temperature reduction. In homogeneous or layered reservoir models (Mijnlieff et al., 2007; Mottaghy et al., 2011; Ekneligoda et al., 2014), the cold-water plume development will have a cylindrical shape. To improve the life time estimations of geothermal doublets in fluvial aquifers, detailed reservoir architecture models have to be taken into account.

The effect of reservoir heterogeneities on reservoir performance are extensively studied for oil and gas production (Larue & Hovadik, 2006; Larue & Hovadik, 2008) and to a more limited extend for geothermal energy production (Mijnlief et al., 2007; Mottaghy et al., 2011; Ekneligoda et al., 2014) and (combined) CO_2 sequestration (Salimi et al., 2012; Issautier et al., 2013; Issautier et al., 2014).

This study aims to improve life time estimations of geothermal doublets in fluvial Hot Sedimentary Aquifers. For this purpose, hundreds of facies models are generated with process-based facies modelling software based on a geological dataset of a Lower Cretaceous fluvial interval in the West Netherlands Basin. In this way facies models are created in which the sandstone bodies have a sedimentologically based spatial relation (Karssenberg et al., 2001). This is crucial for the connectivity analysis. The net-to-gross in the facies models ranges from 10 to 100%. In addition, a group of facies models is generated with random facies distribution. The net-to-gross in this group of models also ranges from 10-100%. First the connectivity is determined in every facies model and related to the net-to-gross of the model. Second, a finite-element approach is utilized to study the geothermal energy production in all models. In every model, a vertical production- and injection well are placed at a 1000m distance. The initial reservoir temperature is 75 °C; the re-injected water has a temperature of 35°C. Geothermal energy production is simulated in the doublet models with a 100 m^3/h production flow rate. The life time of a doublet model is defined as the time at which the production temperature degreased to 74 °C. The life time in all flow rate and minimum production temperature scenarios is related to the net-to-gross and connectivity of the facies models. The facies modelling process, the connectivity analysis and production simulation results are described in the following paragraphs.

Facies models

Process-based facies modelling software Flumy (Grappe et al., 2012) is utilized to create 1 km x 2 km x 50m facies models. In this process-based approach, facies are distributed by simulations of sedimentological processes. As a result, reservoir realisations are created with a sedimentologically realistic relation between net-to-gross and sandstone body geometry. In addition the spatial relation is not random but related to sedimentological processes. For example, the location of a fluvial channel after the avulsion is dependent on the topography that was created by the previous channels (Karssenberg et al., 2001; Grappe et al., 2012). Seven types of facies bodies are distributed in the simulations, pointbars, sand plugs, channel lags, crevasse splays, levees, overbank floodplain fines and mud plugs. The sedimentological processes are described by parameters such as avulsion frequency, flood frequency, paleo-channel width and depth, maximum floodplain deposit thickness and topography of the floodplain which is deposited during every flood. By varying these parameter values, the reservoir realizations in our study have a range of net-to-gross of 10-100%. The 'base case' process parameter values that are used for the modelling are derived from core studies of the Lower Cretaceous fluvial Nieuwerkerk Formation in the West Netherlands Basin (DeVault & Jeremiah, 2020). The paleo flow direction is oriented parallel to the long edge of the realizations (Figure 1). The paleo-channel width and depth used in this study are 40m and 4m respectively. The choice of orienting the paleo-flow direction parallel to the long-edge will increase the connectivity in the reservoir realizations compared to a paleo flow perpendicular to the long edge.

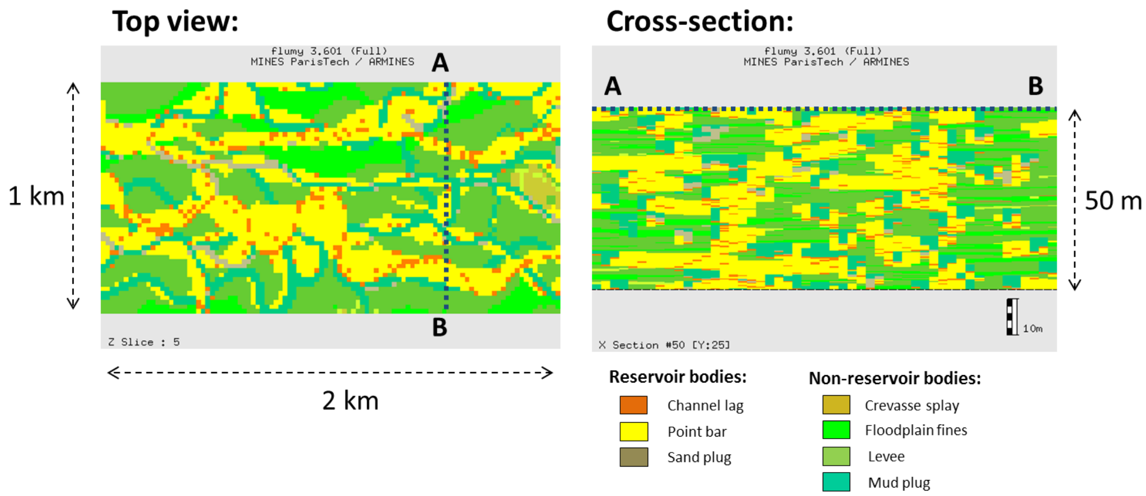

Figure 1: Example of a process-based facies model top view (left) and a cross-section (right).

Property modeling

Reservoir properties distribution is based on the facies models. The process-based facies modelling approach generates reservoir realizations with 7 types of sediment bodies such as channel lags, point bars, sand plugs, mud plugs crevasse splays, levee's, and floodplain fines. For simplicity, sandstone bodies from channel lags, point bars and sand plugs are considered as reservoir bodies, the other units with more fine-grained deposits are considered to be non-reservoir units. The heat capacity, density and heat conductivity of reservoir units are set to 2.05[W/mK], 2650 [kg/m^3] and 775 [J/kgK] respectively. Non reservoir units are assigned different values of these parameters, i.e. 2.30[W/mK], 2680 [kg/m^3] and 860 [J/kgK] respectively. Porosity is assigned to the reservoir units based on a distribution with mean (μ) : 0.28; standard deviation (σ)=0.075 skewness = 0.35 kurtois = 2.3. Utilizing a porosity-permeability relation, permeability values are calculated. Both this relation and the porosity distribution derived are from core plug measurements from the Nieuwerkerk Formation interval of the MKP-1 well in the West Netherlands Basin (TNO, 2015). Non reservoir unit porosity and permeability are set to 10% and 5 mD respectively.

Results

First the connectivity is calculated in both the random and process-based facies models. the connectivity is defined as the volume of the largest sandstone body cluster divided by the total sandstone volume. These results show that the connectivity in the 10-40% net-to-gross (N/G) region is much higher for the process-based models compared to the random facies models. In the 45-100% net-to-gross region the connectivity is similar in both groups of models.

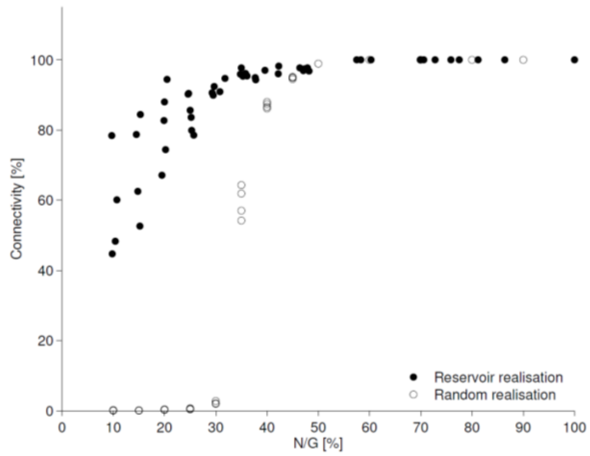

Figure 2: Connectivity of the process-based (filled dots) and random (open dots) facies models.

Second, geothermal heat production is simulated until a production temperature drop of 1°C occurs. The initial reservoir temperature is 75 °C; the re-injected water has a temperature of 35°C. In Figure 3 the life time of a facies model is related to its net-to-gross. Figure 3 compares the life-time of random facies models and process-based facies models.

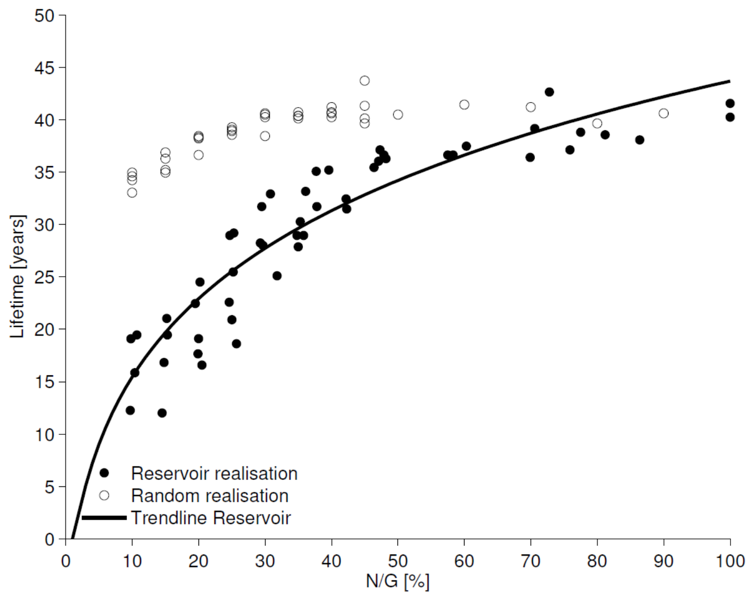

Figure 3: A) Life time simulation results of the process-based (filled dots) and random (open dots) facies models at 100 m^3/h production rate related to net-to-gross (N/G). B) Life time simulation results of the process-based facies models at 80,100,120 an 140 m^3/h production rate. Relations of life time (LT), net-to-gross and flow rate are presented for two net-to-gross regions.

Conclusions

The results of the connectivity analyses and production simulations show that geothermal doublet life time estimations of aquifers in the 15-45% net-to-gross are significantly influenced by the reservoir architecture. Utilizing random facies models could lead to an overestimation of the life time of geothermal doublets. This applies especially for aquifers with a 15-45% net-to-gross range. This is also the range of net-to-gross in which isolated sandstone bodies can be expected and connectivity decreases. At higher net-to-gross values approximately all sandstone bodies are connected in the facies models based on the West Netherlands Basin dataset used in this study.

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