Introduction

The Slochteren Formation in the Upper Rotliegend Group has proven to be an effective aquifer for geothermal heating purposes. Until now four geothermal projects, shown in figure 1, have been developed successfully, providing new data and in-depth knowledge on the variation in reservoir quality and productivity of the Slochteren Formation. This paper presents what these projects have taught us on the prediction of reservoir properties by comparing feasibility studies with actual well test data. These feasibility studies are carried out before drilling of a geothermal well in order to estimate its potential geothermal power and to predict whether the system will be economically viable. Yet, discrepancies between the predicted and observed reservoir parameters show that there are still difficulties in translating the data to geothermal reservoirs. Test drillings, static or dynamic 3D models or new seismic data acquisition would result in better estimations of the reservoir properties, but these techniques are often too expensive. Therefore, studies use available data of previously drilled projects, which mostly consists of hydrocarbon well data. The geothermal projects drilled in the Slochteren Formation make it now possible to both qualitatively and quantitatively assess the methods used for feasibility studies on the quality of the aquifer parameters. This study critically assesses the presently used methods and presents suggestions for improvements that suit the resources of the geothermal industry.

Method and/or Theory

In this study, a comparison is made between pre-drill (predicted) and post-drill (measured) reservoir properties of geothermal projects. This comparison is carried out for all four of the previously mentioned projects drilled in the sands of the Slochteren Formation: Middenmeer, Koekoekspolder, Heemskerk and Luttelgeest. The evaluated reservoir properties are thickness, permeability, transmissivity, temperature and water quality. Predicted values were based on petrophysical data from nearby wells, and, when available, seismic data. Reservoir properties measured after drilling of the well are based on the borehole well log data and pressure build up tests. A pressure build up test is done after the well has been completed: the well is being tested by pumping up a significant amount of water which lowers the water table within the well and in the reservoir close to the well. After a significant amount of time the flow rate drops to 0 m³/h and the water flows back into the reservoir, which recovers the water table level. The rate at which this happens is used as a measure to determine the quality of the reservoir; the transmissivity. Transmissivities can be translated into permeabilities. For each parameter the differences between predicted and measured values are assessed and a new or improved prospective method is proposed.
Predicted and measured reservoir parameters for the completed geothermal projects in the Slochteren Fm. Predicted data is taken from SDE+ applications (IF Technology, 2017a, 2017b; Panterra, 2012), measured data is taken from well test reports (ECW Geoholding B. V., 2014; IF Technology, 2018a, 2018b; PanTerra Geoconsultants BV, 2013), a public end report (Aardwarmteproject Koekoeckspolder, 2012) and composite well logs from NLOG.nl. “Measured” geothermal powers are not really measured, they are calculated using TNO’s DoubletCalc 1D, using the input parameters described in table 2 and table 3. Pump properties are consistent for all four cases: exit temperatures are 35°C, the distance between wells at aquifer level is 1500 m, the pump efficiency is 0.65, the pump depth is 500m, the pump pressure difference is 60 bar and the skin is for all wells set at 0. Note that these outcomes are thus not the measured geothermal powers, but calculated based on measured reservoir properties and used to compare the SDE+ with the “real” reservoir properties.

Results

The thermal power (E, in MW) of a geothermal well depends on the thermal capacity of the produced water ($C_w$, in MJ/m³ °C), the difference in temperature between the production well and the injection well ($ΔT=T_{production} - T_{injection}$, in °C) and the flow rate of the produced water (q, in m³/h), see equation 1.

\[ E = C_w \times ΔT \times q \]  

(eq. 1)

Estimates of the thermal capacity of the produced water do not differ significantly from the measured values. Consequently, this parameter is not discussed here. Reservoir temperatures are usually higher than expected, which, following equation 1, results in a direct mismatch in geothermal power. The causes of this mismatch are evaluated in this study. The flow rate depends on both the thickness and the permeability of the reservoir. Since both of these parameters show a mismatch between the predicted and the measured value they are assessed as well.

Temperature

Reservoir temperatures are usually underestimated. Temperatures are in three of the four cases estimated based on the local thermal gradient, which is a linear relation derived from corrected Bottom Hole Temperatures (BHT). Yet, the temperature of the water produced from the Slochteren Formation is significantly higher than expected. The fourth case study (Middenmeer) based their temperature estimation on wells in the vicinity of the project location. This resulted in a more accurate estimate of the temperature. A plausible explanation can be the presence of faults: this may not only enhance fluid circulation in the Slochteren Formation or the underlying formation, but they also may connect into deeper and hotter water (Bonté, 2014; Lipsey et al., 2016).

Thickness

The thickness of the reservoir is preferably based on seismic data. Unfortunately, the base reflector of the Slochteren Formation is typically very unclear. Therefore, estimations of reservoir thickness are often based on well log data. Although it is thought that the thickness of the Slochteren Formation is locally relatively constant, well logs do not particularly reflect this. Therefore, interpolating the thickness towards the project location can be difficult. For the geothermal projects presented here, reservoir thicknesses are in all four cases underestimated. One case study (Middenmeer) based their thickness estimation on 3D seismic, which resulted in an underestimation of 10%. Two of the case studies based their thickness estimations on 2D seismic and well log data, resulting in an underestimation of 15% to 45%. Predictions based on 3D seismic are considered more accurate than predictions based on 2D seismic or well log data, since it gives a better understanding of the lateral variability of the Slochteren Formation than 2D seismic data. Yet, due to the continuous depositional style of the Slochteren Fm., the reservoir thickness is expected to be relatively constant at the scale of a geothermal doublet. By implementing this, it is possible to improve the estimation of 2D seismic data and well logs. This means that the geological structure should be taken into account when
interpreting the thickness: a data-point on the same fault block as where the project will be located may be more valuable than a data-point closer by but on a different fault block.

Reservoir transmissivity
One of the biggest difficulties in predicting the properties of a geothermal reservoir is the prediction of the transmissivity: for all four case studies permeabilities and thus transmissivities are significantly overestimated. Upscaling is needed to go from core-plug scale to reservoir scale in the vertical direction, but also in the horizontal direction: the properties of the reservoir between the producing and the injecting wells need to be understood in order to predict the productivity of the doublet. Something that has appeared to result in a mismatch between permeabilities measured in geothermal wells and permeability estimates based on hydrocarbon wells, is that both geothermal projects and hydrocarbon projects determine reservoir properties using different analytical methods.

Also, core plugs from hydrocarbon wells might be biased to a certain part of the reservoir with a high permeability. Permeabilities of geothermal wells are usually determined using well tests which yield the combined horizontal and vertical permeability, while permeabilities of hydrocarbon wells are often determined from plug measurements from gas reservoirs. This is illustrated in Figure 2. The transmissivity of a reservoir is best estimated by a well test such as a pressure build up test. Unfortunately, well test results are rarely available; for hydrocarbon wells the permeabilities are often upscaled to reservoir scale based on centimetre-scale core plug data and well log data, which only yield the horizontal permeability. For geothermal wells, the transmissivity determined from a well test can be translated into a combined horizontal and vertical permeability. Well tests usually do not allow to identify vertical production variations across the perforated intervals unless dedicated flow meters are utilized; horizontal variations can never be identified. Following, the expected transmissivity is calculated by making assumptions on which layers are productive and assuming that permeabilities do not vary horizontally.

A potential improvement to the method used to predict reservoir permeabilities would be the quantification of the differences between permeabilities deduced from hydrocarbon well measurements versus those measured in geothermal wells. The results found could be used to derive a correction factor to calculate permeabilities of geothermal wells from oil and gas well data.
Figure 2 Schematic figure illustrating the chronology of a geothermal project through play based exploration. The boxes explain the differences and similarities between the methods of acquiring petroleum well data and geothermal well data.

Conclusions

The Slochteren Formation has proven to be not only a good reservoir for hydrocarbons but also for geothermal purposes. However, it is found to be relatively difficult to correctly estimate its reservoir properties. The main reason for this is the lack of resources available for geothermal feasibility studies. This introduces a lot of uncertainties. However, by analysing the differences in predicted and measured reservoir properties, a few improvements can be made in order to estimate the geothermal capacities of a project location. This starts by signalling which parameter is the most difficult to predict: the permeability is usually significantly overestimated. Upscaling permeabilities from core-scale to reservoir-scale has proven to be very difficult. Static and dynamic 3D reservoir models would improve their accuracy, but building them is unfortunately very costly. As a consequence, the geothermal industry has to work with the available hydrocarbon well data, which needs to processed relatively fast. Permeability estimations can be improved when they are based on well test results rather than core plugs. Unfortunately, these are not yet widely available, but this will change when more geothermal projects are operational in the Slochteren Formation. Until then, predictions of the permeability based on upscaled hydrocarbon well data needs to be handled with care: keep in mind that the permeability is very likely to be overestimated. Temperature estimations can best be based on measurements of water produced from geothermal wells in the vicinity of the project location, instead of on a geothermal gradient based on corrected bottom hole temperatures from hydrocarbon wells. Thickness can best be predicted by consulting the local geological model in addition to 2D or 3D seismic data: within fault blocks, thickness shows to be relatively constant. This study presented the qualitative differences between predicted and measured reservoir parameters. An interesting addition would be to quantitatively determine these differences. They can potentially be translated to an empirical factor which can be applied to the predicted value, to make a better fit with the actual geothermal reservoir parameters.

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