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Geothermal Resource Assessment of Fractured Reservoirs for Deep Geothermal Exploration in the Netherlands

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ABSTRACT

One of the first steps in geothermal project development is to perform a geothermal resource assessment. This resource assessment is necessary to decide if the geothermal resource can be successful and sustainably developed. Generally, geothermal resources are classified into two main categories: conduction and convection dominated systems. In the Netherlands, only conduction dominated systems are present and utilized for geothermal heat production. In the Netherlands, Dinantian carbonate reservoirs are considered to have a high potential for geothermal development. However, during the early exploration phase, no validated resource assessment method is currently available for naturally fractured geothermal systems, such as these carbonate reservoirs. This study presents a newly developed resource assessment method for carbonate reservoirs. In order to develop a new resource assessment method, three existing methods are reviewed. The methods are evaluated based on their applicability for naturally fractured geothermal systems in the Netherlands. The three methodologies evaluated are the volumetric method (Muffler and Cataldi, 1978), the power density method (Cumming, 2016) and DoubletCalc (Mijnlieff et al., 2014). Since the power density method only includes high enthalpy settings, the database is extended and the power density plot updated with data from low enthalpy heat-producing geothermal projects. A workflow was created to gain insight about the parameters which influence the potential of a fracture-dominated reservoir. With the insight gained from the workflow and inspired by existing resource assessment methods, two new methods are developed and tested for fracture dominated geothermal reservoirs: the recovery factor method and the probability of success (POS) method. Since in the early exploration, insufficient data is available to develop a numerical model, a qualitative approach was chosen. Especially the POS method appears to be a promising tool for resource evaluation during the early exploration phase of a geothermal project. This qualitative POS method is based on scoring tables, which standardizes risk quantification and reduces bias stemming from individual expert opinion. Additionally, geothermal projects under development can be compared based on their geological risk in a consistent way. Because POS can be determined relatively fast and is understandable for most parties involved in the development of a geothermal project, the POS method is still of value in the later stages of a project. This new method is tested based on conceptual geological models and a real project; however, it should be tested empirically in the future for validation.

1. INTRODUCTION

When the government-funded joint industry project "Green Deal Ultradiepe Geothermie" (the Ultradeep geothermal or UDG project) began in 2017, it almost immediately raised the question of how the potential of a geological formation should be evaluated at a location. The ultimate aim of the UDG project is to develop the Dinantian Carbonates for heat and steam production. The Dianantian Carbonates are present in the Netherlands between roughly -1,500 and -7,000 m.b.s.l. as a geothermal source, hence the term ultradeep geothermal (UDG). The joint industry partners agreed to cooperate in the project during the exploration phase (Heijnen et al., 2019). The UDG project consortium currently consists of six projects across the Netherland and is managed by the state company EBN and supported by the geological survey of the Netherlands, TNO.

During the start-up phase of this project, numerous discussions were held on what criteria should be used to determine the location of the first well to be drilled. These discussions were mainly driven by the requirements of the existing subsidy and insurance instruments provided by the government, which are designed for geothermal projects realized in siliciclastic reservoirs with a single porosity system. Additionally, the project evaluation tool used, DoubletCalc (Mijnlieff et al., 2014), assumes that data quantity and quality are such that detailed analyses of the reservoir properties can be performed. When considering the properties and data availability for the Dinantian Carbonates in the Netherlands, the differences with conventional geothermal projects in the Netherlands are obvious. First of all, the limestones have a dual porosity system and the available data is very sparse. This implies that the existing methodology used to evaluate the potential of a geothermal prospect is not appropriate for limestone aquifers and that another approach is needed. The alternative approach should be simple and pragmatic. Ultimately, the goal is to objectively evaluate the geothermal potential of different locations and make meaningful comparisons.

In this paper, we explore the suitability of two geothermal resource assessment methods (Cumming, 2016; Muffler and Cataldi, 1978) for evaluating the Dinantian Carbonates in the Netherlands, and analogue formations. Our intention is to start the discussion on these evaluation methods and to develop best practices for evaluating fractured limestone formations for geothermal development. Based on this evaluation we introduce several modifications to these methods in order to adapt them to the specifics of the Dinantian Carbonates. Additionally, as the purpose of the UDG project is to develop a direct heat geothermal project, we calibrate the power density curve (Wilmarth and Stimac, 2015; Cumming, 2016) to data from low enthalpy, direct heat geothermal projects. Finally, we apply the two modified methods to an existing geothermal system to test their validity.

2. EVALUATION AND MODIFICATION OF TWO RESOURCE ASSESSMENT METHODS FOR FRACTURED GEOTHERMAL RESERVOIRS IN LOW ENTHALPY SETTINGS

In the following**,** two geothermal resource assessment methods are compared and slightly modified. The first is the volumetric method (Muffler and Cataldi, 1978) and the second is the power density method **(**Cumming, 2016**)**.

2.1 The Volumetric Method

The volumetric method is a widely known pragmatic and simple method based on the calculation of thermal energy contained in a certain volume of rock. It is also known as the heat in place or stored heat method. Its strength lies in the fact that it can be applied when little data is available. In practice, the volumetric method is used together with Monte Carlo simulations to estimate the uncertainty of the predicted potential. A crucial parameter in the volumetric method is the thermal recovery factor, R_g. The recovery factor determines the effective fraction of the theoretically available volume of heat that can be technically extracted and is defined as:

$$R_g = Q_w / Q_r \tag{1}$$

Here Q_w is the thermal energy measured at the wellhead and Q_r is the total thermal energy present in the reservoir (Garg and Comb, 2011). Initial values for R_g were derived from models of the cooling effects in a geothermal reservoir due to reinjection of cold water (Williams et al., 2008). It is often difficult to determine the recovery factor since it depends on many factors, such as the type of geothermal system, the porosity and the permeability, the reservoir temperature and the extraction temperature. A few R_g estimates for fracture dominated systems have been published and vary between 0.08 and 0.25 (Muffler and Cataldi, 1978; Williams et al., 2008).

2.2 Power Density Method

The basis of the power density method is the assumption that there is a relationship between the tectonic setting of a geothermal resource and the potential it has. This is expressed as a relation between reservoir temperature and the geothermal power output per square kilometer (MW/km^2). As observed in Figure 1, there is a relationship between temperature and electric power density. Generally speaking, an exponential relation can be determined for the expected power output of geothermal systems located in fault-based reservoirs, arcs and rift type settings. Using this analogue-based relation when estimating the potential geothermal power output of a system gives more accurate results in comparison to statistical methods when the data quantity is limited (Cumming, 2016).

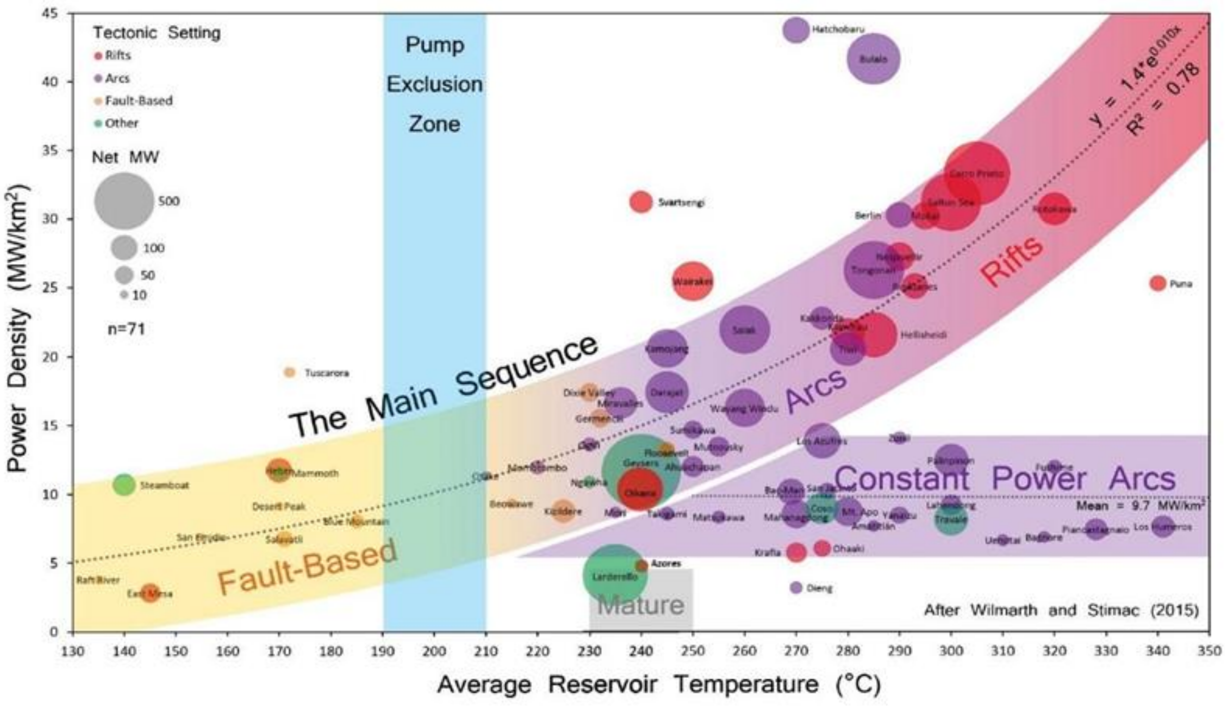

Figure 1: Power density versus average reservoir temperature for various existing geothermal projects and their geological settings. Two trends are recognized in the graph. All projects shown are electricity producing geothermal projects. From Cumming (2016).

Initially, this method was developed as an illustration of geothermal resource capacity uncertainty and used for educational purposes. Later, the economic value of the method was noticed and, currently, it is used prior to the development of geothermal resource capacity estimates. The resulting power density function for the capacity is presented with the commonly used P10, P50, and P90 probabilities. An important aspect of this method is the inclusion of a probability of success (POS) metric. The POS estimates the probability of finding a good resource, based on the quantity and quality of available data. To be able to effectively use this methodology for the Dinantian Carbonates in the Netherlands, the power density plot has to be updated to include projects developed in analogous geological settings, which produce heat and have similar temperatures.

Besides the two methods discussed above, more types of geothermal resource assessment methods exist in the geothermal industry (see, e.g., (Bödvarsson, 1974; Muffler and Cataldi, 1978; Agemar et al., 2018; Suryantini and Wibowo, 2015)).

2.3 Modification of the Methods

To make them more suitable for evaluating the potential of fracture dominated carbonate/limestone reservoirs, we propose modifications of components of the two resource assessment methods discussed above. First, a methodology is introduced to qualitatively estimate the recovery factor used in the volumetric method. Second, a qualitive method is introduced to determine the POS, which is part of the power density method. Both methods are designed such that they capture all aspects affecting the geothermal potential of a fracture dominated carbonate reservoir.

The basis of the qualitative recovery factor introduced here is a general understanding of the main reservoir parameters that affect the amount of heat that can be recovered from a geothermal system. The parameters used to estimate the recovery factor include permeability, temperature, the structural geological setting, and the geological history. The recovery factor can be calculated using the equation shown in Figure 2. Based on the knowledge and understanding of the applied parameters, scores are assigned based on a pre-defined scoring table.

$$R_g = \frac{Q(k) + Q(T) + Q(structuralgeology) + Q(geologicalsetting)}{100}$$

Figure 2: Example of an equation for estimating the recovery factor of a geothermal prospect which can be used in an early-stage volumetric assessment of a fractured carbonate geothermal reservoir. *Q* reflects a quality score for the permeability (*k*), temperature (*T*), structural geology and geological setting.

This POS method is designed to be able to systematically assess the exploration and geological risks during the early exploration stages of a geothermal project. The method builds on framework of existing POS-methods from the geothermal and hydrocarbon industry (Suryantini and Wibowo, 2015; Milkov, 2015). In the POS method introduced here, drilling and operation risk factors are excluded. The factors evaluated in the POS method discussed here are listed in Table 1. To systematically assess the POS, for all factors and sub elements listed in Table 1 a scoring table is designed. When several sub elements are evaluated, the weakest link method is applied (Suryantini and Wibowo, 2015). The total POS is calculated by multiplying the individual probabilities of success of the five risk factors. POS scores of 0.66 (very low risk) to 0.05 (very high risk) are expected when using this methodology to evaluate a fractured carbonate geothermal prospect.

Table 1: Factors evaluated in the proposed POS method. In the third column the evaluated reservoir parameters are listed.

Risk factor	Sub element	Parameters evaluated
Temperature	-	• Local geothermal gradient
Reservoir size	-	• Net-to-gross ratio • Top and bottom depth of reservoir
Permeability	• Fault zone activity • Fault structure • Matrix porosity	• Seismic hazard • Fault displacement / damage zone • Fault connectivity • Matrix and fracture communication
Structural geology	-	• State of stress and fault orientation • Main faults and folds in the study area
Geological history	• Diagenesis • Depositional setting	• Presence of a favorable depositional setting • Karst formation • Other relevant diagenetic processes

3. UPDATE OF THE POWER DENSITY CURVE

Using data from both electricity- and heat-producing geologically analogous geothermal projects with representative temperatures, the power density curve as shown in Figure 1 is updated using a slightly modified methodology compared to the one used by Wilmarth and Stimac (2015). Whereas Wilmarth and Stimac (2015) used a 500 m buffer around all production wells to estimate the production area, we choose to estimate the production area based on the the doublet system well spacing. Adding heat producing systems to the curve is appropriate as the relationship between power output, volume and temperature remains the same. The power densities of existing geothermal projects in the Netherlands, Germany, France, Hungary, and Romania were calculated using public data. The resulting power density plot for temperatures between 60 and 240°C is presented in Figure 3. As diagenetic processes have a large influence on the capacity of a geothermal system realized in a siliciclastic reservoir, the power density of these type systems can decrease with temperature as is observed in Figure 3. A positive linear correlation is observed for geothermal projects realized in fault-based carbonate reservoirs (see Figure 3). Where the main relation in the power density plot by Cumming (2016) is an exponential function, low enthalpy fault-based settings appear to show a more linear relationship for power density versus temperature. It is worthwhile to investigate if, when using exactly the same methodology for all data points in the plot, a more continuous relation can be found.

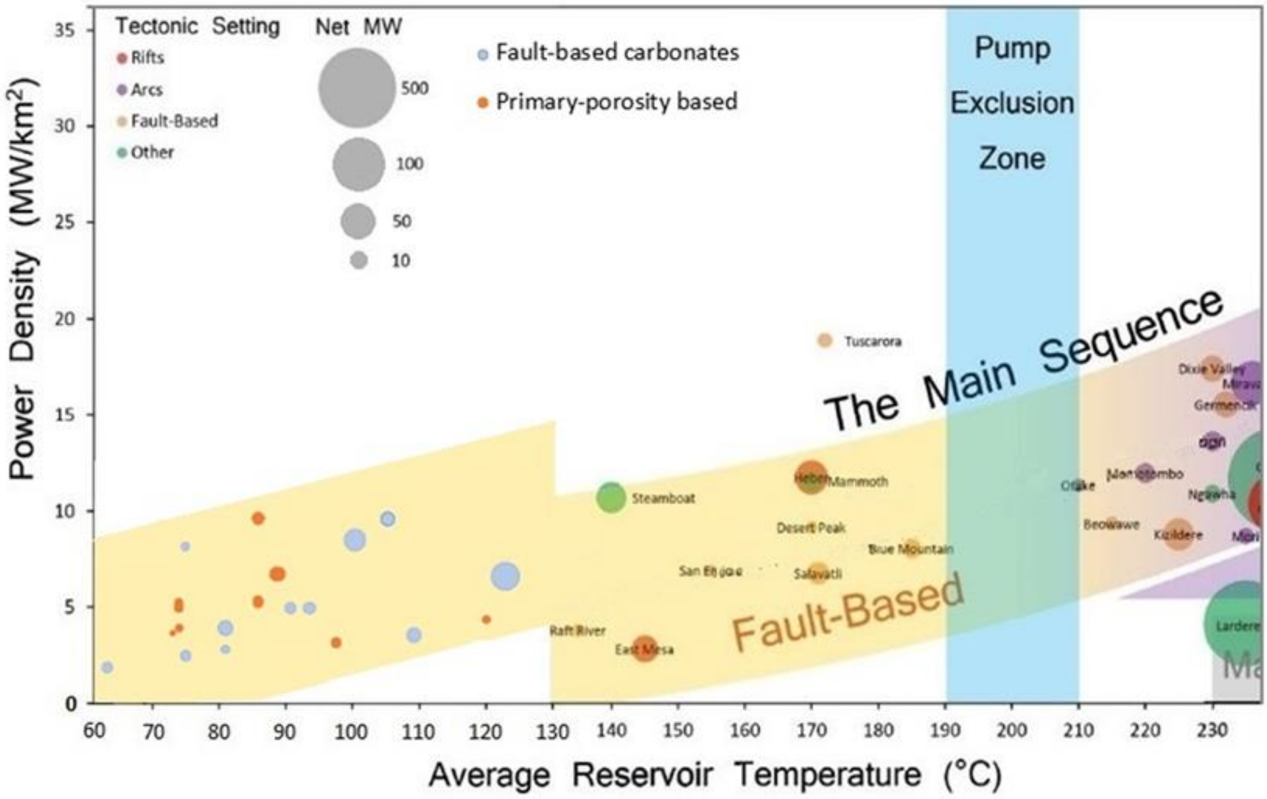

Figure 3: Power density versus average reservoir temperature for various existing geothermal projects and the geological setting in which they are drilled. Geothermal projects shown in the low temperature range consist of a mix of electricity producing and direct heat geothermal projects.

4. VALIDATION OF THE MODIFIED GEOTHERMAL RESOURCE ASSESSMENT METHODS

To validate the two proposed resource assessment methods, two existing geothermal systems—one producing geothermal doublet and a conceptual geothermal system—are evaluated (see Table 2). The geological setting and data quantity of the two geothermal systems are summarized in Figure 4 and Figure 5. Evaluating these two systems results in estimates of values for the recovery factor and POS as listed in Table 2. Based on these values it can be noted that the Venlo project carried some risks, which is consistent with the operational challenges reportedly faced by the project. The evaluation of the Molasse basin fits the recent successful development of several geothermal projects in the area.

Table 2: Overview of the specifics of the two geothermal systems evaluated, the estimated Recovery factor and POS.

Geothermal system	Specifics of the sub models	Recovery factor	POS
Real project: **Wijnen Grubbenvorst**, "Venlo block, actual geothermal project"	Represents the first geothermal project, Wijnen Grubbenvorst. **Depth** = ± 1500 m **Age** = Carboniferous, Dinantian	0.14 (reasonable)	0.14 (moderate risk)
Representative model: **Molasse basin** "Relatively good reservoir quality"	A relatively young carbonate reservoir compared to the other geological models presented here. **Depth** = ± 3000 m **Age** = Jurassic	0.19 (good)	0.30 (low risk)

5. DISCUSSION AND CONCLUSIONS

With the methods introduced in this paper we intend to start a discussion and search for a best practice approach to systematically evaluate the geothermal potential of fractured carbonate geothermal reservoirs during early exploration stages or when limited data is available.

By adding low temperature data of both direct heat and electricity producing geothermal projects to the power density curve, a more complete overview of geological settings in relation to geothermal power output is provided. To improve the relation between low and high enthalpy data, all underlying data of the two data sets used should be checked and compared for consistency. Additional data from geothermal projects in siliciclastic reservoirs is necessary to investigate if there is a correlation between production temperature and geothermal energy output. Additionally, agreement should be reached on the appropriate definition of the production area of a geothermal system, after which all project power densities can be recalculated.

The systematic and qualitative POS method appears to be a promising tool for geothermal resource evaluation during the early exploration phase of a geothermal project, since the POS method is independent of a geothermal power output assessment and it can be easily incorporated into any resource assessment. Scoring tables are used to estimate the recovery factor and the POS are useful for consistent evaluation of different geothermal prospects and for making meaningful comparisons. However, to provide a robust calibration, the values used in the tables and the evaluated parameters require validation by applying them to projects under development and to historical cases.

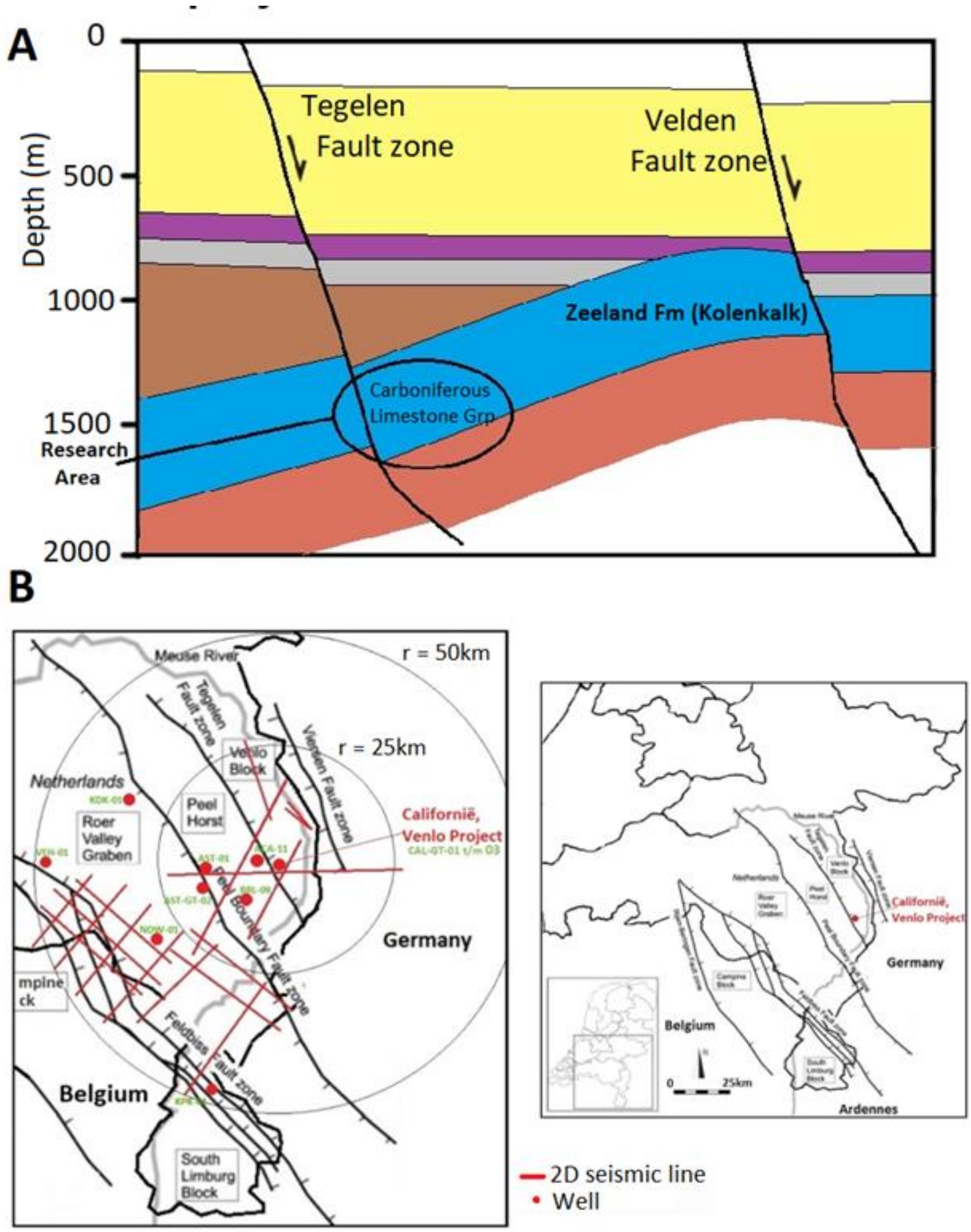

Figure 4: Overview of the Venlo geothermal system in the Netherlands. A) Basic structural setting, the black circle represents the location of the geothermal reservoir. The reservoir target formation is the Dinantian Carbonates (shown in blue). B) Left: Geological setting showing available wells and seismic lines. The black circles represent areas with radii of 25 km and 50 km around the target area. Right: regional geological setting (modified from (Broothaers et al., 2013)).

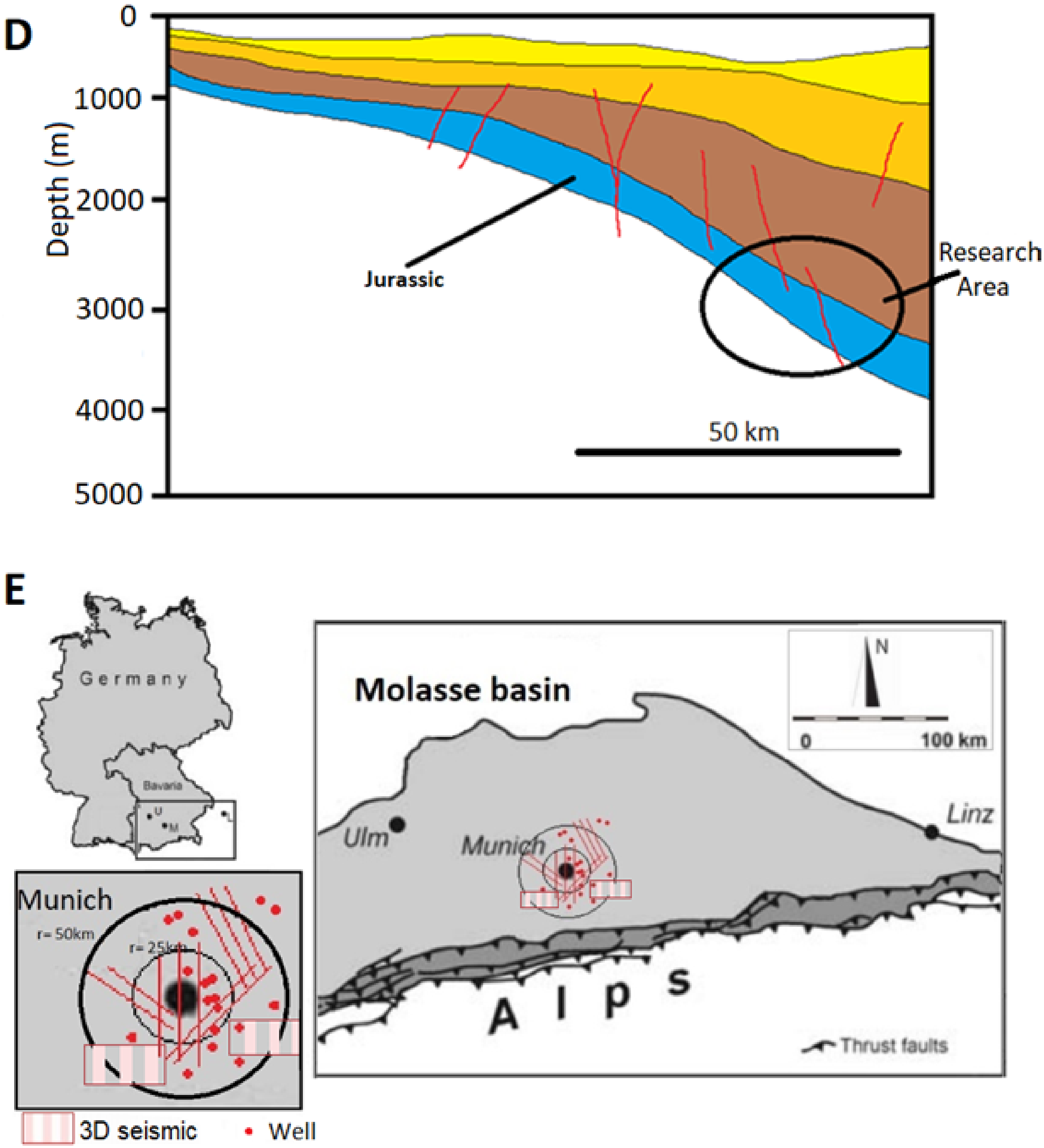

Figure 5: Overview of the Molasse Basin in Germany. D) Basic structural setting, the black circle represents the location of the geothermal reservoir. The reservoir target formation is a limestone layer from the Jurassic (shown in blue). E) Left: Geological setting showing available wells and seismic data. The black circles represent areas with radii of 25 km and 50 km around the target area. Right: regional geological setting (modified from (Böhme, 2010)).

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