Proceedings European Geothermal Congress 2007
Unterhaching, Germany, 30 May-1 June 2007

Probability Concepts for the Evaluation of the Risk concerning Temperature and the Production and Injection Rate in Hydrothermal Reservoirs

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Keywords: geothermal, probability, production rate, geostatistics

ABSTRACT

The economic success of a geothermal power project depends very much on the production rate and the injection rate which can be established in the wells tabbing the reservoir. The risk to reach the predicted rates is crucial for developers and investors of geothermal power plants.

Therefore models are being set up to cover this risk. The concepts are either to cover the risk using private insurance or setting up a fund which is fed by different sources. Both concepts need an evaluation mechanism to assess the probability of success in other words the probability to reach the proposed production and injection rate.

Evaluating the probability usually is based on statistics. Data availability in the geothermal reservoirs is scarce. In the Molasse region more than 30 data are available. They are of different quality and are spread irregularly in the region. The spatial distribution of the data calls for a geostatistical evaluation.

This cannot be reduced to a mathematical approach only, but geology plays the decisive role in the geostatistical evaluation of the data. The type of reservoir focusing on karst features and on fault zones in the Malm limestone has to be taken into account. The data evaluation has to be coupled with data available from seismic surveys. The geostatistical approach bears the advantage that not only an assessment of the production flow value but also the quality of the assessment is given, based on the spatial distribution of the data in the region.

In the case of the upper Rhine valley the data availability is even worse. There are less than 10 data available to assess the hydrothermal production in the geothermal reservoirs of the Buntsandstein and the Upper Muschelkalk. The successful wells are coupled with hydraulic active fault zones in the graben. The geostatistic approach is based on data availability. There need to be more wells drilled and tested to start following this approach for the assessment of the production rate directly. A concept is presented to cope with the problem assessing the probability of finding the planned production. The concept is based on the scarce data available, geostatistical values derived from other spatially distributed variables in the geothermal region of the upper Rhine valley.

With the scarce data available at the moment there are also soft facts to be looked at to come to an assessment of probability. Soft facts are the quality of the exploration of the project being assessed and stimulation methods which give the best chance to reach the productivity desired in an economically bearable way. The types and sequence of stimulation methods should lead to a probability of success which can be accepted by insurance companies and funds.

1. INTRODUCTION

Since the renewable energies law EEG adjusted the feed in tariffs for geothermal power production in 2004 the activity in the deep geothermal market picked up enormous speed. This resulted very rapidly in a large number of geothermal concessions in the Molasse Basin MR and the Upper Rhine Graben URG covering most of the high and medium potential areas. After a period of two years of intensive exploration particularly seismic exploration in the URG a number of geothermal power projects are now ready to be drilled. Still some of these projects lack financing. This is due to the exploration risk, the risk of finding the temperature and flow rate needed for a commercially successful project.

To cover the exploration risk either very expensive venture capital is needed or a risk coverage coming from insurance companies and/or from a federal fund.

To decide if a project can be covered and to assess the premium a probability of success has to be defined for each one of the projects seeking coverage. Usually the insurance companies are well prepared to assess probabilities using the statistical tools. In the geothermal field data is scarce and experience not yet at hand. Until the number of data is grown a workable concept is needed to start with and the geostatistical tools have to be looked at which will be needed and applied when more data is available.

2. UPPER RHINE GRABEN (URG) GEOTHERMAL PROVINCE

The URG is a graben structure formed mainly during the last 60 Mio years. In between the main boundary faults on the east and west, the inner part of the graben broke into blocks and subsided by up to several thousand meters. The graben was filled by sediments. The geothermal reservoir rocks are the brittle rocks of the Mesozoic and the fractured base rock in depth deeper than 2500m.

In the URG geothermal province (figure 1) temperature ranges are above 150°C. Flow rates of 80 l/s plus appear reasonable in this region, if fracture zones are tapped. The economic success of a geothermal project in this area depends on flow rates rather than on the temperatures. The prediction of temperatures proved to be reliable, with all of the projects carried out in the last few years showed the temperatures expected or even higher values. The flow rate depends very much on the local structural situation with high flow rates in and around open fault zones and low flow rates in healed or compressive fault zones and between fault zones.

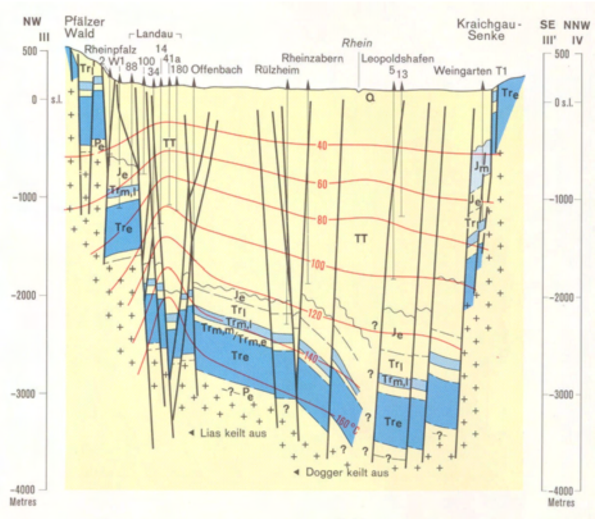

Figure 1: The Upper Rhine Valley geothermal province Haenel and Staroste (1988).

3. MOLASSE (MR) GEOTHERMAL PROVINCE

The geothermal reservoir of the MR is the Malm limestone inclining towards the Alps (figure 2). South of Munich thermal waters of about 120°C can be found in depths reaching down to 4000m. High flow rates reaching well above 100l/s were found. The high flow rates are due to karstification of the limestone especially in fracture zones.

With only low temperatures between 100 and 130°C coupled power and heat generation is crucial for a profitable geothermal project here.

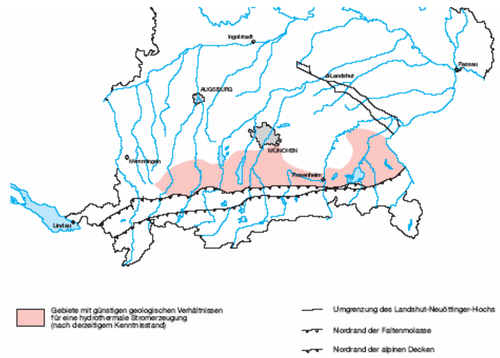

Figure 2: The Molasse geothermal province. Staatsministerium (2005)

4. UPSIDE POTENTIAL, INVESTMENT AND RISK

Ongoing exploration and project development lead to more and more reliable calculations of the upside potential for geothermal power production of the URG an MR Provinces. A total power production potential in the range of 200 MW el. appears realistic today for the middle URG using hydrothermal reservoir rocks present. Assuming that the installation of 1 MW el. costs approx. 5 Mio €, we are looking at a market of about 1000 Mio € in this region.

Geothermal projects require a total investment of around 20-30 Mio. €. The initial development costs for exploration until the first well proves the resource are risk capital because of lack of specific data and immature experiences with geothermal reservoirs.

There are three different ways to define the success of a geothermal project. From a scientific point of view a project is successful if a new idea can be proven on a technical scale. From an insurance company point of view success is defined as the point where the client is protected against damage, here the loss of money. From an investors point of view a project is successful if the return on invest fulfills his expectations. An investor is certainly not willing to spend too much money for R&D and an insurance company will not cover the investors ROI.

These different points of view describe the environment of probability of success and the expectations of the different parties involved.

5. GEOSTATISTICS

5.1 Concept of Geostatistics

Geostatistics is a well known tool to quantify the spatial variability of geological data using deterministic and statistical tools. Geostatistical methods were first used in mining after experience showed that ore content in a deposit varies with space and the variable is called a regionalized variable.

Models like the variogram are used to characterize the spatial continuity of regionalized variables. Using model variograms parameters like sill, range and directions of anisotropy can be defined. The Kriging interpolation method is based on these parameters. With Kriging interpolation values of a variable are estimated and presented in an isoline map. The Krige interpolation method bears many advantages in calculating the estimated values which are especially important analyzing geological variables. While Kriging e.g. the spatial arrangement of the data points are taken into account. These advantages are described in detail e.g. in Journel et. al. (1978) and Deutsch et. al. (1992)..

In our case especially important is the calculation of a Kriging variance which quantifies the reliability of the estimate. In geothermal applications an estimated value of a temperature at a well site planned is given (e.g. 156°C) and the Kriging variance of e.g. ± 4°C. The Kriging variance depends only on the spatial arrangement of the data points, not on there value. With Kriging also extra exploration wells can be planned minimizing the Kriging variance with the number and location of the wells planned.

Applying geostatistics geology plays a major role. Geological aspects like the definition of the area under investigation and abrupt changes in data values due to tectonic structures like folds and faults have to be taken into account. The role of geology in Geostatistics is shown in Isaaks et. al. (1978) and Kreuter (1996).

5.2 Application of interpolation on temperature data

Examples of isoline temperature maps are numerous. Most of them leave the impression that geology hasn't been taken into account adequately. The temperature map of the URG is shown in figure 3. It can be easily seen that interpolation has been done across the boundary faults of the URG which violates the definition of the geological entity to be examined. Temperature values in the graben have been estimated with data outside the graben that have geologically nothing to do with the heat flow and distribution of temperatures inside the graben. An appropriate study of the temperatures in the URG and other geothermal regions on geostatistical basis is still missing.

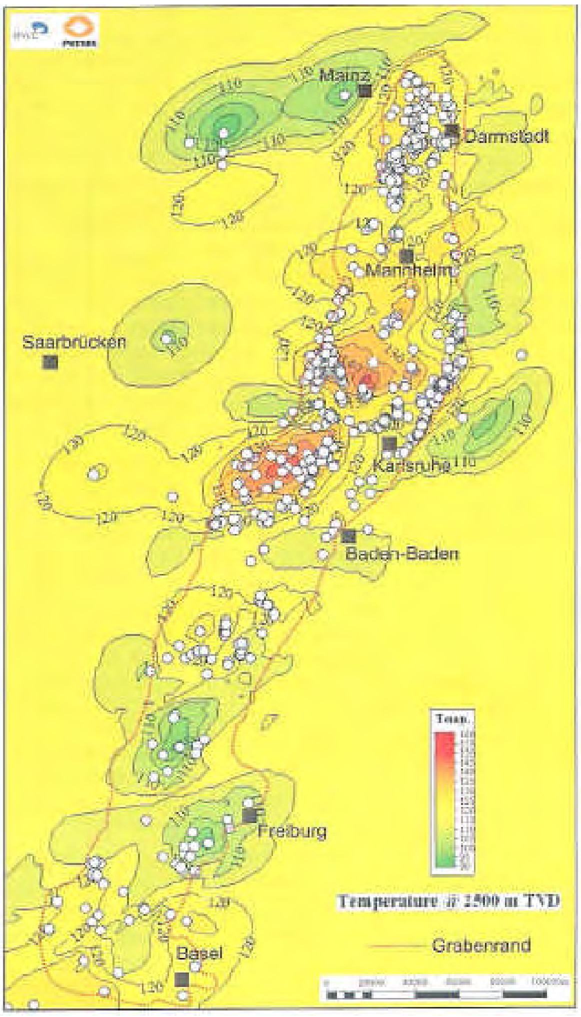

Figure 3: Temperature isoline map of the URG. Münch et. al. (2005).

5.3 Application of geostatistics on flow rate data

To apply geostatistics a minimum of data is required. The number of data needed to analyze flow rate is not yet sufficient, especially for the calculation of variograms describing the spatial continuity. Assuming the spatial continuity of flow rate data follow the same spatial continuity as the temperature data, Kriging can be applied on the few flow rate data points. Estimation values and the Kriging variance can be calculated. This concept could be applied in the MR already today with the data available.

The heat in the URG reservoirs is fed by fault zones reaching deep into the basement. Covered by impermeable beds the temperature spread in the reservoir even beyond long distances and across fracture zones with time. However high flow rates are bound to open fracture zones. Therefore the geological structures, their hydrological activity and their spatial arrangement and continuity are of much higher importance. Geostatistic tools could also be used in the future to describe their frequency and spatial continuity.

5.4 The importance of fault zones in the URG

A key to the understanding of a geothermal region is certainly the spatial fault distribution and the knowledge of the potential of a certain fault pattern to be conductive for thermal water.

Major fault zones with displacements between several hundred meters up to one thousand meters occur frequently in the URG. Both normal faults and strike slip faults can be recognized on 2-D seismic images. The kinematics of a fault zone can be detected from displacement studies on seismic images. The present condition of a fault zone is determined by its kinematic history and the geometrical position with regard to the present stress field. The regional stress directions are fairly well known. However, local stress magnitudes are difficult to predict without direct measurements.

Whether a single fault plain or a fracture zone related to a fault zone provides the flow is a matter of debate. It is well known that faults can be conductors as well as seals. The available data in the URG does not yet allow accurate predictions of hydraulic fault behavior. It is believed that in the near future results from geothermal wells will provide more and more insight into this important matter.

However, it is generally accepted and proved by a couple of wells, that large fault zones are good candidates for high thermal water flows.

5.5 Seismic surveys in the fault controlled geothermal reservoirs

Seismic surveys were conducted for decades in the hydrocarbon industry. Commonly 2-D seismic surveys are used for overview exploration followed by 3-D and 4-D seismic surveys for reservoir characterization.

Seismic surveys are still hesitatingly used in the geothermal industry. With regard to the budget of a geothermal power project, this is a surprising observation. It is even more so, if one takes into consideration, that a high amount of the investment for deep drilling is subjected to the risk of finding sufficient flow rates of hot water or not. Moreover, geothermal doublets or triplets require hydraulic connectivity in the far field on one hand but no hydraulic shortcut on the other hand. In order to plan well trajectories to match these requirements a good picture of the reservoir is very important.

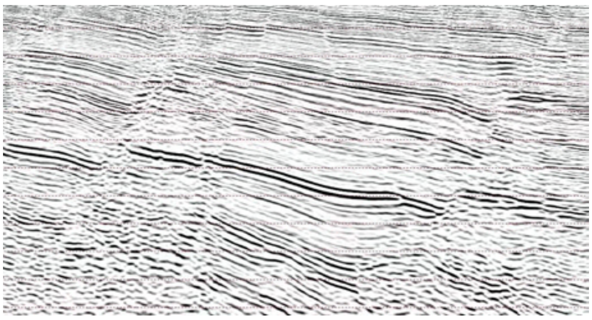

Figure 4: Seismic image of fault zones in the URG.

Consequently project sites with a high exploration status bear less risks of drilling and reservoir stimulation than those without. This is not yet proved statistically in the geothermal provinces in Germany, but experiences from the hydrocarbon industry can be taken as analogues. Therefore future risk assessments and possibility of success studies should take much stronger account the results of local seismic surveys.

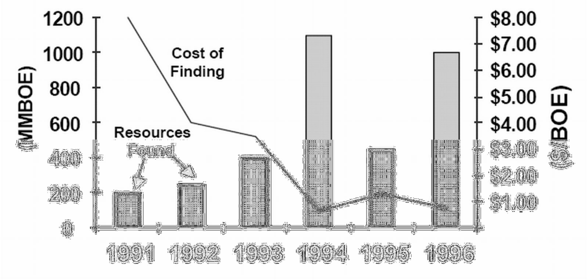

Figure 5: The impact of 3D seismic surveys on exploration costs and resources found in the oil and gas industry. Aylor (1998).

6. CURRENT CONCEPT TO ESTIMATE PROBABILIY FOR FLOW RATES

As a result of ongoing negotiations of insurance concepts in the main geothermal provinces in Germany general concepts are established that account for the given data bases and the experiences of developed geothermal projects.

6.1 Probability concept

In the MR statistical and probabilistic concepts are currently based on 35 data points. Up to now geostatistics haven't been applied. The data points closer to the wells planned have just been weighted with a higher factor than the ones further away.

In the URG only few exploration wells were drilled to the depth of the Triassic or even deeper. In the middle part of the URG between Karlsruhe and Landau, where most of the geothermal activity takes place we are looking at a number of about 7 wells. Although these wells reach some of the sequences that are considered good reservoirs e.g. the Muschelkalk they were not necessarily placed into or close to fault zones.

Geothermal wells that were drilled recently do have fault zones as primary targets. They clearly show considerable flow in the vicinity of fault zones and lower or no flow in a considerable distance away from a major fault zone. The results of the older deep wells for example calculations of thermal water production therefore need to be evaluated carefully for probabilistic purposes.

To calculate a probability of success only on seven data points can not be done with sufficient reliability. Therefore only a range of probability can be given which alone doesn't suffice to get the flow rate planned covered.

6.2 Reservoir development concepts

6.3.1 Drilling concepts

Fracture zones in the URG are mostly orientated in a NNE-SSW direction following the direction of the URG. To tab a fault zone in the reservoir the well orientation should be perpendicular to the fault zone direction. An inclining or horizontal drill path will also optimize the way the fault zone fractures are coupled to the well (figure 6). To follow this concept, the location and direction of the fault zone have to be known exactly, which calls for 2D and 3D seismic surveys. Seismic prediction while drilling would permit to steer directly into the fracture zones.

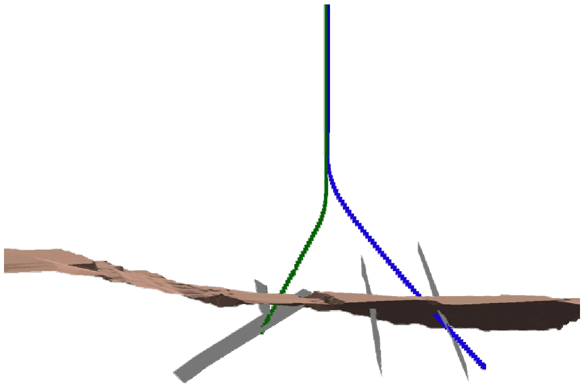

Figure 6: Drill paths of inclined wells orientated towards fracture zones.

Side tracks and fish bone drilling is state of the art in the hydrocarbon industry. In the geothermal industry side tracks are considered as an option, if the first target zone is not productive. A major concern of side tracking is the loss of one casing size, which needs to be accounted for in the original casing design. Otherwise there is a risk that the casing size in the production zone gets too small.

Fish bone drilling is used to deplete oil or gas bearing single layers such as productive sand stone beds. In order to match a certain layer with a horizontal well a very accurate exploration is needed. For geothermal purposes high water flows are required. Presently geothermal reservoirs are mainly seen in faulted and fractured zones rather than in single sequences with high rock porosities. It is therefore questionable whether the fish bone concept in its original sense is suitable for the development of geothermal reservoirs. If several neighboring fracture zones are present fishbone drilling could be used.

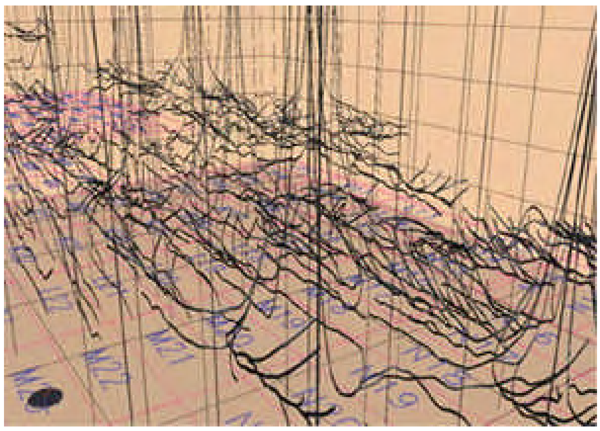

Figure 7: Fishbone wells in an oil reservoir of the coast of Venezuela, Anonymous (2002).

6.3.1 Acid stimulation

Acid stimulation is known to be very effective in carbonates. There are excellent examples from geothermal wells where acid stimulation was applied very successfully e. g in the Malm limestones of the Bavarian Molasse but also in the Muschelkalk limestones in Switzerland and Romania. Improvements of flow rates in the order of 2-3 times of the primary flow have been achieved.

Acid stimulations were also performed in sandstone reservoirs and even in granites. In these formations the effects are comparably low. However, acid stimulations can help to remove skin effects or calcite cements in fractures.

6.3.2 Hydraulic stimulation

Massive hydraulic stimulation concepts were originally designed and applied to geothermal wells of HDR projects in crystalline rocks. Prominent examples are Soultz-sous-Forêts, Bad Urach and Basel. Massive hydraulic fracturing was also performed in sedimentary sequences mainly in sandstones e. g in the Horstberg and Groß Schönebeck wells. From the results of hydraulic fracturing in geothermal projects it is concluded that hydraulic fracturing is more effective in crystalline rocks compared to sedimentary rocks.

In order to layout hydraulic stimulations a number of reservoir parameters need to be known. Most important is a good knowledge of petrophysical rock properties and “in situ” stress conditions. Moreover it is important to have a good understanding of reservoir geometries preferably in three dimensions.

To stimulate reservoirs which already show a good permeability e.g. above 50l/s high flow rates and large volumes of water are needed. In those cases hydraulic stimulation may be too expensive and alternatives like acid stimulation should be carried out.

6.3.3 Coupled stimulation concepts

In the URG three main potential reservoir sequences are recognized namely the Muschelkalk, the Buntsandstein and the crystalline basement of mostly granites. The Rotliegend between the Triassic and the basement contains both sedimentary rocks and volcanic rocks. Its thickness and composition varies considerably in different places of the URG. The Rotliegend might be considered as a reservoir in certain areas. However there is very little information about its distribution in the central URG.

Different stimulation techniques can be considered, depending on the number, thickness, lithology and spatial distribution of potential reservoir sequences. First, the reservoir fracture zones should be tapped with an optimal drill path orientated on the basis of seismic surveys.

If limestones are the main target, acid stimulation would be the first choice. If the potential reservoir contains both limestones and sandstones, a combination of acid stimulation and massive hydraulic fracturing is a reasonable option. In crystalline rocks hydrofracs certainly are the most promising procedure. The selection of stimulation techniques depends on the reservoir characteristics of each individual project.

6.3.4 Probability of success of reservoir development

Each of the proposed methods to enhance the flow rate of a well has a certain probability of success but produces costs at the same time. The economy of a project is calculated as power or heat output per invested money. The output depends on the established flow rate at a given temperature.

Taking only the costs for flow enhancement procedures like side tracks or stimulation methods into account here, a number of questions arises for each particular well of how to find the best development concept. What is generally more effective the side track option or the stimulation option? What are the costs for each enhancement procedure and to what percentage does that increase the probability of success? Which risks go along with each operation? How far should procedures be applied in other words how much money should be invested to enhance the flow in a particular well?

As has been explained earlier, data that allow statistical analyses are not yet available in sufficient number and probabilistic approaches are necessary to answer the questions above. In the process of well planning and planning of the enhancement procedures each step needs to be analyzed for costs and probability of success. The quality of the analysis of course depends on the quality of data input and the calculation method.

7. PROPOSED CONCEPT TO ESTIMATE PROBABILIY OF SUCCESS

Geostatistics should be applied to estimate values for geothermal projects. For temperature the number of data available is sufficient in the MR and the URG. The spatial continuity can be defined e.g. using variograms and temperature values can be estimated by Kriging. The Kriging variance can be used to assess the reliability of the estimated values. The geology, especially the definition of the area under examination and the discontinuities present have to be taken into account.

For flow rate, the spatial continuity parameters of temperature can be used and applied in Kriging. The Kriging variance will be low in MR and higher in the URG.

Especially in the URG the development of the reservoir using drilling techniques and stimulation methods have to be used and need to be taken into account when the probability of success is calculated. The step to evaluate stimulation and drilling concepts for the assessment of probability is still to be taken.

Not only stimulation methods should be looked at, but the analysis of the structures and the selection of the target using seismic surveys and the orientation of the drill paths are of even greater importance in the URG.

8. DRILLING RISK

Exploration risk is not the only mayor risk geothermal developers have to cope with. Also problems frequently arise even before the reservoir has been reached. The risks associated with drilling deep wells can amount to 100% or more of the cost of drilling the well. Oil companies distribute the extra costs over a large number of wells. Geothermal developers e.g. a city have only one project.

The majority of geothermal projects use a design of two or more deviated wells that are drilled from the same well site. Because well site development is restricted by a number of factors such as infrastructure, environmental protection and others the higher costs and risks of deviated drilling need to be taken into account. In the URG problems with borehole instabilities in deviated wells were experienced but at the same time successful wells with moderate deviation angles were drilled. Risks of deviated wells especially in mudstones can be mitigated by the right selection of well trajectories, casing designs, mud compositions, drilling procedures and other factors. Deviated drilling requires the use of expensive down-hole equipment in the bottom-hole-assembly BHA such as motors and measuring while drilling tools MWD. As a consequence a lost-in-hole event can produce considerable extra costs.

Considering the structure of the geothermal developers in Germany an insurance concept should absolutely include the cover of such risks and the associated costs.

5. CONCLUSION

The assessment of the probability of success is currently based on a small number of available data for the flow rate, as the most decisive parameter for the success of a geothermal project.

The application of geostatistics has the potential to estimate the flow rate values and quantify the reliability of the estimate. The spatial continuity derived from temperature data can also be used with flow rate data. This can actually be done in the Molasse region.

In the Upper Rhine Graben geostatistics alone are not yet reliable because of low data availability. Especially directional drilling toward promising targets, hydraulic active fracture zones and using side-tracks and fishbone drilling show a high potential of high flow rates and successful projects. This concept is based on a geological models derived from 2D and 3D seismic surveys.

The potential of acid stimulation and hydraulic stimulation have already been proven to enhance flow rate.

Not only the coverage of the exploration risk is necessary but also the coverage of the drilling risk.

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