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MODELLING OF PORE PRESSURE RESPONSE DUE TO HYDRAULIC STIMULATION TREATMENTS AT THE GEOTHERMAL RESEARCH DOUBLET EGRSK3/90 AND GTGRSK4/05 IN SUMMER 2007

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ABSTRACT

In order to complete the doublet system for geothermal power production, a second research well has been finished in January 2007 at the geothermal research drill site Gross-Schoenebeck (40 km north of Berlin/Germany).

To enhance the productivity of the production well GtGrSk4/05 three hydraulic fracture treatments were performed at different reservoir sections. The reservoir is located in -3850 to -4258 m depth within the Lower Permian of the NE German Basin. The reservoir rock can be classified into two lithological units from base to top: volcanic rocks (andesitic rocks) and siliciclastics ranging from conglomerates to fine grained sandstones (fluvial sediments). The first treatment (water frac) took place in the volcanic rocks followed by two gel proppant treatments in the sandstones that are characterised by a permeability of 50-100 mD.

During the stimulation the water table at the injection well EGrSk3/90 (500 m distance from production well) as well as the micro-seismic events were monitored.

Two important facts were observed: An instantaneous pressure response due to the hydraulic stimulation treatments and a long-termed pressure increase depending on the injected water volume. The rapidly water level increase in the offsetting well EGrSk3/90 was unexpectedly high and led to a wide range of interpretations.

To reveal the hydro-thermal-mechanical conditions during stimulation a 3D model was developed, which can reconstruct the stimulation treatments. This model includes a hydro-thermal-mechanical coupling, a discrete modeling of the fractured reservoir rocks and the implementation of the deviated well.

We will present the development from a structural-geological model (developed with earthVision/DGI) to a 3D hydro-thermal-mechanical finite element model. (RockFlow/Geosys).

Furthermore, we will show how the model can reduce the ambiguity of the observed field data.

INTRODUCTION

The technical feasibility of geothermal power production will be demonstrated by means of the geothermal research wells Gross Schoenebeck (40 km north of Berlin/Germany) using a borehole doublet as shown in Figure 1.

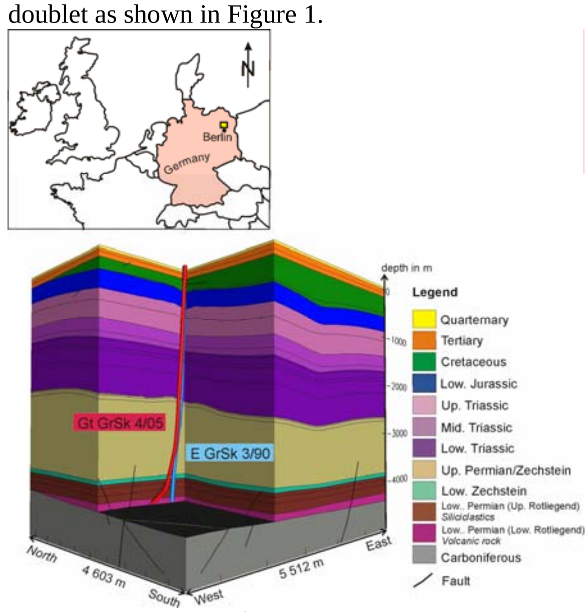

Figure. 1. Location of the research drill site (top) and 3D view of the two research wells and the geological horizons; the reservoir is situated in the Lower Permian within a depth of -3850 and -4258 m (bottom).

The existing well Gross Schoenebeck EGrSk3/90 was tested to investigate scenarios of enhancing productivity of thermal fluid recovery from the underground (Legarth et al., 2005; Reinicke et al., 2005; Zimmermann et al., 2005). In order to complete the doublet system a second well GtGrSk4/05 with a total depth of -4198 m has been finished in 2007 followed by three stimulation treatments to enhance productivity. For the development of a maximum effective pay zone the new well is inclined in the reservoir section by 48°

and was drilled in the direction of the minimum horizontal stress (σ_h=288°) for optimum hydraulic fracture alignment in relation to the stimulated pre-existing well EGrSk3/90. Hence the orientation of the fractures will be 18°N in the direction of the maximum horizontal stress (Holl et al., 2005).

During the elapsed time of the geothermal project it became obvious, that for planning the well path and fracture design, for interpretation of hydraulic tests and stimulations as well as for prediction of reservoir behaviour during the time of geothermal power production an appropriate numerical model becomes increasingly important.

To satisfy the requirements of the planned simulations the model should implement all the acquired knowledge of the reservoir. This includes the reservoir geology and structure, the geometry of wells and fractures, the hydraulic, thermal and mechanical conditions of the reservoir and generated fractures due to changes of the reservoir conditions.

RESERVOIR GEOLOGY

The reservoir is located in -3850 to -4258 m depth within the Lower Permian of the NE German Basin. The reservoir rocks can coarsely classified into two rock units from base to top: volcanic rocks (Lower Rotliegend) and siliciclastics (Upper Rotliegend) ranging from conglomerates to fine grained sand-, silt- and mudstones.

For the hydro-thermal-mechanical modeling these two main units were sub-classified depending on their lithofacies properties into the following numbered horizons:

- I Hannover formation: silt- and mudstone
- II Dethlingen formation:
  - A Elbe alternating sequence: silt- to fine grained sandstone
  - B Elbe base sandstone II: fine grained sandstone
  - C Elbe base sandstone I: fine to middle grained sandstone
- III Havel formation: Conglomerates from fine sandstone to fine grained gravel
- IV Volcanic rocks: Ryolithe and Andesite

Due to the high hydraulic conductivity and porosity, the Elbe base sandstone I and II are the most prominent horizons for geothermal power production.

RESERVOIR STRUCTURE

To model the geothermal reservoir it is important to define the model area depending on the reservoir structure. As mentioned above, the geothermal reservoir is built up by six sub-horizontal layers. The low permeable overlying and underlying horizons ban be taken as no flow boundaries. The mean and total thickness of the layers can be calculated as shown in Table 1:

Table.1. Nomenclature for the reservoir horizons including the vertical dimensions (TVDSS – True Vertical Depth Subsea).

Layer	Top [m]	Bottom [m]	Thickness [m]
I	-3850	-3996	146
IIA	-3996	-4026	30
IIB	-4026	-4086	60
IIC	-4086	-4133	47
III	-4133	-4178	45
IV	-4178	-4258	80
Total	**-3850**	**-4258**	**409**

The horizontal extension should be chosen depending on the maximal hydro-thermal-mechanical influence of stimulation treatments and planned geothermal power production and geological given boundary conditions. Therefore, we defined the model area by a EW dimension of 8 km and a NS dimension of 6 km around the research wells.

In addition to the geological layers, the reservoir included a fault system with an azimuth of 130° for major faults and 30° and 170° for minor faults. A major fault in NE-SW orientation is interpreted with some uncertainty from two seismic sections (Moeck et al., 2006). The NE-SW oriented structures can be classified as extensional faults and the NW-SE oriented structures are transcurrent faults (Scheck, 1997). Generally, the orientations of the faults is vertical (dip of 90°) but for some faults the dip value can drop below 40° (Fig. 2).

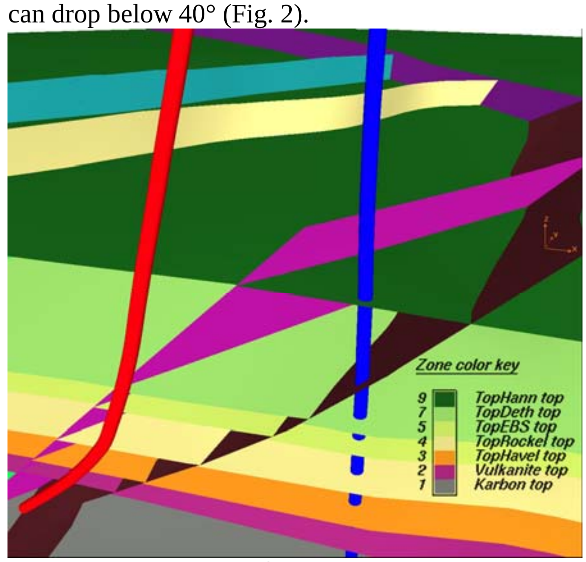

Figure.2. 3D view of the reservoir around the research wells, including the interfaces of the geological units and the significant fault zones.

Besides the natural structures of the reservoir the additional geometries of the hydraulic fractures and the research wells (Fig. 3) have to be implemented into the model. Actually, four hydraulic fractures exist (Tab. 2).

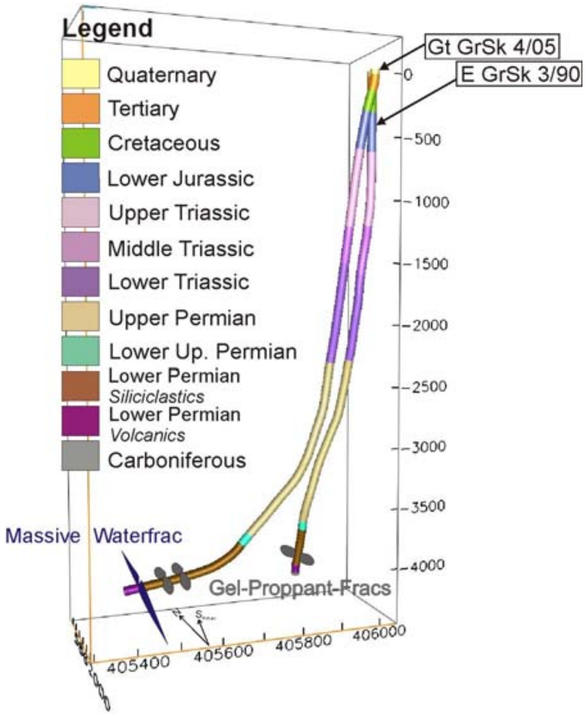

Figure.3. 3D view of the four hydraulic fractures along the two research wells including the geological units

Table.2. Description of the four hydraulic fractures, including location, type and dimension.

Well	Type	Depth [m]	Length [m]	Height [m]
EGrSk3/90	2xgel/proppant + 2xwater	-4085	150	80
GtGrSk4/05	water	-4175	190	120
GtGrSk4/05	gel/proppant	-4070	50	80
GtGrSk4/05	gel/proppant	-4005	50	80

The fractures are orientated perpendicular to the minimum horizontal stress. This means for the recent in situ stress field an azimuth of 18°.

The arrangement of the two wells has to fulfil two important conditions. First, the wells should be located in such a way, that the pressure in the reservoir would not drop significantly during production and second, a temperature drop in the production well should be avoided. At the surface the two wells have a distance of 28 m. Due to the fact that the well EGrSK3/90 is vertically orientated and to ensure a distance of 500 m within the reservoir, the second well GtGrSk4/05 is deviated. At the top of the reservoir (-3850 m) the inclination is 18° and increases progressively to 48° at -4200 m. Therefore, the distance of the two wells increases from 254 to 473 m from top to bottom. Besides the realization of the required distance within the reservoir, the deviation also leads to an increase of the well-reservoir intersection. Thus, the thickness increases from 350 m for the vertical well EGrSK3/90 to an apparent thickness of 442 m for the deviated well GtGrSk4/05.

MECHANICAL RESERVOIR CONDITIONS

The fault pattern analysis of a 3D structural model indicates normal to strike slip faulting for the Lower Permian sediments in the vicinity of the geothermal well Gross Schoenebeck.

In addition to the fault pattern analysis, stress ratios were calculated for the -4035 m deep Rotliegend sediments from frictional equilibrium. By means of the stress ratios and the vertical stress $S_V=\rho gz=105$MPa the maximum horizontal stress $S_H=100$MPa and the minimum horizontal stress $S_h=55$MPa were determined (with average density of $\rho=2.6$ g cm^{-3}, g=9.81 m s^{-2} and z=4100 m).

Furthermore, bore hole televiewer (BHTV) images after hydraulic fracturing provide an azimuth of $S_H=18.5° \pm 3.7°$ (Holl et al., 2005).

The formation pressure is $P_p=43.8$ MPa, determined by p,T–logs at stationary conditions of the geothermal target horizon (Legarth et al. 2005).

According to the stress relation of normal faulting the effective vertical stress $\sigma_{Veff}=\sigma_1-P_p=61.3$ MPa and the effective mean stress $\sigma_{meff}=(\sigma_1-\sigma_2-\sigma_3)/3-P_p=42.9$ MPa can be calculated.

Besides the stress condition the elastic moduli for homogeneous isotropic materials can be determined. The Youngs Modulus (*E*) for the sandstone and for the volcanic rocks is 55 MPa and the Poisson's ratio (ν) is 0.18 and 0.2, respectively (Zimmermann et al., 2007).

THERMAL RESERVOIR CONDITIONS

Temperature is the most important thermal parameter. According to the continental geothermal gradient, the lowest temperature of the reservoir can be found at the Hannover formation with 138°C and increases continuously to 147°C for the volcanic rocks. Further parameters are the heat conductivity λ of the medium that indicates its ability to conduct heat and the heat capacity c, which is defined as the measure of the heat energy required to increase the temperature of the medium by a certain temperature.

A detailed overview of thermal parameters of the north German basin is given by Lotz (2004) and Gehrke (2007), which is summarized in Table 3.

The values of the heat conductivity were determined by laboratory experiments at 20°C and were corrected by its temperature dependence as shown in the section „Coupled processes". The heat capacity values for the north German basin can be taken from SCHECK (1997) and MAGRI (2005).

Table.3. Hydraulic and thermal parameters of the reservoir rocks (Gehrke, 2007)

Layer	Permeability k [mD]	Porosity φ [%]	Temperature T [°C]	heat conductivity λ [W/(m*K)]	heat capacity c [J/(kg*K)]
I	0.05	1	138.2	1.9	920
IIA	12.5	3	141.7	1.9	920
IIB	25	8	143,2	2.9	920
IIC	50	15	145,2	2.8	920
III	0.1	0.04	146.5	3	1000
IV	0.1	0.5	147.4	2.3	1380

HYDRAULIC RESERVOIR CONDITIONS

In most sedimentary rocks the porosity is interconnected, which makes the rock permeable for flow. The permeability *k* of a rock can be measured by the steady state method making direct use of Darcy's Law, thus assuming laminar flow conditions:

$$k = -\frac{Q*\eta}{A*\nabla p}, \tag{1}$$

where *Q*, *A* and η denote the flow rate, the cross section of the flow path and the dynamic viscosity of the fluid.

The highest reservoir permeability was determined in the clean sandstones of the Elbe basis sandstone with up to 50-100 mD (Trautwein & Huenges, 2005). In addition to matrix permeability, potentially existing natural fractures and faults might increase the permeability of this formation.

In contrast, the permeability of the volcanic rocks of the Lower Rotliegend is characterized by a fracture system. Generally, the bulk permeability of fractured reservoirs is low, but flow and transport through the fracture system can be high. The hydraulic parameters, including porosity and permeability are listed in Table 3.

As shown in equation (1), the flow rate and pressure gradient depend on the dynamic viscosity η, which is the product of the fluid density ρ and the kinematic viscosity ν. Under in situ conditions, the fluid density in the GrSk wells is 1109 kg/m³ (salt content of 265 $g*l^{-1}$). The dynamic viscosity at a temperature of 150°C and fluid pressure of 44 MPa is calculated to 374 µPa s.

COUPLED PROCESSES

In the last sections we described the mechanical, thermal and hydraulic conditions of the static reservoir. But it is evident, that due to the stimulation treatments as well as the geothermal power production, the reservoir conditions will change.

During the last stimulation treatments in summer 2007 a maximum well head pressure of 58.6 MPa were observed. This well head pressure is equal to the mean effective pressure drop of 38 MPa at the reservoir.

Besides pressure also the temperature differs for both wells. The production temperature is approximately 150°C (section "Thermal Reservoir Conditions") and of the injection fluid the temperature is 70°C (Köhler & Saadat, 2004), so a temperature difference of 80°C exist in the course of geothermal power production.

These described changes of fluid pressure and temperature lead to a change of the reservoir characteristics which are described below.

Hydro mechanical processes

As mentioned above, porosity and permeability rank among the most important parameters in gas, oil and water reservoirs. Hence, we investigated the permeability and porosity dependence on changes in effective pressure, of the Flechtinger sandstone (Rotliegend sandstone, an outcropping equivalent to the reservoir rock) by laboratory experiments. The samples were cylindrical in shape with a diameter of 3 cm and a length of 4 cm. Both experiments were performed at a constant temperature of 40°C. A 0.1 molar NaCl-brine was used as the pore fluid. The permeability experiment was performed at a maximum confining- and pore pressure of 47 MPa and 42 MPa, respectively. A constant flow rate of 0.05 ml/min was applied. We adjusted the effective pressure by increasing the confining pressure to its maximum and subsequently increased the pore pressure. Then, the pore pressure and the confining pressure were successively reduced to 2.5 MPa and 5 MPa, respectively.

The porosity experiment was performed at a maximum confining pressure of 70MPa and the pore pressure was kept constant at 5 MPa. We adjusted the effective pressure by increasing the confining pressure continuously to its maximum and subsequently decreased to 10 MPa. The results in Figure 4 show, that both porosity and permeability decrease with increasing effective pressure. For an effective pressure interval between 5 and 30 MPa, permeability decreases approximately by 18% and porosity by 6%. Therefore, we can conclude that a change of effective pressure (conditions during production and injection) leads to a change of the hydraulic reservoir properties. On one hand, it is caused by a geometry change of the matrix and on the other hand the fluid properties are changing due to effective pressure change. As shown in Figure 5 density and dynamic viscosity are pressure dependent. According to equation (1), these changes will also change the flow rate and/or the pressure gradient.

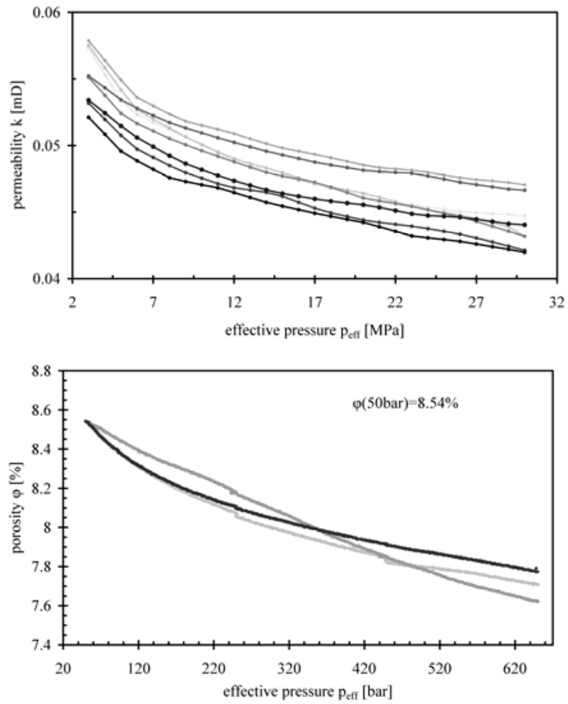

Figure.4. Permeability and porosity change of the Flechtinger sandstone as a function of effective pressure.

Besides matrix porosity and permeability the hydraulic conductivity of the induced fractures and of the fault system are influenced by a fluid pressure change (Huenges & Winter 2004). At high fluid pressures the hydraulic conductivity should increase due to an opening of the fracture. For the research well EGrSk3/90 a in situ fracture closing pressure of 49.8 MPa was determined (Huenges and Winter 2004). During the injection time the fluid pressure will be above the fracture closing pressure and the fracture remains open. The difference pressure is 6 MPa, calculated by the fracture closing pressure and the stationary fluid pressure. To inhibit a closure of the fractures of the research well GtGrSk4/05 we propped the volcanic fracture with a low concentration of sand and the sandstones with high strength proppants (Zimmermann et al., 2008).
The detailed hydro-mechanical behaviour of the fracture system can be investigated by the described 3D model.

Hydro thermal processes

It is well known, that fluid properties such as density and viscosity are temperature dependent (Fig. 5). The density dependence can be expressed in terms of thermal expansion coefficient β and compressibility γ (Magri, 2005):

$$\rho = \rho_0\left(1 - \beta(T - T_0) + \gamma(p - p_0)\right). \qquad (2)$$

This density dependence influences the dynamic viscosity and results in a change of the fluid flow properties.

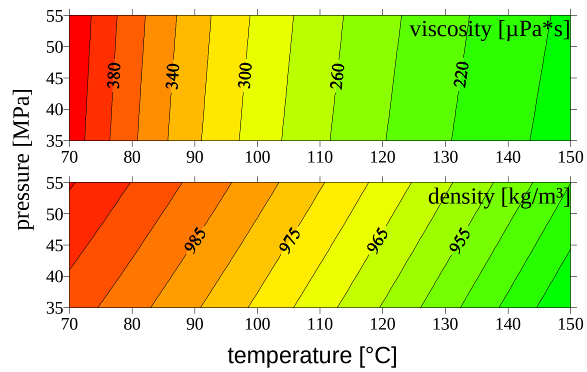

Figure.5. Dynamic viscosity and density in dependence of temperature and pressure for pure water (NIST).

Besides hydraulic conductivity, heat conductivity λ also changes due to a temperature change. The functional relation is given by Somerton (1992):

$$\lambda(T) = \lambda_{20} - 10^{-3}(T - 293)(\lambda_{20} - 1.38)\left[\lambda_{20}(1.8 * 10^{-3} * T)^{-0.25\lambda_{20}} + 1.28\right]\lambda_{20}^{-0.64}. \qquad (3)$$

By means of equation (3) we are able to calculate the heat conductivity at any point of the reservoir with defined temperature.

MODEL DEFINITIONS

At the current state, we are reconstructing the model geometry based on a structural geological model (Moeck et al., 2006). The geometry reconstruction contains the geological units, the major faults, the induced hydraulic fractures and the diverted research wells. In order to ensure the direct reproduction of the well and fault geometry (non vertical) a tetrahedrization of the model area was chosen. For the numerical stability each 3D object should contain more then eight tetrahedrons. This means, that a geological unit must be filled by a minimum of 8 tetrahedron layers. This implies a minimum of approximately 50.000.000 tetrahedrons for the total model area. Less tetrahedrons lead to an inadequate refinement of the reservoir geometry, as shown in Figure 6.

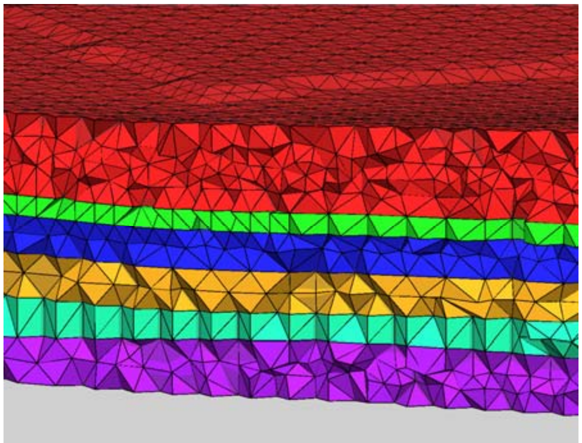

Figure.6. Cross section of the model area showing the six geological units, filled by only 4.000.000 tetrahedrons. Therefore, thin geological units (green and turquoise) are only filled by one tetrahedron layer.

After the successful reconstruction of the model area the solid (matrix), medium (bulk) and fluid parameterisation with the acquired properties will be performed. For this purpose the simulation software Rockflow/Geosys (KORSAWE et al., 2003; WANG and KOLDITZ, 2005) will be used. Furthermore, the following coupled processes have to be implemented:

- pressure dependent medium properties (porosity and permeability)
- pressure dependent fluid properties (density and viscosity)
- pressure dependent fracture properties (hydraulic conductivity)
- temperature dependent fluid properties (density and viscosity)
- temperature dependent heat properties (heat conductivity).

By means of the final model the characteristics of the reservoir during the stimulation treatments and the geothermal power production can be simulated, the results can be compared with the field data and the influence of every coupled process can be quantified.
The model results can be validated by flow rates and pressure changes, acquired during stimulation, testing and monitoring.

CONCLUSIONS

During stimulation treatments as well as geothermal power production, the pressure and temperature conditions of the geothermal reservoir at Gross-Schoenebeck are changing. Due to uncertainties in interpreting the measured field data, a numerical model becomes increasingly important. By means of the well known reservoir geometry, structure geology, hydro-thermal-mechanical conditions and the occurring coupled processes we will simulate the change of these reservoir conditions.
This will lead to a better understanding of reservoir behaviour, to an interpretation of the stimulation treatments and to a prediction of the reservoir characteristics during geothermal power production.

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