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MICROSEISMICITY AT GROß SCHÖNEBECK - A CASE REVIEW

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ABSTRACT

A cyclic hydraulic fracturing experiment has been performed to enhance the productivity of the geothermal research well at Groß Schönebeck (Germany) in 2007. During and after the stimulation treatment the recorded seismicity has been negligible compared to other similar hydraulic fracturing in crystalline rock.

Towards the end of the treatment three small clusters of very low magnitude events (M_w max -1.0) have been located. The spatial distribution of hypocenters may indicate the reactivation of a small patch of a nearby fault: focal mechanism compatibility with shearing processes supports this interpretation, too.

The authors investigated the causes of the delay in the occurring seismicity with respect to the beginning of the injection, modeling the variation in stress state by the aid of numerical model in a simplified environment and quantifying the increase in the probability of failure occurrence, through Hoek-Brown criterion.

Water level data from the production well suggests limitations in the size of the fractured volume by a fault. Whether this is related to recorded seismicity or not has been analyzed.

Microseismicity may be triggered by numerous causes. Changes in temperature and pressure distribution during stimulation treatment has been numerically modeled. The possible mechanisms behind the events recorded at Groß Schönebeck then has been reviewed, basing the analysis on their temporal and spatial distribution.

INTRODUCTION

Seismic events triggered by fluid injection has been identified for the first time in the 1968 (Healy *et al.*, 1968), studying earthquake activity recorded after injection of waste fluid into a deep well.

Different studies linked variation in pore pressure and shearing mechanisms seismicity, as reduction in normal stress is promoted by an increase in fluid pressure like in the case of Matsushiro research well (Ohtake, 1974), Rangley experiment (Raleigh, 1976) and more recently in Basel (Deichamnn and Giardini, 2009). Various events related to impoundment of hydraulic reservoir has been linked showing correlation with both the weight load and the pore-pressure diffusion.

Based on data collected in various and heterogeneous geothermal sites, different mechanisms have been suggested as responsible of induced seismicity (Majer, 2007).

The most likely causes of induced seismicity involved in short duration stimulation treatment (days or weeks) seem to be pore-pressure diffusion, temperature decrease and stresses driven by change of the volume of the reservoir. These mechanisms do not generate strong seismic events by themselves but promote the energy release from already critically stressed structures.

In the following work we will focus our analysis on the potential causes of seismic events in the 5 day water-frac stimulation treatment that took place in the test site of Groß Schönebeck, Germany.

RESERVOIR CHARACTERIZATION

Geology

The Groß Schönebeck field is a EGS research site located in the Northeast German Basin, 50 km north of Berlin.

The reservoir lies between -3815m and -4250m below sea level and it is composed by two major rock units capped by a Zechstein salt formation, lying over a Carboniferous formation.

The two rock units are of Lower Permian age: andesitic volcanic rocks compose the Lower Rotliegend formation, lying below the siliclastics Upper Rotliegend, that is instead composed of sandstones of various origin, ranging from conglomerates to fine-grained silt stones.

While volcanic rocks are naturally fractured, the sandy sedimentary beddings are generally intact but much more porous, with porosity ranging from 8% up to 15% compared to 0,1% for andesitic rocks, as seen in drilling sample and on a bigger scale in representative outcrops of North German Basin.

Active seismic prospection showed a system of faults characterized by major NW-striking faults and NNE-striking minor faults. Natural fractures in the reservoir are parallel to the NW-striking strike-slip faults and N- to NE-striking normal faults.

The stresses calculated at the reservoir depth are σ_v= 100 MPa, σ_h=55 MPa and σ_H between 78 and 100 MPa, while the horizontal stress direction is 18.5 °N determined from borehole breakouts.

The stress regime in the sandstone is known as transitional from normal to strike-slip faulting, due to the similarity between maximum horizontal stress and vertical stress.

In this stress field then the NNE-striking faults bear highest ratio of shear to normal stresses, exhibiting increased likelihood to incur in slipping events. Critically stressed faults are described also as hydraulically transmissive, so the preferential flow paths will be the minor faults and the fracture N- to NE-striking fractures.

Wells

The research site is composed by a well doublet. The two wells were drilled to reach the reservoir at a target depth of more than 4300m.

The injection well stands at 28m distance from the production well at the surface, going deeper vertically oriented. The production well was drilled deviated, it is 18° vertically deviated at the top of the reservoir, increasing progressively up to 49° at the bottom. The distance between the two wells is at the bottom 470m, to ensure minimum drop in both reservoir pressure and production fluid temperature.

The path of the wells crosses interesting structures (Fig.1).

We suppose the two western fault to be conductive because critically stressed, while the eastern one is known to be conductive, as there was almost immediate water level response in injection well to an impulse in the production well.

Stable 150°C has been recorded at 4300m depth in the injection well, before the completion of production well and before any major injection test or stimulation treatment.

Stimulation treatment

Three stimulation treatments have been performed in the production well to enhance productivity. Different lithology requires different stimulation treatment, to avoid fracture closure, hindering permeability decrease. Where self-propping mechanism are not yet proven, like siliclastics rocks, gel-proppant fracs were applied.

Where rocks shows some self-propping properties, like in the volcanic layer, due to the opening and shearing of the natural or induced fractures present, water frac stimulation containing few amounts of sand were performed.

The production well was stimulated three times, with a 5 days water-frac treatment in the lower Rotliegend volcanic layer and two smaller hydraulic-proppant fracturing treatments in the upper Rotliegend sandstone formation.

We will focus our study on the water-frac treatment which took place between the 9th and the 14th August 2007. An amount of 13000 m^3 of water was injected through a cyclic procedure, ranging from 1.2 m^3/min up to 9 m^3/min, into the permeable volcanic rocks. Wellhead pressure needed to reach that flow was ranging from 30MPa up to 58.6MPa wellhead pressure, while computed minimum pressure to achieve fracturing was 24,5MPa.

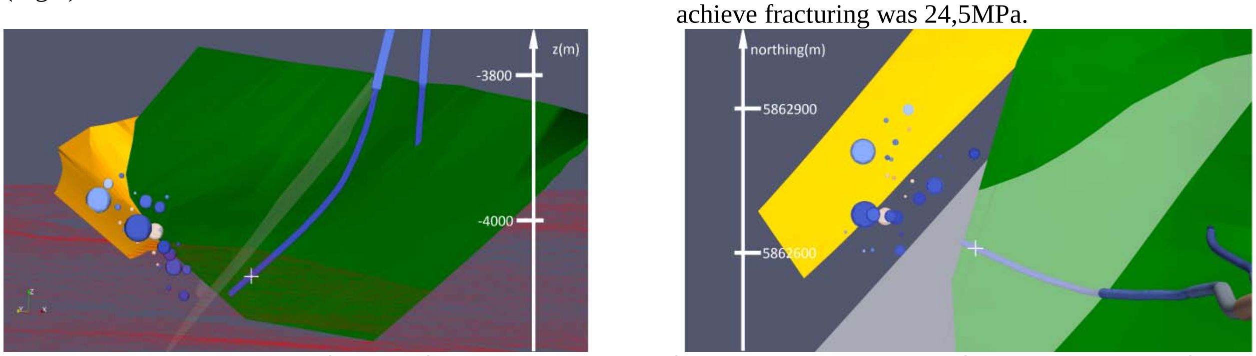

Fig.1: Overview of the Groß Schönebeck relevant faults and seismicity, view from S-SW (on the left) and from above (on the right). The two nearest faults to the wellbore are in green and transparent white, in yellow the mapped fault near to the seismic events. The white cross marks the injection point location. The red wireframe on the left represents the top of the volcanic layer. Seismic events colors represents time of occurrence: before (blue to light blue spheres) and after stimulation (yellow spheres). The earlier the events, the darker the color.

The fracturing process was simulated with software FRACRO, to estimate length, height and width of the fracture, leading to an estimate fracture half-length of 180m, an average width of 17mm and an average height of 60m. The fracture (Willis and Hubbert, 1957) will be vertical and propagating parallel to the maximum horizontal stress (18°N), according to the stress state determination and to the failure mechanisms.

Seismicity

The site is located on a the eastern part of North German Basin, where no signs of recent tectonic activity are present. The nearest recent events are human induced, due to mining activities at circa 300km distance.

The reservoir capping (Zechstein salt formation) and the reservoir depth itself, make it very hard to record seismic events through surface or shallow borehole recording equipment.

In fact, readings of the 80 events that were recorded during stimulation treatment came only from the 3-component seismometer located at a depth of 3730m in the injection well. This seismometer could record only some events, because of intrinsic properties of the sensor and the high noise from the injection pumps hindered recordings of higher frequency and/or small magnitude events. Due to the reservoir rock properties, mostly of the seismic events that could happen are very small or are characterized by high corner frequency.

Thus, the recorded events are fewer than what is available in other massive water-frac treatment, not only in number of them but also in maximum magnitude recorded.

In fact, estimate of expected fracture size and knowledge of the general stress state made it possible to predict a cloud of seismic events in direction 18°N during the massive injection, but the prediction was largely disappointed, since there were few events recorded and in spite of the cyclic high pressure applied (58.6 MPa overpressure at the maximum) the recorded seismicity (Fig.2) was quite sparse.

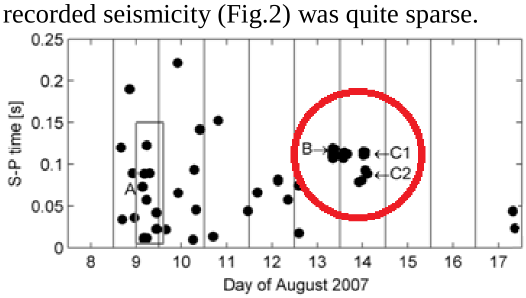

Fig.2: Events recorded and picked during and after the water-frac. Cluster B happened before the shut-in.

Just 80 events could be picked for P- and S-wave arrivals. From these recorded events, 29 events have been located and clustered in 3 distinct groups, presenting similar waveform and S-P arrival time.

The first cluster happens before shut-in, it comprises 20 events, among them the strongest event (M_w=-1.1). The other two clusters happens short time after the shut-in.

These events are located at a distance of 100-300m and over or at the same depth, with respect to the injection point. The depth location respect to the time shows a strongly upwards migrating pattern for the first cluster: some events can be identified as happening in the sedimentary rocks.

They present energy ratio typical of shearing events and their clustering can be interpreted as repeated slipping of the same weak patches in a fault plane.

The hypocentral distribution confirmed a previous analysis: the located events area defines a plane striking 17°N and dipping 52°ESE which was a likely direction of slipping, as the slip tendency analysis (Moeck *et al.*, 2009) suggested.

No reliable information about the focal mechanisms can be extracted from the recorded data regarding the faulting mechanisms. We stick to the interpretation based on stress field, assuming the events are due to normal faulting.

The other 51 picked events happened for the major part during and shortly after the start of the treatment. The estimate of their distance from injection point shows that most of them occurred immediately near the well. The signal recorded was pretty weak, due to focal mechanisms and also due to the small capacity of andesitic rocks in sustaining deformation without failing. In fact, the signal was so weak that no reliable information has been extracted, apart from the S- and P- wave arrivals.

The time lag between injection and the strongest event is similar to other induced seismicity events experience, but the strongest event happening before shut-in altogether with the absence of consistent seismicity before that raise some questions, especially since the events can be located near a fault, but in the sedimentary beddings.

The occurrence of the events on an already mapped structure suggested us to look for the possible trigger of the slipping on the faulted plane.

The almost instantaneous pressure response recorded in the future injection well during the treatment of the volcanic layer supports the idea that the large faults may quickly propagate the pressure variation, transmitting a pore pressure variation in water level 500m far from the injection point, also if not critically stressed.

This support the mechanism of pore pressure as trigger of events over an already stressed failure plane, with the fault itself conducting pore pressure variation from the andesitic rocks to the stiffer sedimentary layer.

GOVERNING EQUATIONS

The governing equations of heat and pressure diffusion in a saturated porous media are derived from the conservation principles for linear momentum, mass and energy.

The conservation of fluid mass equation can be written as:

$$S_0 \frac{\partial h}{\partial t} + \frac{\partial q_i^f}{\partial x_i} = Q_\rho + Q_{EB}(C,T) \qquad (1)$$

where S_0 is the specific storage coefficient, h is the hydraulic head, q_i the Darcy velocity, Q_ρ the mass source/sink term and Q_{EB} an additional term to incorporate mass-dependant and temperature dependant compression effects.

The momentum conservation equation can be expressed:

$$q_i^f = -K_{ij} f_\mu \left(\frac{\partial h}{\partial x_j} + \frac{\rho^f - \rho_o^f}{\rho_o^f} e_j \right) \qquad (2)$$

leading to an expression of Darcy velocity depending by hydraulic conductivity tensor K_{ij} , the constitutive equation for dynamic viscosity f_μ and fluid density ρ. from sample measurements.

It is possible to define a power law (Shapiro & Dinske, 2009):

$$K = (n+1) K_o p^n \qquad (3)$$

to relate increased conductivity to pressure, defining through n the linearity or the degree of non linearity of the fluid rock interaction, while p is a ratio between injection pressure and reference pressure.

The assumed value for hydraulic conductivity has been determined according to this law: this way increased flux through pressure-opened fractures present in the layer is taken into account, by means of reference K_0 and the injection pressure measured in field.

NUMERICAL MODEL

We used FEFLOW (Diersch, 2005) to model the geothermal reservoir as a confined hydro-thermal aquifer. We use this software because of the full support to hydraulic-thermal coupling plus the possibility to define discrete features (such as faults).

Two axisymmetric 2D model have been built.

They have equal dimensions (1 km length, 500m depth) and share the same properties, but a discrete element representing a fault (dip 45°, length 250m) has been included in one of them.

The size of the elements is varying because the distance between the nodes varies from 0,5m to 10m. The mesh has been refined in keys zone, like the interface between the reservoir layer and the fault surroundings in the second model, as visible in Fig.3:

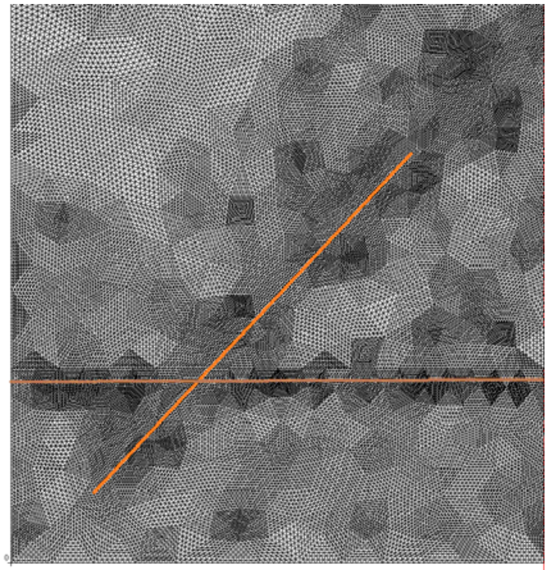

Fig. 3: detail (300m x 300m) of the model with the fault inserted, derefined mesh. The lines follows the fault and the division between the layers.

The structure has been included to assess how strong can be its contribution to drive pore-pressure and to potentially enhance/propagate build-up of thermoelastic stresses.

The model is a rectangular 2D element, the left vertical side being the axis of symmetry, horizontally long enough to leave the right side untouched by the model marching, while the top and the bottom boundaries of the model are hydraulically nonconductive, as the reservoir capping Zechstein salt formation and the underlying Carboniferous are.

The different rock units composing the reservoir are then represented with four different layers, representing the main characteristics.

The porous upper sandstones and the conglomerates are represented by a single layer of common properties, while the other layer simulates the andesitic rocks, whose natural fractures are the main reason behind its assumed hydraulic conductivity.

No model of opening-closing cracks has been implemented: the fractures are supposed to be opened and permeable by the high pressure applied during the injection treatment.

Therefore, the hydraulic conductivity K for the volcanic layer has been estimated not on a rock sample basis, but as a reservoir volume-averaged property.

The value then has been tuned, to match the volume injected according to the real schedule. A good agreement, within 10%, has been obtained.

The hydraulic conductivity for the upper Rotliegend were obtained through the core sample permeability measurement (Trautwein & Huenges, 2005), through the relation:

$$K = \frac{k \rho g}{\mu} \qquad (4)$$

where k is the permeability, ρ is density of the fluid, g the gravitational acceleration and μ the dynamic viscosity of the fluid. Viscosity of pure water shows significant changes in the range of temperature involved near the injection well, but since the conductivity for the volcanics has been assigned on the basis of direct dependency of permeability to pressure and the injection takes place in the volcanic layer and not in the sedimentary layer, density and viscosity has been calculated in relation to the reference temperature of 150°C.
A ratio between vertical and horizontal permeability of 0.25 has been measured in the same core samples measurements, so hydraulic conductivity has been assigned the same anisotropy.
We ignored wellbore heating storage capacity.
Initial temperature has been set to 150°C, with fixed bottom at same temperature.
The model was initialized calculating the stationary state, having fixed hydraulic heads at the bottom and on top, without any injection, to obtain the pressure reference state.
The injection well is then set on a single node, on the axis of symmetry, to simulate the perforated interval of the well.
The fault is then unidimenisonal in our mesh (then flat and bidimensional in the 3-dimensional model) and characterized by constant conductivity and thermal properties. The fault is starting in the volcanic layer and cutting upwards through the sedimentary layer. The thermal properties are assumed equal to the volcanic layer, due to a posteriori considerations about the temperature perturbation limited range.
An implicit forward Euler/backward Euler time integration scheme is used to solve diffusive problem, with target error of 10^{-5} and initial time step length of 10^{-8}.

SIMULATION OF INJECTION RESPONSE

For simulating the stimulation treatment the real injection, visible in Fig.4 has been approximated and smoothed, but the volume injected has been conservated, as per the peaks in pressure.

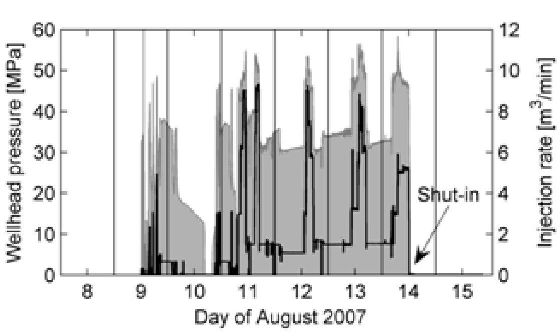

Fig. 4: real data for water-frac treatment in Groß Schönebeck production well.

In our model we do not consider the fracture creation, since the fracture volume itself is not relevant with respect to the volume injected (180 m^3 vs. 13000 m^3) The injected fluid, at the surface at 20°C, exits from the well at a temperature that is assumed to reach 60°C from a rough estimate of the heat exchanged between the water injected and the surrounding fractured hot rock.
A set of time dependant Dirichlet boundary condition, T=60°C constant and pressure according to injection schedule at the injection point, for the length of the injection, has been set-up.
The condition on the well has been fixed on the hydraulic head, with a minimum constrain on the flow-rate of 200 m^3/d.
The top and the bottom side of the model are not conductive by initial definition of the aquifer.
In the layered model control points are horizontally distributed along the line of injection, to evaluate the propagation of the pressure tip, while in the faulted model there are some control points in the upper layer and in the fault to evaluate pressure diffusion in those structures, too.
In table 1 all the relevant hydraulic and thermal parameters are written. We will evaluate pore pressure propagation and the heat transfer from the injected fluid, since the pore pressure is strongly responsible for weakening of the shear to normal stress ratio in the fault, while the thermal stress can effectively change local stress field.

Table 1: Hydraulic and thermal properties of the modeled layer and of the fluid.

	Thickness (m)	Hydraulic conductivity (10^{-6}m/s)	Porosity (%)	Vol.heat capacity (MJ/m^3/K)	Heat conductivity(J/m/s/K)
Sediments	350	0.2	10	2.4	2.8
Volcanics	100	1.5	0.1	3.6	3.0
Fault	0	10^4	100	3.6	3
Fluid	-	-	-	4.2	0.65

RESULTS

The pressure and temperature trend are plotted in the following figures. In Fig.5 it's plotted the temperature trend at two stages. Data plotted come from the model without fault. There are no relevant differences in the temperature profile between the two model, consequently the data are representative of both models.
The difference due to the fault in the pressure distribution are quite relevant in the vertical direction, since the fault transmit effectively the pressure variation in the upper layer. In Fig. 6 and Fig. 7 the two model are put in direct comparison.

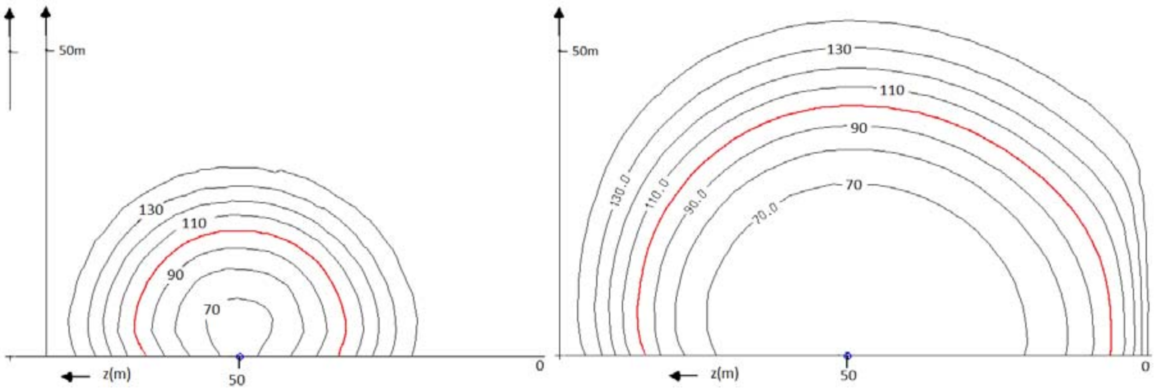

Fig. 5: Temperature (°C) after 1 day (on the left) and right before shut-in (right). Red line indicates 100°C front, the artifact on the right side is due to fixed temperature as boundary condition. Lines spaced of 20°C

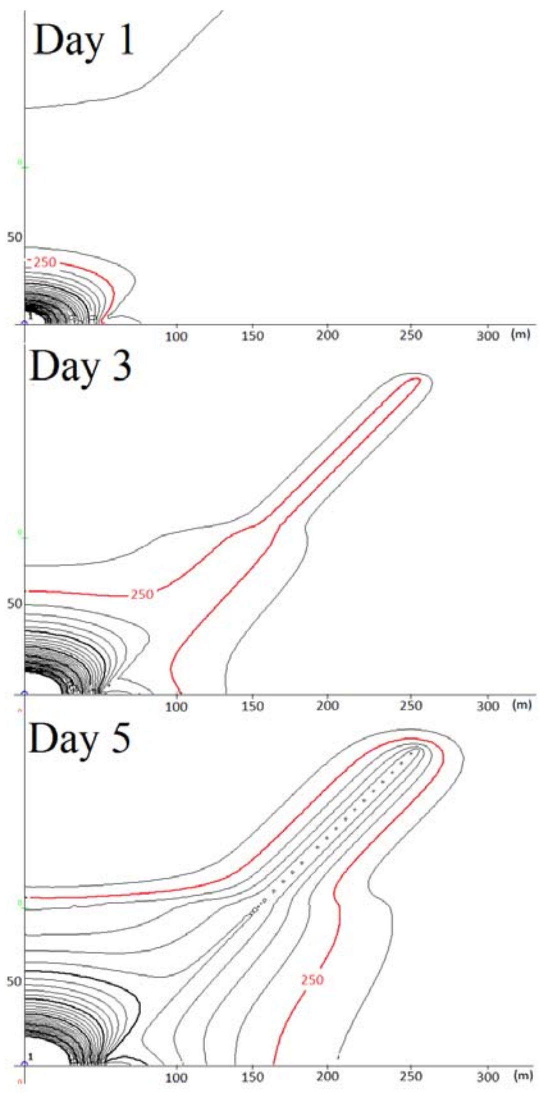

Fig. 6: Hydraulic head (m), model with fault, after 1 day, 3days, and immediately after shut-in. Red line indicates 250m isoline. Isoline spaced of 25m (0.25 MPa).

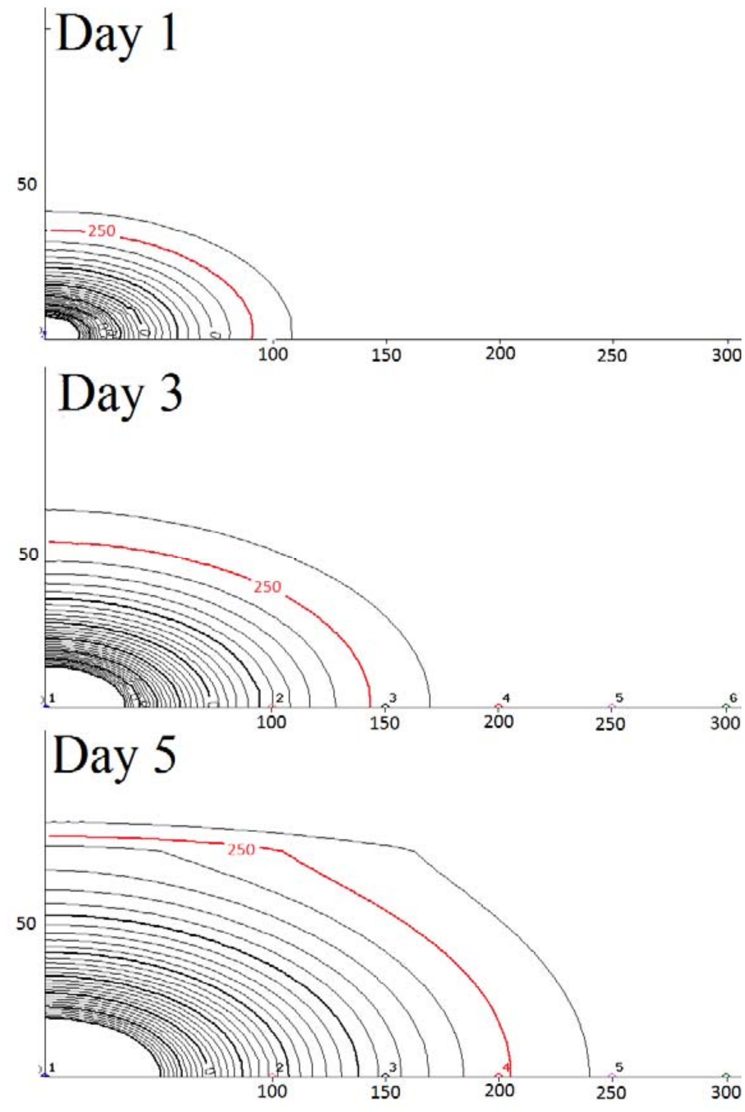

Fig. 7: Hydraulic head (m), model with fault, after 1 day, 3 days, and immediately after shut-in. Red line indicates 250m isoline. Isoline spaced of 25m (0.25 MPa).

DISCUSSION AND CONCLUSION

The behavior of the volcanic rocks is poorly constrained due to gaps in comprehension of the fundamental mechanisms.

Matching injection history and model results required a tuning in the hydraulic diffusivity parameter of the volcanic rocks, which was set to $1.5*10^{-6}$m/s, 1000 times higher than the determination from the samples.

The real behavior of the fractured rocks and potential heterogeneity in the volume considered are smoothed out by this estimate: locally the value can be higher, especially near the wellbore where pressure is higher and more effective in promoting opening of crack.

The inflow from the well to the reservoir rock supports the Hoek-Brown (HK) criterion findings. This criterion defines an envelope for stresses acting on a certain rock to check for failure or not. It is very similar to Coulomb criterion, but it takes into account some additional intrinsic properties of the rock mass. A typical expression of the HK criterion is:

$$\sigma_1^{'} = \sigma_3^{'} + \sigma_{ci}\sqrt{m\frac{\sigma}{\sigma} + s} \qquad (6)$$

where σ'_1 and σ'_3 are the major and minor effective principal stresses at failure, σ_{ci} is the uniaxial compressive strength of the intact rock material and m and s are material constants, where s = 1 for intact rock.

In a previous investigation (Moeck, 2009), the lower Rotliegend rock was assumed to be fairly intact, with natural joints separated by a distance in the range 30-100 cm. Thus the overpressure needed to open fracture was estimated at 24.5 MPa. Recordings from the field operation (Zimmermann et al., 2010) instead noted that the overpressure needed was just 20 MPa. The difference has been explained as an overestimate of the integrity of the rocks or taking into account errors in the measurement of σ_{ci} the estimate became compatible with the injection pressure.

This discrepancy between the theoretical value and field data can be explained otherwise.

Due to thermoelastic strain, stress build up due to the interaction between cool fluid and hot surrounding rock. The stress build up inside the rock volume, due to differences between the surface temperature in contact with the cold fluid and the inner volume, can bring rock to failure itself or promote other failure mechanisms. The thermal stress can be roughly evaluated following (Kingery, 1975):

$$\sigma_t = \frac{Ea}{1-\mu}\left(\Delta T\right) \qquad (7)$$

Considering for the andesitic Rotliegend rock the Young's modulus E=55 GPa, thermal expansion coefficient $a=7*10^{-6}$ K^{-1} and the Poisson's ratio μ=0.2, the stress is 4MPa every 10°C temperature difference, difference between the surface and the inner part of the rock.

The resulting stress can be relevant, accounting the temperature of the fluid injected (20°C at the surface) with the reservoir temperature (150°C). After just one day of injection the fluid temperature at 10 m from the injection point is simulated to be 40°C cooler than the initial rock temperature. According to McTigue (1990), there is a strong interplay between thermal and fluid transport process when the respective diffusivities are in the same range of magnitude. Since thermal diffusivities of rock is typically of the order of 10^{-6} and the andesitic rock during injection presents hydraulic diffusivity in the same range, we can expect an interconnection between the two processes.

The heat transfer and the radius of influence on the seismicity is although relevant just in the immediate vicinity of the injection point, no relevant transfer is happening outside a small radius (<50m) in the first days. Our model in this range cannot resolve details regarding the failure mechanisms.

Regarding the three clusters of seismicity that occurred on the mapped plane fault, the pore pressure diffusion is the principal phenomenon affecting the reservoir at that distance. The confrontation between the two models put in evidence the role played by the fault to diffuse pore-pressure.

Regarding the pressure response recorded in the injection well during the stimulation treatment, from the pore-pressure propagation obtained in the model without the fault, there is no chance that the pore pressure perturbation can propagate through the volcanic layer so quickly. A different scenario is depicted if we consider the model with the fault.

Although there are no precise boundaries to define the conductivity of a fault, considering the model as a representation of the fault located between the two wells, tweaking a bit the parameters to obtain a reasonable response in a point located 500m along the fault, lead to a value for the conductivity of 10^{-2} m/s. The fault is then assumed conductive, although conductivity is not associated to high failure probability, since its strike direction is 1°N, while the critical stressed planes are striking 17°N.

Assuming that the critically stressed faults on the western side of the wells has similar or even higher conductivities, we have two distinct effects.

First, the fault effectively transmits pore-pressure variation upwards, diffusing the perturbation in the overlying sedimentary layer, overcoming the strong vertical anisotropy. Permitting the perturbation to move upwards does not influence much the pressure horizontal diffusing, as visible in fig.6 and 7

Referring to the first fault encountered going west from the injection point, the fault is highly stressed and conductive, it allows pore-pressure to propagate horizontally and along the fault direction. For pore-pressure propagation it does not make that difference,

the fact that volcanic rocks have really low compliance can explain the absent seismicity.
The seismic events can be identified as laying on the distant western fault for two reasons:
-the pore-pressure will go up only through a conductive fault;
-the fault is critically stressed and conductive and there were no other similar size sources of seismic events in the andesitic layer.
Pore pressure is very likely to be the triggering mechanism, since it fits the spatio-temporal pattern of the seismicity, but the combination of pore-pressure diffusion and the presence of the critically stressed fault are the causes of the seismicity recorded at Groß Schönebeck.

CONCLUSIONS

With respect to other massive water injection that took place in a similar environment, the poor seismicity occurred during the waterfrac is due to unfavorable recording conditions, and part to an intrinsic property of Andesitic rocks, having really low compliance and thus the impossibility to stand big deformation and release high amount of energy through rapid and big shearing mechanism.
In fact, as soon as the pore-pressure reached the distant fault the seismicity started to be detected.
Since the cluster started his activities before the shut-in, the onset of seismic activities and the shut-in procedure are not related as in other stimulation treatment events. As previous studies showed, the pore pressure variation needed to activate a critically stressed fault can be lower than 1 MPa (100m variation in water level). A relation between seismicity onset and pore pressure could be investigated with better quality seismic data, unavailable for the test location.
Knowledge or assumption of a more realistic hydraulic permeability (for instance pressure dependant) for the andesitic rocks may permit to better define the pore-pressure threshold that initiate the slip.

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