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DOWNHOLE MONITORING DURING HYDRAULIC EXPERIMENTS AT THE IN-SITU GEOTHERMAL LAB GROß SCHÖNEBECK

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ABSTRACT

During the current project phase the geothermal water loop at the Groß Schönebeck site is being set up and short- to long-term hydraulic experiments are performed in the well doublet in order to assess the hydraulic properties and the sustainability of the engineered reservoir. Downhole measurements are carried out during production in order to observe the performance of the stimulated zones and the naturally occurring permeable intervals. The production string has been constructed in order to allow for access to the reservoir with logging tools during fluid production using a new developed Y-tool to bypass the submersible pump. In addition a novel hybrid wireline production logging system for combined measurements with electrical tools (pressure, temperature, flow meter, gamma ray, casing collar locator) and fiber-optic distributed temperature sensing (DTS) has been developed. The results of the first measurement campaigns show that valuable data for the observation and understanding of reservoir flow dynamics can be collected with the new system. The observed hydraulic behavior is mainly controlled by a variable contribution from a hydraulic fracture zone, which appears to be influenced by the production history and induced reservoir processes.

INTRODUCTION

The Groß Schönebeck site, located approximately 40 km North of Berlin, Germany, was selected in order to set up an in-situ laboratory for the development of technologies related to the production of energy from Enhanced Geothermal Systems. The geological setting is characteristic for many sedimentary basins worldwide: temperatures necessary for geothermal power generation are sufficient but permeabilities of the sedimentary rocks are too low for a direct exploitation [*Holl et al.*, 2005].

The geothermal reservoir is at a depth of 4100–4300 m with a bottom-hole temperature of 150 °C. The main targets are the permeable sandstones of the Upper Rotliegend (Dethlingen Formation) and the underlying volcanic rocks (andesites) of the Lower Rotliegend, where permeability is mainly due to connected fractures. The Dethlingen sandstones have a connected porosity of 8–10 %, and an in situ permeability of up to 16.5 mD [*Trautwein and Huenges*, 2005].

The Gt GrSk4/05 well was drilled in 2006/2007 adjacent to the E GrSk3/90 well to a measured depth of 4400 m. In the reservoir interval the well is deviated in the direction of the minimum horizontal stress with an inclination between 37 and 49°. Hydraulic stimulation techniques have been applied to enhance the permeability of the sandstones and the underlying volcanic rocks [*Zimmermann et al.*, 2011]. In the low permeability volcanic rocks, a cyclic water frac treatment was performed, where a total of 13,170 m^3 of water was injected. In the overlying sandstones two gel-proppant treatments were performed. Short term production tests show that the productivity index (PI) was increased from an initial value of 2.4 m^3/(h MPa) to 10.1 m^3/(h MPa) after stimulation. In 2009, an acid matrix stimulation was performed, and a short term production test indicated a further increase of the PI to a value between 13 and 15 m^3/(h MPa). The sustainability of these PI-values is the matter of an ongoing long-term experiment performed in 2011 and 2012.

In the summer of 2010 an electrical submersible pump (ESP) has been installed in the Gt GrSk4/05 well. The production string has been equipped with a special Y-tool in order to allow access to the reservoir with logging tools during production (Figure 1). For this purpose a new hybrid wireline production logging system for combined measurements with electrical tools and fiber-optic distributed temperature sensing (DTS) has been developed. Here we report on the results of the first application of this system during hydraulic experiments which were carried out in September 2011. Until now, no long-term hydraulic test has been performed yet, but the production data recorded during the commissioning of the surface equipment already indicated that the productivity would likely be lower than after the previous tests. Moreover the well exhibited different drawdown characteristics at different times. The aim of the logging campaign was therefore to record production profiles and to observe the reservoir dynamics during the hydraulic tests in order to find explanations for the observed behavior.

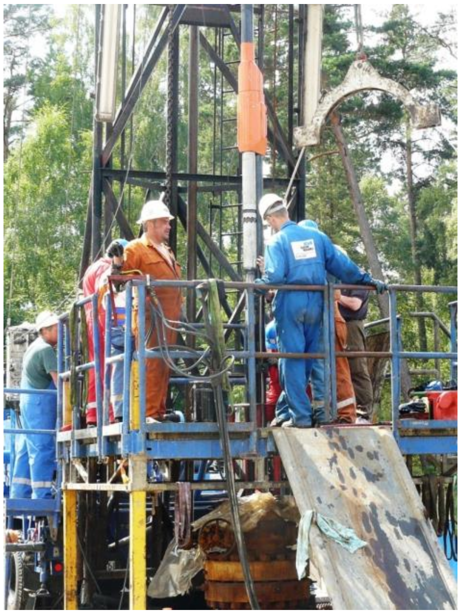

Figure 1: Installation of the production string with the Y-tool to bypass the ESP with downhole logging tools during production.

THE HYBRID WIRELINE LOGGING SYSTEM

Classic PL includes downhole measurement of pressure, temperature, and fluid velocities, e.g. with a spinner flow meter, to estimate flow rates and phase composition within a flowing well. Temperature logs can also be used to locate fluid movement along a well. Using DTS, profiles can be registered almost instantaneously over long distances and changes over time can be conveniently monitored once the sensor cable is in place.

In the past ten years there is a rapidly growing number of DTS applications in the petroleum industry, e.g. with permanent downhole sensors for production monitoring in wells which are not accessible with wireline or coiled tubing, e.g. [*Brown et al.*, 2000]. Within an earlier study, a prototype slickline DTS sensor cable has been used to assess the effect of water frac stimulation treatments in the E GrSk 3/90 well [*Henninges et al.*, 2005].

The new 5,500 m hybrid wireline logging cable contains both electrical conductors and steel tubes for inclusion of the optical fibers. For the optical fibers, a polyimide/carbon coating was selected to allow for the required stability and resistance to chemical degradation (e.g. hydrogen ingression) of the fibers at elevated temperatures [*Reinsch and Henninges*, 2010]. The electrical tools include pressure, temperature, and a spinner flow meter, as well as gamma ray (GR) and casing collar locator (CCL) for depth correlation.

In November 2010 the first baseline logging runs with the hybrid logging system had been performed under static conditions [*Henninges et al.*, 2011]. For an integration time of 30 minutes the DTS data exhibited a temperature resolution of up to 0.06 °C, which shows that even small temperature differences can be resolved along this rather large profile of 5,500 m length.

PRODUCTION LOGGING RESULTS

Two logging campaigns during production tests were performed on September 8 and 9, 2011, in the GtGrSk04/05 well. The logging tool was placed at a depth of about 4350 m, which is 5 m above the beginning of the pre-perforated 5” liner and about 10 m above the maximum accessible depth of the well. With this set-up, the pressure at bottom-hole and DTS profile data over the reservoir interval can be acquired simultaneously during the production phase. Unfortunately, no bottom-hole pressure and electrical wireline data could be recorded during the production test on Sept. 8 due to a failure of the electrical data transmission which occurred when the ESP was started. After this problem had been fixed, both bottom-hole pressure data and spinner logs during the following day could be recorded.

In addition to the recorded logging data, surface water flow rates and pressure data from a sensor located below the ESP at a depth of 1202.49 m were available for evaluation.

Day 1 (September 8, 2011)

The first discovery was that no indications for solids deposition within the 5” liner across the reservoir interval could be observed, based on the cable tension and motion sensor data recorded during the first decent into the well. Therefore a substantial blockage of the well which could be responsible for the reduced productivity could already be excluded.

The first production phase is characterized by a decrease of well temperatures in the lower part of the well (Figure 2), which is gradually progressing in upward direction. In addition to this, the DTS profile at 13:28 hrs displays a local increase of temperature occurring at a depth between 4240 – 4220 m. This indicates that flow is mainly occurring from the volcanic rocks in the lowermost part of the well and the perforations at the base of the Dethlingen sandstones at this time. Shortly afterwards a sudden temperature increase was noticeable at the position of the perforations of the 1st gel/proppant frac located just below 4200 m depth, which is visible in the 13:47 hrs profile.

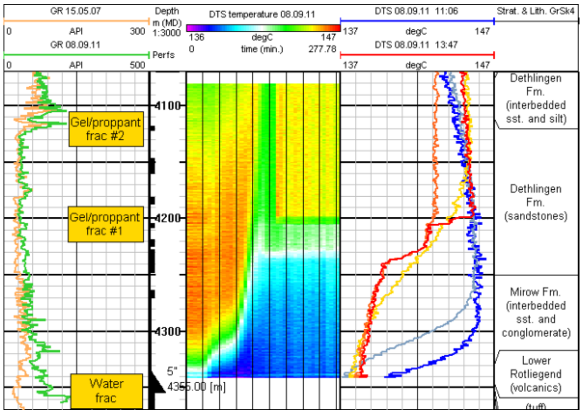

Figure 2: DTS temperature data production test Sept. 8, 2011. Acquisition times of DTS profiles not displayed in log header: light blue 12:29, gold: 13:02, orange: 13:28.

For a more detailed analysis of the temporal evolution, DTS data of four depth intervals located above and below the main inflow zones described above, together with flowrate and pressure data is displayed in Figure 3. The main production phase was preceded by a very short production phase of about six minutes duration. After this, a temperature response at the lowermost observation point at 4335 m is already visible, which indicates that flow from the slotted liner interval in the volcanic rocks had already taken place. During the first part of the main production phase, a similar decline in temperature at the three upper observation levels is occurring with a successive temporal delay corresponding to the distance along the flow path.

After about 45 minutes, the temperature increase at the 4250 m observation point located above the perforation interval in the lower part of the Dethlingen Formation sandstones is visible. This is followed by the even more pronounced increase at the 4195 m observation point above the 1st gel/proppant frac occurring after about 60 minutes. This time coincides with the beginning of a noticeable phase with decreasing drawdown at the ESP, which was characterized by a steep and almost linear increase beforehand. Despite a short fluctuation, the trend of the production rate remained rather constant during this intermittent recovery period. Afterwards, temperatures remained rather constant for the rest of the production phase.

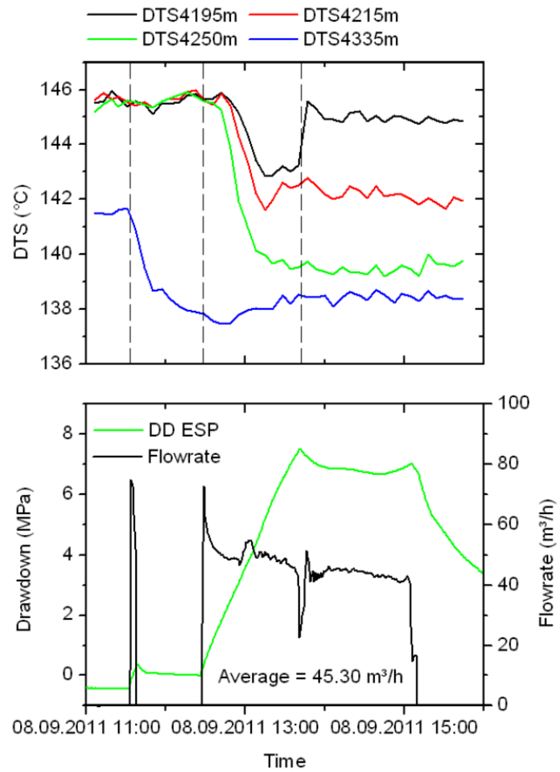

Figure 3: Surface water flow rate, drawdown at pump (DD ESP), and DTS data for different depths within the reservoir interval, Sept. 8, 2011. In the temperature data plot, the times for start of the production phase 1 and 2, as well as the beginning of the pressure increase are marked.

Day 2 (September 9, 2011)

Before the start of the production test during the second day, the borehole temperatures are still slightly reduced compared to the preceding day (Figure 4). After the start of pumping, temperatures below the 1st gel/proppant frac are decreasing in a similar fashion as during day 1 (Figure 5). But in contrast to the first day, the temperature at the 4195 m observation point above the 1st gel/proppant frac is remaining almost constant during the entire observation phase. This indicates that a significant amount of fluid is produced from the 1st gel/proppant frac interval throughout the production phase.

Parallel to the acquisition of the DTS data the bottom-hole pressure was recorded with the electrical downhole tool (Figure 5). The recorded pressure yields a drawdown curve with a gradually higher slope than the curve derived from the sensor at the ESP, which is most likely due to increasing contribution of flow from the reservoir interval and corresponding friction losses.

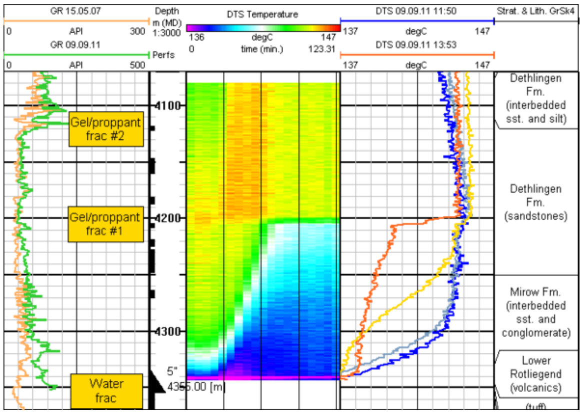

Figure 4: DTS temperature data production test Sept. 9, 2011. Acquisition times of DTS profiles not displayed in log header: light blue 12:16, gold: 12:35.

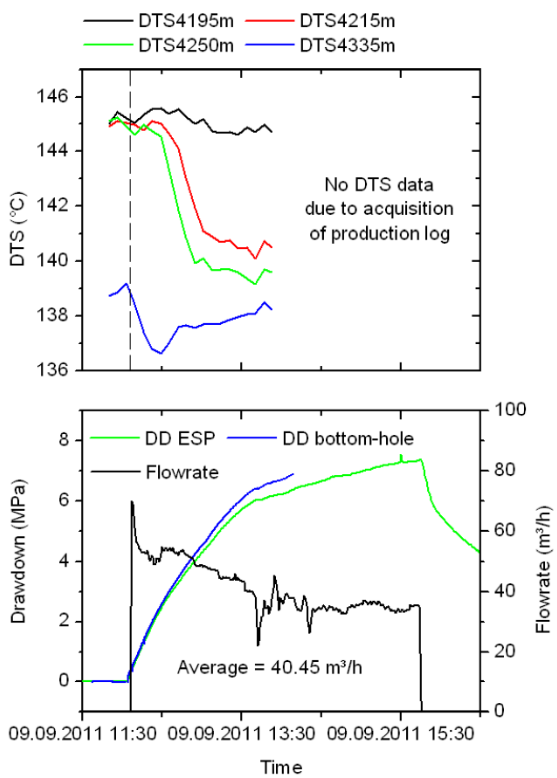

Figure 5: Surface water flow rate, drawdown at pump (DD ESP) and at downhole logging tool (DD bottom-hole), and DTS data for different depths within the reservoir interval, Sept. 9, 2011. In the temperature data plot, the time for start of the production phase is marked.

Flowmeter logging

After the DTS monitoring period, one upward spinner log with a cable speed of 10 m/min was recorded (Figure 6). Due to temporary blocking of the spinner, not a complete suite of down- and upward runs with different logging speeds could be recorded. Therefore it was decided to record stationary spinner readings above the main inflow zones which had been identified on the basis of the DTS monitoring during the production test of the previous day. A total of four stationary measurements at depths of4300 m, 4228 m, 4200 m, and 4080 m with a duration of about five minutes each were performed (Figure 6).

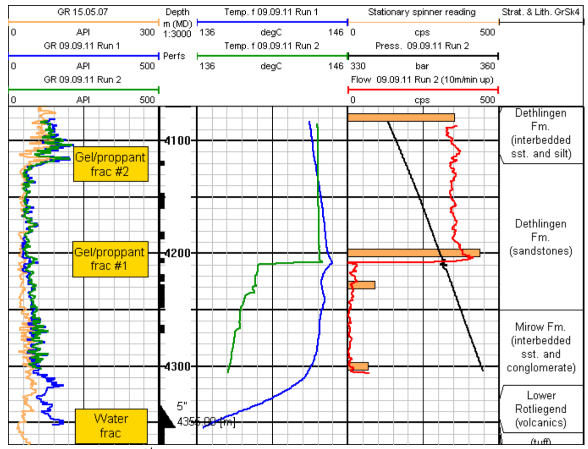

Figure 6: 1st downward logging run (Run 1), spinner log (Run 2), and stationary spinner readings, Sept. 9, 2011. The main inflow zone is located at the 1st gel/proppant frac, with minor contributions from the bottom of the well, i.e. the water frac, and the perforations in the lower section of the Dethlingen sandstones. No inflow at the position of the 2nd gel/proppant frac.

For the evaluation of the spinner data a calibration of the spinner response was performed based on recordings with different cable speeds during the first downward run (Figure 7). The derived flow velocities are summarized in Table 1. The readings at 4200 m are disturbed by turbulences caused by the strong inflow at the perforations of the 1st gel/proppant frac, which is also visible in the data from the upward logging run. Above the disturbed zone the spinner log shows rather constant readings and no further temperature anomalies are visible, which indicates that no inflow into the well is occurring. It was therefore assumed that the flow above the position of the perforations of the 1st gel/proppant frac is equal to the flow recorded at the top of the reservoir at 4080 m depth. The computed flow velocity at this depth of 64.74 m/min is very similar to the average flow velocity for the 5” liner within the reservoir section of 63.20 m/min, which can be calculated from the average surface flow rate of 35.14 m³/h during the stationary spinner readings.

Relative contributions of the individual reservoir intervals to total flow are given in Table 1 and were directly computed from the determined flow velocities, as the volumetric flow rate is directly proportional to it.

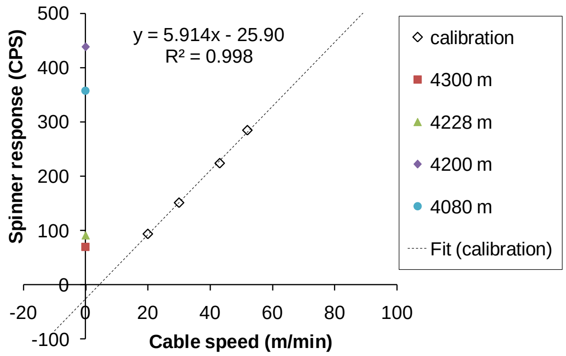

Figure 7: Average spinner readings during the stationary measurements and calibration curve derived from response at different cable speeds during shut-in.

Table 1: Sept. 9 stationary spinner readings, computed flow velocities, and contributions to total flow of the individual dept intervals. For comparison, the results of the 2007 survey are given.

Depth interval	Spinner reading	Flow velocity	Contri-bution (2011)	Contri-bution (2007)
m	cps	m/min	%	%
4080	357	64.74	0.00	14.08
4200	438	78.43	69.47	52.03
4228	91	19.77	5.75	6.85
4300	69	16.05	24.78	26.81

DISCUSSION

The recorded DTS data display favorable conditions for flow profiling using temperature, because of the remaining temperature anomaly within the volcanic rocks at the bottom of the well resulting from the injection of large amounts of cold water during the water frac treatment in 2007. During production, relatively colder water from this level is produced and ascending to the shallower production intervals, in which fluids with higher temperatures are produced. Therefore inflow from these shallower production intervals is obvious because of the temperature difference of the produced fluids.

Two different inflow regimes can be derived from the recorded temperature data: The first is characterized by inflow from the water frac in the volcanic rocks at the bottom of the well and the perforations at the bottom of the Dethlingen Fm. Sandstones (first production phase during Sept. 8), followed by a sudden inflow at the 1st gel/proppant frac. The second one shows a predominant contribution to flow from the 1st gel/proppant frac with a minor contribution from the water frac in the volcanics over the entire production phase (Sept. 9 test).

The shape of the drawdown curve is significantly different for the two inflow regimes. The first regime displays a steep an almost linear drawdown at the beginning, followed by an intermittent recovery phase. The second regime exhibits a drawdown which is steadily increasing with a significantly lower slope. This is remarkable, since both the average production rates during day one and day two of 45.3 m^3/h and 40.45 m^3/h, respectively, are comparably high, and the initial pressures only differ by about 0.1 MPa. The different observed behavior must therefore be related to the production history. Nevertheless, despite of their different shapes, the drawdown curves arrive at similar values after a production time equal to the duration of the first test.

When comparing the flow contributions of the individual reservoir intervals for the Sept. 9 test to the results from the 2007 test data [*Zimmermann et al.*, 2010], the following observations can be made: The relative amount of inflow from the volcanic rocks is rather similar and the largest contribution is coming from the 1st gel/proppant frac in both cases. But during the 2011 test, a lower inflow is occurring at the perforations at the bottom of the Dethlingen sandstones, and the 2nd gel/proppant frac is showing no production at all. At the 1st gel/proppant frac a relatively higher inflow of approx. 69 % is occurring in 2010, compared to a contribution of approx. 52 % in 2007.

CONCLUSIONS

A new developed production string including a Y-tool to bypass the submersible pump has been used for access to the reservoir with logging tools during fluid production. This system allows to record transient reservoir performance data. First preliminary conclusions are given here.

Based on the recorded logging data the following aspects of the reservoir flow dynamics are observed: Two different inflow regimes could be recognized which are responsible for the variable drawdown behavior. The difference is mainly based on a variable inflow from the 1st gel/proppant frac, which is probably depending on the production history and processes in the reservoir system induced hereby.

The shortfall of flow from the second gel/proppant frac located in the upper part of the Dethlingen sandstones and reduced inflows from the perforations in lower part of the Dethlingen sandstones can at least explain a partial reduction in productivity with respect to the test performed in 2007. Further

hydraulic testing with longer-term production phases need to be performed in order to determine the productivity.
The new hybrid wireline production logging system was successfully deployed and valuable data for the evaluation of reservoir hydraulics could be gathered. Further effort will be put into improved configuration of the DTS measurement and integrated evaluation of the flow, pressure, and temperature data.

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