

Reservoir Behaviour and Borehole Processes during EGS Operation: Experiences From Three Years of Production and Injection at the Groß Schönebeck Site

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ABSTRACT

At the Groß Schönebeck site, Germany, an Enhanced Geothermal System (EGS) has been created in Lower Permian (Rotliegend) volcanic and sedimentary rocks. Short-term production tests have shown success of the applied hydraulic stimulation treatments, with an up to 6-fold increase of the initial productivity. Until 2013, extensive circulation tests were carried out with a cumulative production volume of approx. 20.000 m³. A non-linear trend towards lower productivities is observed. Production logging revealed that inflow from the main production zone is variable, explaining short-term changes in productivity. Additionally over time, an obstruction of the well at successively shallower depths was observed. Downhole sampling showed that the well was clogged with scales, mainly comprised of variable amounts of native copper (up to 50 wt%), laurionite and barite. After a partial clean-out of the well the accessible depth of the well could be increased again, allowing for an inspection of the well liner in the perforation interval. Average metal losses in the order of 7-12 % have been observed. This is in accordance with a geochemical model for the formation of the copper scaling, enabling to unmask the original mineralization of the formation fluid. The results up to now clearly show the challenges related to utilization of this potentially vast geothermal resource in Central Europe, and the need for further research: The initial increase of productivity gained through stimulation treatments was not sustainable. As possible mechanisms of permeability reduction, the formation of a free gas phase by degassing of formation fluid, clogging of pores by copper scales, and impairment of the hydraulic fractures were identified. The observed scaling revealed a previously unquantified composition of the geothermal brines of Rotliegend reservoirs in the North-East German Basin, asking for modified well completion or water treatment concepts.

1. INTRODUCTION

At the Groß Schönebeck site, Germany, an Enhanced Geothermal System (EGS) has been created in order to test the feasibility of electric power generation from geothermal reservoirs in the North German Basin and to advance the required technologies. The geological targets are Lower Permian sandstones of the Upper Rotliegend (Dethlingen Formation) and the underlying volcanic rocks (andesites) of the Lower Rotliegend, which occur at a depth of 4.100–4.300 m with a bottom-hole temperature of 150 °C at the Groß Schönebeck site.

As a geothermal doublet, the wells E GrSk3/90 and Gt GrSk4/05(A2) (abbreviated as GrSk3 and 4 in the following) are used for injection and production, respectively. The GrSk3 well is a vertical gas exploration well, which has been re-opened and deepened to 4309 m (Huenges et al. 2006). In 2006/2007 the GrSk4 well was drilled to a measured depth of 4400 m with an inclination up to 49° in the reservoir interval (Moeck et al. 2009). In both wells, hydraulic stimulation techniques have been applied to enhance the permeability of the reservoir rocks (Zimmermann et al. 2009; Zimmermann et al. 2010). In the low permeability volcanic rocks, cyclic water frac treatments were performed, whereas in the overlying more permeable sandstones the gel-proppant stimulation technique was applied. Subsequent short-term production tests showed that the productivity could be increased step-wise. In the GrSk4 well, an up to 6-fold increase of the productivity, from an initial value of 2.4 m³/(h MPa) to a value between 13 and 15 m³/(h MPa) could be achieved after an additional acid matrix stimulation treatment in 2009 (Zimmermann et al. 2011).

An overview of the composition of the fluids sampled at surface and downhole until 2009 has been presented by (Regenspurg et al. 2010). The fluids are characterized by high salinities, with up to 265 g/L total dissolved solids, and can be classified as Ca-Na-Cl type, which is typical for Rotliegend reservoirs in the North German Basin (Wolfgang et al. 2003). Observed changes in composition are caused by dilution of the formation fluid with the fluids used for stimulation. Dissolved gases are primarily N₂ (80 vol%) and CH₄ (15 vol%), with minor amounts of H₂, CO₂ and He. The gas/water ratio is generally variable, with a frequent value of around 1 at standard conditions (see Section 4.1 for details).

The performance of the geothermal doublet during utilization for power production was simulated using a coupled thermal-hydraulic model, which was set up based on the available geological, geophysical and hydraulic data (Blöcher et al. 2010). In 2010 a thermal water loop has been set-up, with installation of a downhole electrical submersible (ESP) pump, production string, as well as surface facilities for a research plant (Frick et al. 2011). In order to be able to investigate downhole processes occurring during operation of the thermal water loop, the production string has been equipped with a special Y-tool which allows access to the borehole with logging tools during production. In this contribution, an overview of the main following operations with respect to the subsurface part of the thermal water loop is given (Table 1), and the major observed reservoir processes relevant for EGS operation are described.

2. OVERVIEW CIRCULATION TESTS AND WORKOVER ACTIVITIES

Fluid circulation started in March 2011, after the thermal water loop had been commissioned. Due to a much higher drawdown in the production well than expected from the results of the earlier hydraulic tests, only intermittent circulation could be established.

Table 1: Overview of main hydraulic testing, logging, sampling and workover operations in the GrSk4 production well. TD: maximum depth accessible with logging tools. PI: approximate productivity index.

Begin	End	Operation	TD (m)	PI (m ³ /(h MPa))
26.07.10	30.07.10	Installation of production string and ESP		
02.11.10		Pressure and temperature (p/T) log	4357.6	
Mar. 11		Start of fluid circulation		6
08.09.11	09.09.11	Production logging (PL)	4362.7	4
15.12.11		Last circulation test 2011		
17.04.12	24.04.12	One-week circulation test		1.5
20.06.12		p/T-log	4203.5	
26.07.12		Bailer run	4200.0	
07.08.12		Bailer run GrSk3		
11.09.12	23.10.12	Circulation test with additional injection		1.8
24.10.12		p/T-log	4115.6	
25.10.12		Camera inspection production string		
26.11.12	17.12.11	Cleanout with coiled tubing, circulation test		1.9
21.12.12	29.12.12	Bailer run, multifinger caliper log	4162.8	
13.01.14	15.01.14	Pulling of production string		
15.01.14	01.02.14	Cleanout with drill rig	4346	
04.02.14	07.02.14	Perforation, lift test, PL, fluid sampling	4248	2

In the following, circulation with alternating production and shut-in periods was performed, until a cumulative production volume of approx. 10.000 m³ was reached in December 2011 (Figure 1). After re-examination of the experiences gained until then and suitable fine-tuning of the plant parameters, a circulation test with continuous operation for seven days could be performed in April 2012. During a followup wireline logging campaign, an obstruction of the production well at about 4200 m depth was observed. Analysis of samples recovered with a bailer from downhole revealed that the well was blocked with solid scales and fragments of coating material from the production string (see Section 4.2). After a further circulation test, the obstruction was encountered at even shallower depth of 4115.6 m, indicating that further solids were accumulating in the reservoir section of the well during production.

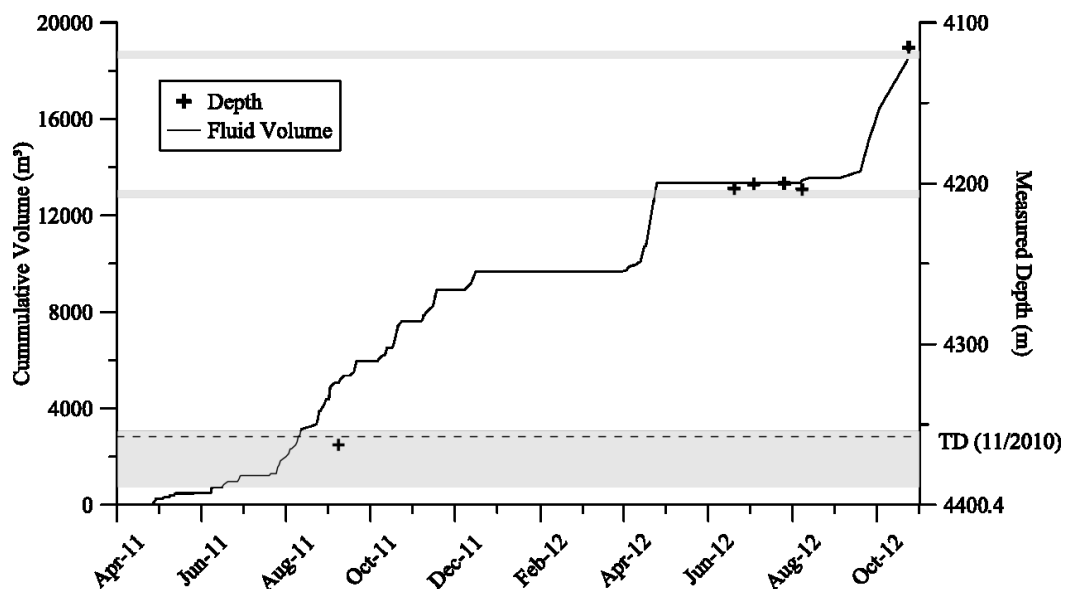


Figure 1: Plot of the cumulative volume of produced fluid and the change of depth accessible with logging tools (TD) over time. The shaded intervals indicate the position of the perforations of the three stimulated intervals.

As the obstruction could not be removed using available slickline tools, it was decided to perform a cleanout of the well with a coiled-tubing (CT) unit in December 2012. Through the bypass tubing of the Y-tool, it was possible to deploy a 2" tubing, and after crushing of the solids with a jet blaster, the fill should be removed by reverse circulation. But the size and rheology of the solid particles caused repeated blocking of the CT (Reinsch et al. accepted). As a result, only about 70 l of solids could be removed from the well to a depth of 4157.5 m. With forward circulation, it was possible to drive the CT down to a depth of 4212 m below the perforation of the lower sandstone frac, where an acid treatment was applied.

A second attempt to clean the well was performed during a workover operation with a drill rig from December 2013 to February 2014 (Reinsch et al. in preparation). After pulling of the production string and ESP, a telescopic 5", 3-1/2", 2-7/8" drill string was installed down to reservoir depth and reverse circulation was performed at balanced conditions. Again, the drill string was repeatedly clogged with solid particles, but nevertheless a final depth 4346.5 m with removal of about 375-395 l of solids was achieved. Subsequently, the perforations of the upper (4117 – 4123 m) and lower (4203 – 4210 m) stimulation intervals in the sandstone interval were re-perforated. In order to quantify the effect of the workover on reservoir performance, a lift test with production logging and subsequent downhole fluid sampling was performed in the following.

3. HYDRAULIC RESERVOIR BEHAVIOUR

3.1 Change of productivity with time

During the intermittent production phases, flow rates of 20-70 m³/h were established, resulting in pressure drawdowns of up to 7 MPa. In order to characterize changes of the drawdown behaviour with time, a dynamic productivity index (PI) was calculated as the quotient of the current production rate and the pressure drawdown for tests of sufficient length (Blöcher et al. in preparation). Figure 2 shows that both variations during individual tests, as well as a general trend towards lower values over time can be observed.

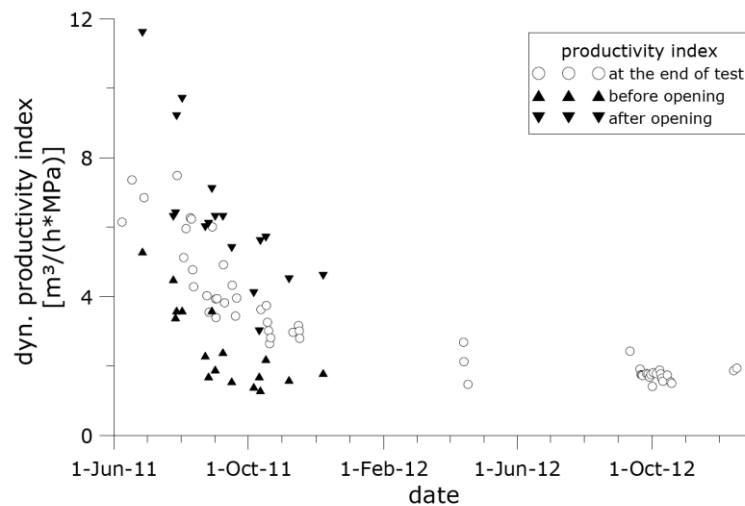


Figure 2: Dynamic productivity indices of representative tests with more than 90 min duration and more than 100 m³ production volume. Data of the last 30 minutes of each test were analyzed. Further shown are the dynamic productivity indices (10-min. mean) before and after opening of the lower sandstone frac.

Especially during the initial production period, sudden increases of productivity during or between individual tests occur. As results from a production logging campaign in September 2011 show (see Section 3.2 below), these short term changes are caused by a variable contribution of the lower sandstone frac. This results in a low dynamic PI at the beginning of a test, followed by a sharp increase of the PI as a result of the additional influx (“opening”) from the lower sandstone frac, which is the most productive reservoir interval, both during tests carried out directly after stimulation in 2007 and in September 2011 (Henninges et al. 2012).

After this, the PI is decreasing gradually and then stabilizes at an intermediate level between the values before and after opening of the frac. These late-time PIs exhibit a non-linear trend from 6-8 m³/(h MPa) initially (June 2011) to a value of about 1.8 m³/(h MPa) in October 2012. After the two cleanout operations, only marginal increases of productivity to values around 1.9 and 2 m³/(h MPa), respectively, were observed (see Table 1).

3.2 Reservoir flow profiling

Production profiles measured using a hybrid downhole logging system (Henninges et al. 2011) revealed that inflow from the main production zone is variable, explaining the short-term changes in productivity (Henninges et al. 2012). In Figure 3, a comparison of temperature logs from the production tests performed in September 2011 and after the second cleanout operation in February 2014 are displayed. The locations of inflow zones are indicated by changes in the temperature profile during production. At the position of the lower sandstone frac, the temperature change in September 2011 indicates the strong contribution of this interval during this time. The upper sandstone frac, which initially after stimulation in 2007 had contributed with about 14 % to total production (Zimmermann et al. 2010), does not show any inflow, neither in September 2011, nor as a result of the cleanout operations and the re-perforation in February 2014. The lower reservoir intervals could not be logged during this time due to a constriction which had formed during the re-perforation of the lower sandstone frac interval.

4. GEOCHEMISTRY, SCALING AND CORROSION

4.1 Fluid composition

The gas content of downhole fluid samples retrieved with a pressurized positive displacement sampler (PDS) has been determined for several campaigns over the history of both wells (Wiersberg et al. 2004; Regenspurg et al. 2010). The gas/water ratio of these samples is mostly in the order of 1 (under standard conditions), which indicates that the fluid is slightly undersaturated with respect to the solubility of the individual gas components. Individual samples from the reservoir depth also exhibit higher gas contents with

a gas/water ratio of up to 1.6. The determination of the gas/water ratio produced at surface is hampered due to limitations of instrumentation at surface. A quantitative estimation was nevertheless possible for the fall 2012 injection test, where a significantly higher ratio of 2.8 was determined. This indicates that the produced fluid has a volumetric gas fraction in the per mill range under in-situ conditions.

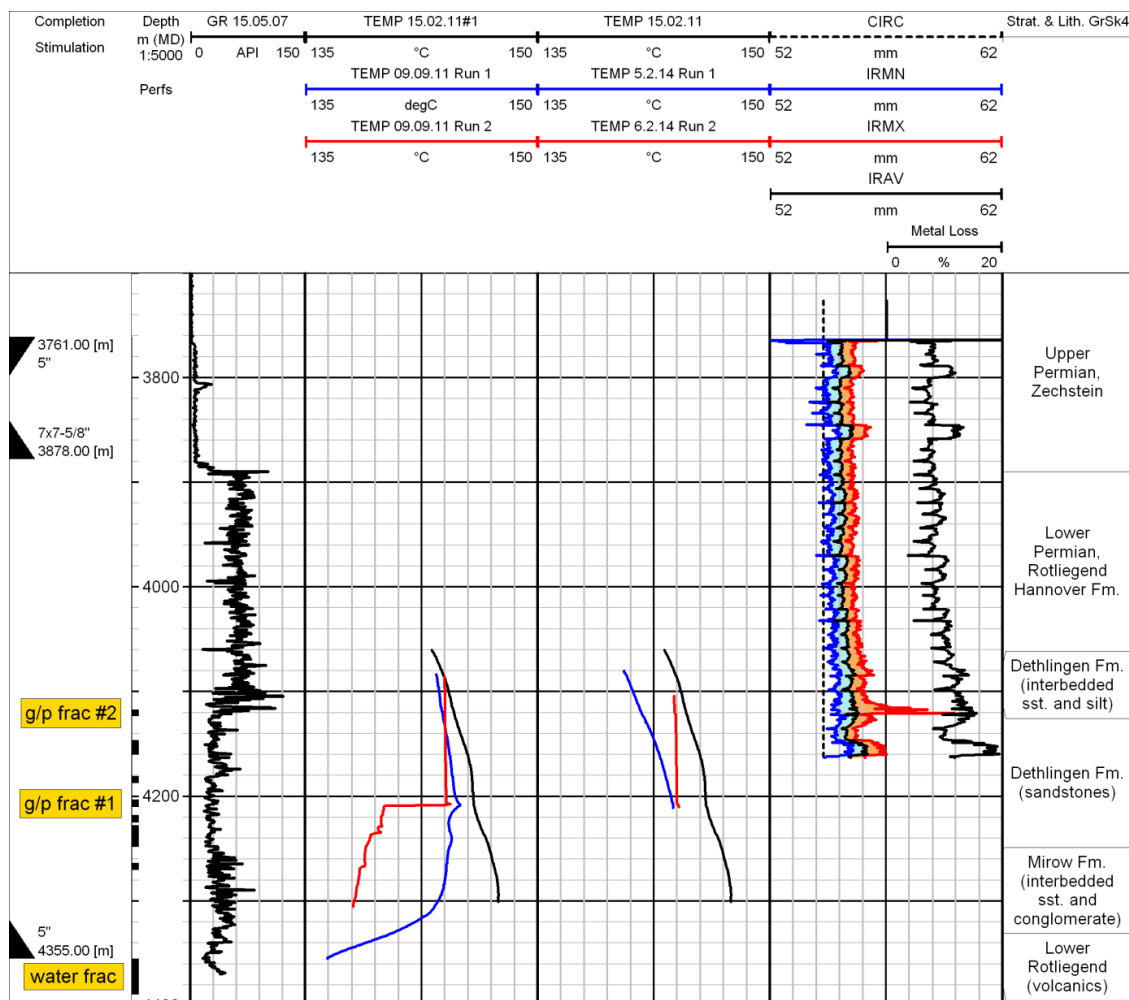


Figure 3: Montage of logging data from production tests September 2011 and February 2014 (TEMP: temperature) before (run 1) and after (run 2) start of production, as well as the multifinger-caliper log from December 2012 (CIRC: nominal inner casing radius; IRMN, IRMX, IRAV: minimum, maximum and average radii).

Brine samples from reservoir depth, also obtained by the PDS sampler, were analyzed for total composition since beginning of well operations. Salinity initially decreased due to stimulation treatments (water frac) but since April 2012 the initial salinity (265 g/L TDS) was re-established.

The composition of the produced fluids was monitored during the 7-day circulation test with continuous operation of thermal water loop in April 2012 (Feldbusch et al. 2013). Physicochemical properties (pH, redox, density, temperature, pressure) were measured online with a newly developed fluid monitoring unit (Milsch et al. 2013), and additional fluid samples were taken at the wellhead and analyzed subsequently. Generally, most of the parameters remained relatively stable over time. Variations which occurred during the initial production phase can be attributed to the increase of temperature of the produced fluid during this time. A temporal anomaly, with change of pH, Eh, and density, could be indicative of a change in composition of fluid produced from the reservoir, or a difference in contribution from different reservoir intervals (Feldbusch et al. 2013). Dissolved components showing more variable concentrations over time are iron (Fe), barium (Ba), sulfate (SO₄), and lead (Pb) indicating that they might be involved in precipitation reactions occurring during fluid production.

4.2 Composition of scales

During circulation tests samples have been collected from filters (1-2 and 10-20 µm) that are installed before the reinjection pump. Frequent changes of the filters at the surface were necessary, especially at early times of fluid production and always after long shut-in phases, when cooling of the fluid resulted in oversaturation of certain salts. Additionally, solid samples have been recovered from the downhole obstruction with a drive-down bailer, or flushed to the surface during cleaning operations.

The mineral composition of the different samples is displayed in Figure 4. The dominant mineral phases identified are native copper (Cu) and barite (BaSO₄), with minor amounts of laurionite (PbOHCl), magnetite (Fe₃O₄), calcite (CaCO₃) as well as an amorphous phase consisting of mainly Si, Fe, Ca, and Pb (Regensburg et al. 2013; Regensburg et al. accepted). Native copper

amounted up to 50 wt.% in the bailer samples, which are considered as most representative for the borehole fill. The clean-out samples exhibit a high variation in composition, which is interpreted as a result of fractionation due to the pumping activities. In the filter residues, copper content was generally lower (around 10 wt.%), indicating that most copper particles are too heavy to be transported to the surface during production.

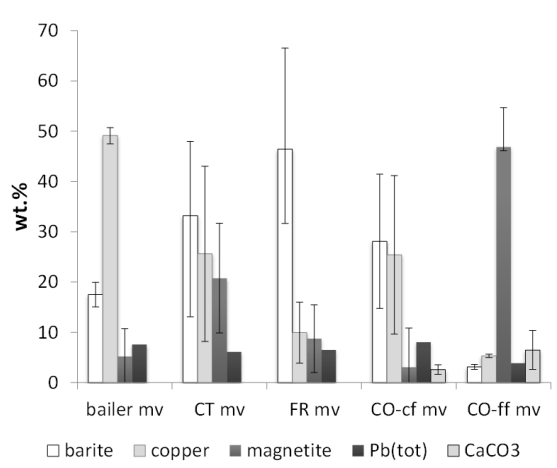


Figure 4: Mineral composition (mean values, mv, with standard deviation) of solid samples calculated from elemental and XRD analysis. Samples originate from bailer, coiled tubing (CT) cleanout, filter residues (FR), and drill-string cleanout (CO-cf: coarse fraction, CO-ff: fine fraction).

While barite precipitates immediately as consequence of cooling thus oversaturating the fluid during a shut-in phase, native copper and magnetite (Fe_3O_4) are forming as product of a redox reaction between dissolved Cu chloride complexes and the iron of the steel liner of the well (Regenspurg et al., 2013).

4.3 Downhole corrosion

After the cleanout in December 2012, several sections of the well were inspected for corrosion and scaling with a multifinger-caliper tool. The reservoir section was logged between the top of the 5" liner (3761 m) and the maximum depth accessible at this time (4162.8 m). Figure 3 shows the variation of the measured inner radius, together with the nominal inner radius of the liner. The difference between the measured and nominal radii increase from the top to the bottom of the logged section, corresponding to an average metal loss from about 7 - 12 %, respectively. The magnitude of the observed metal loss generally correlates with the process proposed for the formation of the Cu-scales above, which involves the oxidation of the Fe from the steel liner. As a further information from the caliper log, there is no evidence for blocking of the perforation channels, e.g. by solidified scales.

Because fragments of coating material had been retrieved from the well repeatedly, the inside of the production string has been investigated. A camera inspection in October 2012 showed extensive detachments of the epoxy resin coating along at least 9 individual tubing pipes.

5. DISCUSSION

Some of the observed scales like barite and Fe-oxides, as well as laurionite, had already been predicted to occur, based on the composition of the formation fluid and the changes to be expected during production (Regenspurg et al. 2010). The high amount of native copper was nevertheless not expected, as the concentration of copper in the fluid samples was usually rather low. Most samples showed a concentration around 0.07 ppm, with individual exceptions of 7 ppm for a PDS sample retrieved from the GrSk3 well in 2001 (Wolfgang et al. 2004), and 18 ppm for a PDS sample from GrSk4 after the cleanout in 2014. Before the start of circulation tests in 2011, only a minor amount of copper scale had been observed during a production test in GrSk3. It is assumed that the described reaction leading to formation of the copper scales happens immediately when the fluid enters the borehole through the perforated liner. This explains why the copper concentration measured in the fluid is generally very low. Due to the relatively high content of heavy metals, an origin of the formation fluids in the underlying metal-rich volcanic rocks had been proposed early on (Wolfgang et al. 2003) and the occurrence of copper can be linked to models for the formation of epigenetic Kupferschiefer ore deposits, e.g. (Borg et al. 2012).

Based on the amount of solids recovered during the cleanout operations, the properties of the obstruction which had formed in the production well can now be determined. A volumetric balance between the volume of recovered solids and the liner volume yields that the concerned interval has been filled to about 21 % on average. The accessible depth was only limited by formation of local bridges. The specific mixture of the borehole fill was difficult to recover. The fragments of the production string coating are a likely reason for blockage of the coiled tubing used for cleaning (Reinsch et al. accepted).

With respect to the observed change in productivity, several aspects have to be taken into account. Short-term variations of productivity can be explained by variable contributions from the lower sandstone frac (Henninges et al. 2012). Several causes could be responsible for the general decrease over the long-term:

The accumulation of scale inside well only seems to have a minor influence on productivity. During September 2011, the PI had already dropped to a value of ~ 4 , prior to formation of significant amounts of scale within the well. After the scales had then

accumulated, the cleanout operations did not result in a significant increase of productivity, even though the scales above the main inflow zones within the sandstone reservoir section could be removed.

Another possible influence could have been the formation of a hydraulic barrier close to the well, e.g. by clogging of the perforation channels by solid scale deposits. But no indications for this have been observed during the caliper measurement, at least within the upper perforation intervals covered by the log. This correlates with the fact that no significant improvement of the productivity has been observed after re-perforation of the two sandstone frac intervals.

The formation of scales within the formation and the resulting clogging of the pore space could also be a possible reason for a reduced permeability close to the well. Indications for such a process could already be observed during simplified laboratory tests, which show the need for further investigation in this direction. Nevertheless, hydraulic test analysis yields negative skin factors, which indicate a good hydraulic connection between well and reservoir. And again, no improvement could be gained by re-perforation, which has an estimated depth of penetration of about 1.5 m.

The occurrence of gas could be another factor influencing the hydraulic reservoir properties, by reducing the relative permeability. Assuming a gas/water ratio of 1, as determined from previous downhole samples, a degassing of the formation fluid due to depressurization is only occurring at depths above about 3300 m within the well under production conditions (Francke et al. 2013). Also no indications for the production of larger amounts of gas could be observed in the production logging data, e.g. by reduction of the bulk fluid density, or temperature anomalies due to Joule-Thomson cooling. But the significantly higher gas/water ratio determined from the produced fluids at surface clearly indicates that small amounts of free gas should be present in the produced fluid at in-situ conditions. Possibilities for accumulation of gas within the reservoir by depressurization, relative permeability relationships for the reservoir rocks, and the variability of downhole samples with respect to the individual production history therefore need to be investigated in further detail.

Another influence to be considered is a degradation of the mechanical integrity of the hydraulic fractures due to cyclic pressure changes during the intermittent production phase. Even though the fracture treatments were performed with supporting meshed sand or proppants (Deon et al. 2013) to stabilize the fracture conductivity under production conditions, this cyclic loading could lead to an impairment of the fracture performance. Similar effects with mechanically induced fracture-face skin leading to a reduced permeability have been observed during laboratory experiments (Zimmermann and Reinicke 2010; Reinicke et al. 2013).

6. CONCLUSIONS

During the operation of the thermal water loop at the Groß Schönebeck site valuable experiences for the geothermal utilization of Rotliegend reservoirs could be gained. A key element was the possibility to have access to the reservoir section of the well during production, which enabled to perform frequent well logging and sampling operations, as well as deployment of a coiled tubing. Important reservoir and borehole processes influencing the performance of the EGS could be identified in this way.

The applied stimulation concept to increase the productivity of the wells has shown success initially, but the gained productivity enhancement was again lost rather quickly during the subsequent fluid circulation. The transmissibility determined from hydraulic data during this time is lower than for previous tests. Possible causes are a reduction of permeability, most likely further away from the well, a lower reservoir thickness and extent (compartmentalization), and lower frac heights. As possible mechanisms of permeability reduction, the formation of a free gas phase by degassing of formation fluid, clogging of pores by copper scales, and fracture impairment were identified. In order to enable a sustainable EGS reservoir exploitation, further investigations including laboratory tests and acquisition of further site-specific field data in order to quantify the relative influence of these processes on the observed decrease in productivity, as well as the development of new stimulation concepts are required.

From the occurrence of native copper scales during the course of production, new evidence on the occurrence of copper in formation waters of Rotliegend reservoirs could be gathered. The concentrations determined from fluid samples might very often not be representative due to interaction with ferrous materials of drilling, completion, or sampling equipment. The occurrence of dissolved copper within Rotliegend reservoir formation fluids needs further attention: For geothermal development, either suitable measures to prevent downhole corrosion of completion and sedimentation of solids need to be applied, or locations exhibiting lower concentrations must be identified.

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