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Stimulation experiments in sedimentary, low-enthalpy reservoirs for geothermal power generation, Germany

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Abstract

Hydraulic stimulation experiments were conducted in a re-used Rotliegend well situated in the eastern part of the North German Basin. The well is used as an "in-situ geothermal laboratory" and as a reference location for several ongoing research projects. The aim of the projects and experiments is to develop technologies that will put primary low-productive aquifer structures into use for geothermal power generation. The frac operations in 2002 were designed to enhance the inflow performance by connecting the well to productive reservoir zones. Two consecutive zones within the Rotliegend sandstones were selected. Here core measurements show the most promising petrophysical reservoir properties with respect to a productivity increase. The stimulation treatments were performed as hydraulic proppant fracturing operations. Proppants were used to support the fractures and to guarantee a long-term fracture aperture. The treatment intervals are located in the open-hole section of the well at depths between 4080 m and 4190 m and at temperatures of about 140 °C. The technical demands were therefore unprecedented in these challenging conditions. An open-hole-packer at the top and a sand plug at the bottom of each interval were used as hydraulic barriers. Applying this configuration the intervals were fracture-treated by injecting about 11 tonnes of proppant (high-strength ceramic grains) and over 200 m^3 of frac fluid (highly viscous gel) into the formation. The fracture treatments were conducted by means of two successive operations in each interval: first, a diagnostic treatment (datafrac), followed by the main treatment (mainfrac) with the proppant stages. The frac operations were successful. Propped fractures were created in both intervals and the inflow behaviour of the reservoir was decisively enhanced. The effective pressures applied for fracture initiation and propagation were only

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slightly above the in-situ pore pressures. The stimulation ratio predicted by modelling, however, could not be achieved. There were a number of reasons for this mismatch. Probably chemical and mechanical processes during closure led to a reduced fracture conductivity. The insights gained from the experiments are important for future fracture treatment projects on this site and in comparable locations.

Keywords: Reservoir; Fracturing; Open-hole treatment; Modelling; Germany

1. Introduction

In order to generate electricity of geothermal origin in the North German Basin, we need reservoirs that are fluid-bearing and with temperatures of at least 120 °C. Because the prevalent average geothermal gradient is 30 °C/km in the Basin, we need wells that are more than 4 km deep. Apart from this target temperature, we are also looking for a high production rate of more than 50 m^3/h (Köhler et al., 2001). In the geological setting of this study area the potential pay zones of primary concern are therefore the Rotliegend sandstones (Hurter et al., 2002). Good permeable zones are known to exist within these formations from intensive hydrocarbon exploration and exploitation. However, there have been no attempts at exploring the Rotliegend formations for geothermal heat or power production.

The well Groβ Schönebeck is drilled through the Rotliegend sandstones. The initial productivity of the well was significantly lower than expected from core measurements. It is mainly inflow restrictions (skin) that limit fluid production. For this reason, multiple hydraulic proppant fracturing experiments have been conducted at a depth of 4.2 km. This treatment was applied to selected intervals of the open-hole section of the borehole using an innovative hydraulic barrier system, consisting of an open-hole packer assembly and a sand plug. The objectives of the experiments were: (1) to verify the technical feasibility of multi-zonal open-hole fracturing technology, (2) to connect the productive reservoir zones to the well, and (3) to considerably enhance the overall productivity of the well.

2. Experiments in the "in-situ geothermal laboratory"

The former exploratory gas well Groβ Schönebeck 3/90 was drilled in 1990. Because of insufficient gas deposits, the well was closed immediately after drilling. In 2000 the well was selected to serve as an "in-situ geothermal laboratory" and consequently re-used and deepened to 4294 m (true vertical depth). The site is located northeast of Berlin (Fig. 1). The well meets a sequence of different geological formations that are typical for the North German Basin. A series, 2370 m in depth, of Quaternary to Triassic sediments is followed by 1492 m of the Zechstein salinar (Huenges et al., 2002). The well has an open-hole section of about 400 m that penetrates Rotliegend formations consisting of siltstones, about 100 m of sandstones and conglomerates, and 60 m of underlying volcanic rocks down to the final depth.

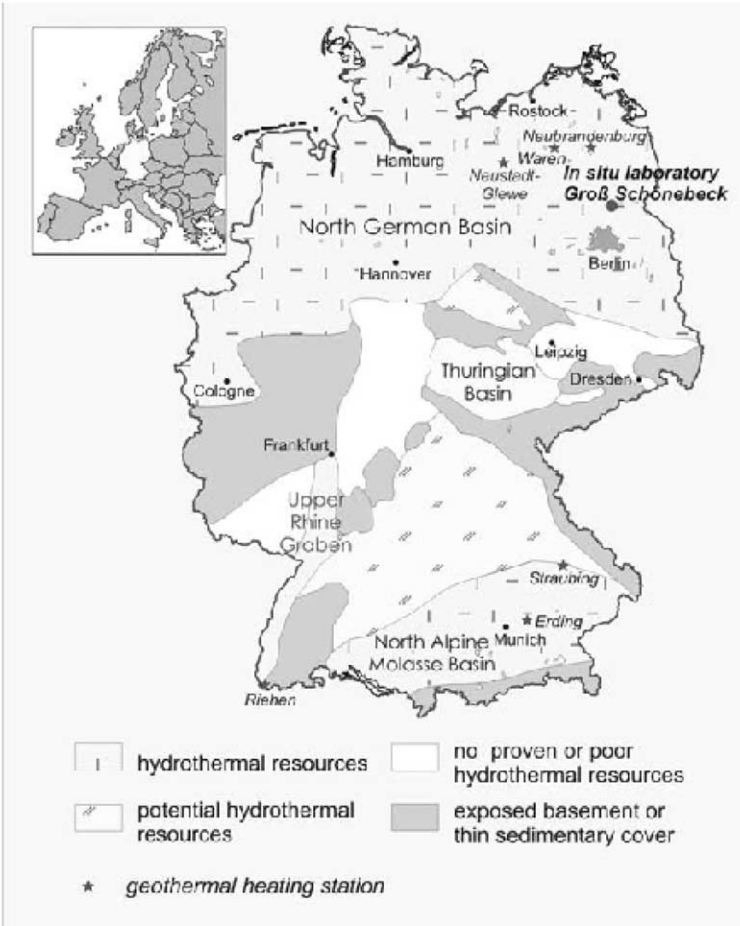

Fig. 1. Location of the "in-situ geothermal laboratory" Groβ Schönebeck in the re-used Rotliegend exploratory gas well E GrSk 3/90 (Huenges et al., 2002).

The type of well completion used guarantees a maximum inflow area that would allow commingled production from each productive reservoir zone in order to achieve the desired productivity values for an efficient high-rate fluid production. Furthermore, continuous, unaltered monitoring and borehole logging before, during, and after all periods of treatment are facilitated by the direct contact with the reservoir rock.

The stimulation experiments were focused on the Rotliegend sandstones for which core measurements indicated promising petrophysical properties. Two intervals were selected: 4130–4190 m and 4078–4118 m. The concept involved the application of a retrievable hydraulic barrier system to independently and successively treat the two intervals in the open-hole section of the well (Fig. 2). The annulus between frac string and casing was filled with saline fluid and remained open to the atmosphere.

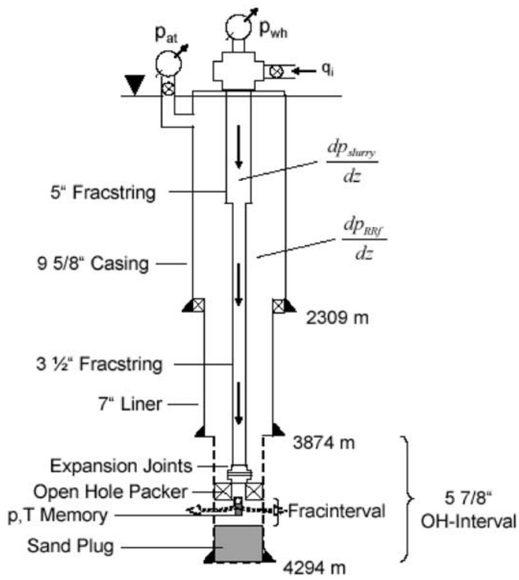

Fig. 2. Schematic of the frac treatment set-up in the well E GrSk 3/90.

During treatments the fluid level (annulus pressure) was monitored at the wellhead and stayed constant. In each interval a diagnostic treatment (datafrac) was conducted prior to the mainfrac with proppants. The datafrac was designed as a step-rate pure fluid treatment with downhole p,T recording. The volume and type (linear, low-pH gel) of the fluid system were comparable to the mainfrac. The main hydraulic and rock mechanical parameters could therefore be determined, including the hydraulic height and volume of the created fracture, by p,T logging and history matching the pressure response. This was needed in order to achieve an adequate mainfrac design and to guarantee safe operations (Fig. 3). During the proppant fracturing treatments in the open-hole section, some difficult and partly unprecedented circumstances had to be faced. The high temperatures and open-hole conditions meant packer operations were risky. Fracture height growth, in particular, had to be curbed and by-passing the packer with proppants had to be avoided. This situation resulted in a less-aggressive frac design.

3. Results and discussions

Hydraulic propped fractures were created with treatments in both intervals, injecting more than 11 tonnes of proppants and 200 m^3 of frac fluid into the formations. Before and after the stimulation, production tests (nitrogen lift) were performed. Fig. 4 shows the pressure responses and flow rates for both tests.

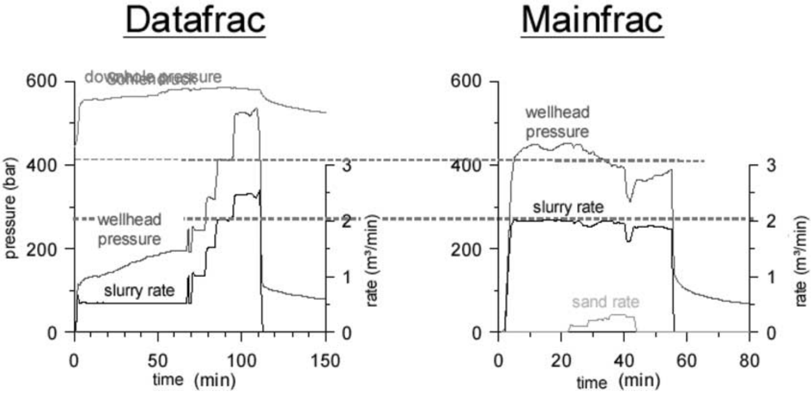

Fig. 3. Pressure and flow-rates for frac treatment in the interval 4130–4190 m. Determination of maximum wellhead pressure and slurry rates (frictional losses) for the mainfrac treatment by applying a step-rate test (datafrac).

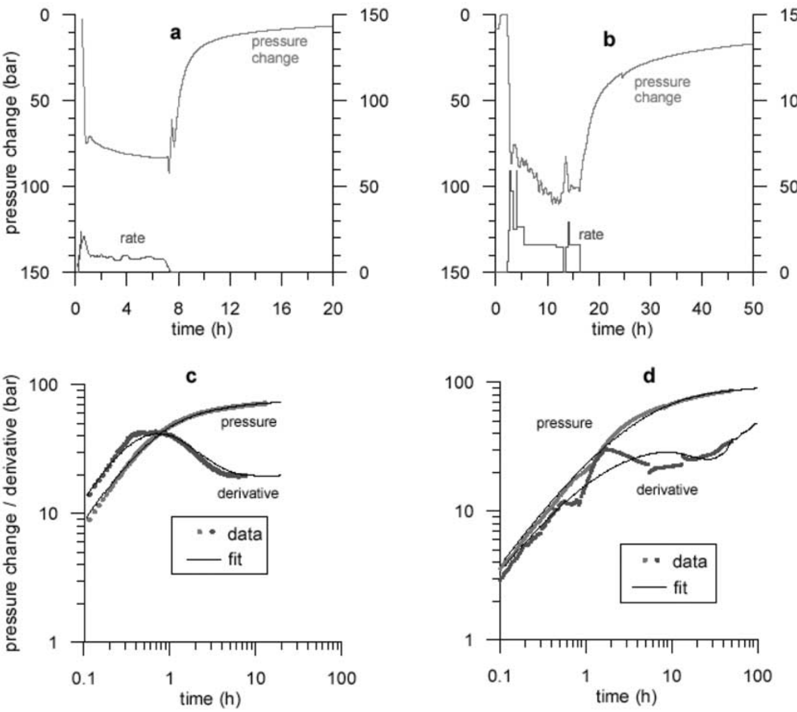

Fig. 4. Pressure change and production rate for the lift test before stimulation (a) and after stimulation (b). Diagrams c (and d) show the log–log-plot for the build-up periods before (and after) stimulation. In c and d the fit curves are obtained assuming a radial composite model. (c) The following important parameters were obtained by nonlinear regression: Before stimulation (c) skin = −1.0; after stimulation (d) skin = −4.9. The transmissivity of the inner zone is in the range (0.5–1.1) E-13 m^3 and the transmissivity in the outer zone is in the range (1–7) E-14 m^3. According to the assumed composite model the transition between inner and outer zone occurs at a radial distance between 30 and 80 m.

3.1. Transient production analysis

Interpretation of the transient production periods indicates a significant increase in productivity. Considering a production time of 10 h in both tests the productivity increases from 1.2 to 2.1 m^3/h MPa, i.e. by a factor of about 1.8. The build-up periods have been analysed to characterize any changes in the hydraulic system. A peak in the derivative before stimulation indicates a significant skin. Almost no peak is observed after stimulation, indicating the reduction of skin. The pseudo-stabilized level of the derivative is almost constant in both cases. Thus, the transmissibility of the production zones remained unchanged.

The increase in productivity is the result of a skin reduction caused by the creation of artificial fractures. In contrast to expectations, no additional high permeability zones were connected to the wellbore.

No hydraulic signatures of fractures (slope of 1/2 or 1/4) could be observed in the log–log-plot after stimulation. Probably less conductive or short fractures were created and the hydraulic characteristics of the fractures are masked by the large wellbore storage. A non-homogeneous reservoir must be assumed in order to fit the pressure response of the well. For example, good matches are obtained from a composite model with two consecutive zones with radially decreasing transmissivity (Fig. 4).

3.2. Fracture performance analysis

The post-frac productivity is still below the predefined objectives. Modelling the frac dimensions created by net-pressure matching and simulating the resulting fracture performance values for the stimulation, a factor (FOI) of 7 to 8 was expected. The mismatch between the observed (FOI = 1.8) and modelled (FOI = 7–8) results can be explained by re-modelling the fracture performance taking various effects into account.

The reservoir is situated below the gas–water contact (GWC) with large lateral, stratiform extensions. Measurements on cores showed clear evidence for the presence of pay-zone porosities between 5 and 15% and transmissibilities of several Darcy-m (Legarth, 2003). A limited reservoir is therefore unlikely to account for this behaviour. Obviously, multiple frac-dominated effects cause the failure to increase productivity. In this context, the first assumption is that a frac was created without properly connecting the productive zones to the well (Tischner et al., 2002). This could be the result of either a short frac that fails to by-pass a damaged zone, as already identified by transient production analysis, or a frac of appropriate length but accompanied by low conductivity so that the intended permeability contrasts with the matrix were not achieved. Of course, a combination of both scenarios is also possible. Another explanation is that the frac initially is of adequate size, but that conductivity deteriorated as a consequence of proppant crushing, embedment and proppant flow-back events occurring during drawdown. Other possible reasons for the phenomena, such as proppant convection and failed tie-back, multiple fracture growth and out-of-pay zone growth, are discussed in Aud et al. (1999), Berghofer (1998), and Cleary and Fonseca (1992). Finally, the assumptions need to be individually checked for plausibility, which we achieved by including the effects in a fracture and reservoir model and attempting an adequate pressure match (fracture performance modelling). It turned out that the observed behaviour could only be adequately explained by either a severe post-treatment conductivity reduction or a failed tie-back of the frac to the well (Legarth, 2003).

Proppant crushing and embedment due to increasing effective stresses during drawdown lead to a reduction in fracture width and thus can cause a reduction in fracture conductivity (Fig. 6). Theoretically the proppants get crushed or embedded in the rock matrix as a consequence of the relationship between their mechanical strength and that of the rock. As rock is an anisotropic, inhomogeneous medium, especially when naturally fractured, both effects are likely to occur at different parts of the fracture–rock interface.

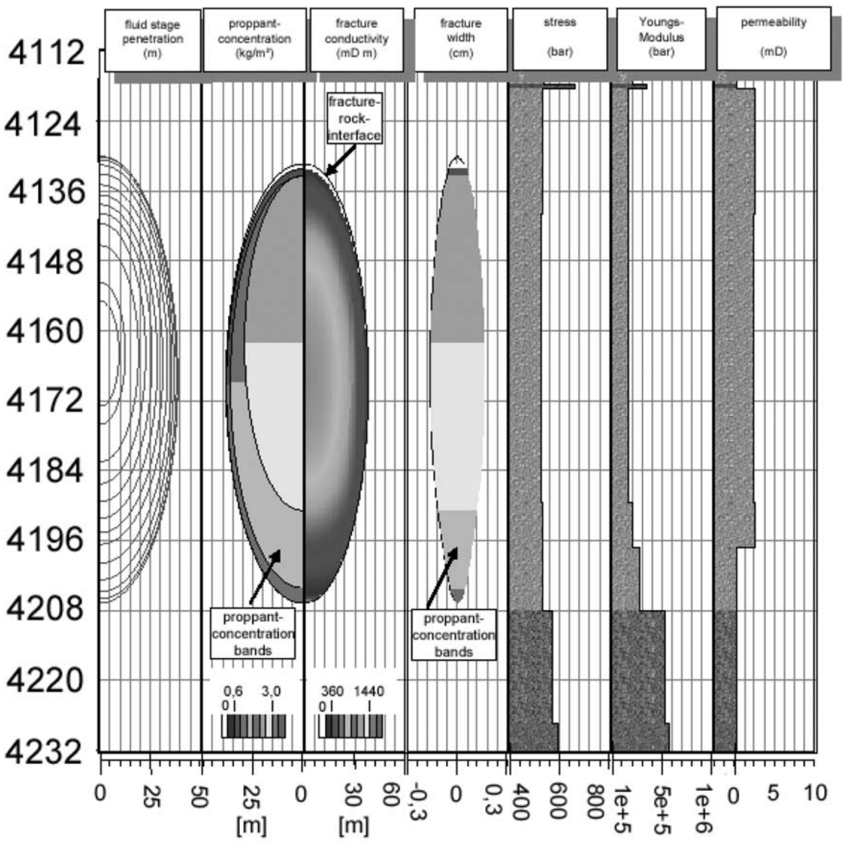

Fig. 5. Frac dimensions from three-dimensional fracture modelling (fracture properties: proppant concentration of about 1.9 kg/m²; conductivity of 300–500 mDm; half-length of about 32 m; height of about 72 m; maximum width of 0.16 cm); first frac interval at 4130–4190 m (Sato and Ichikawa, 1998).

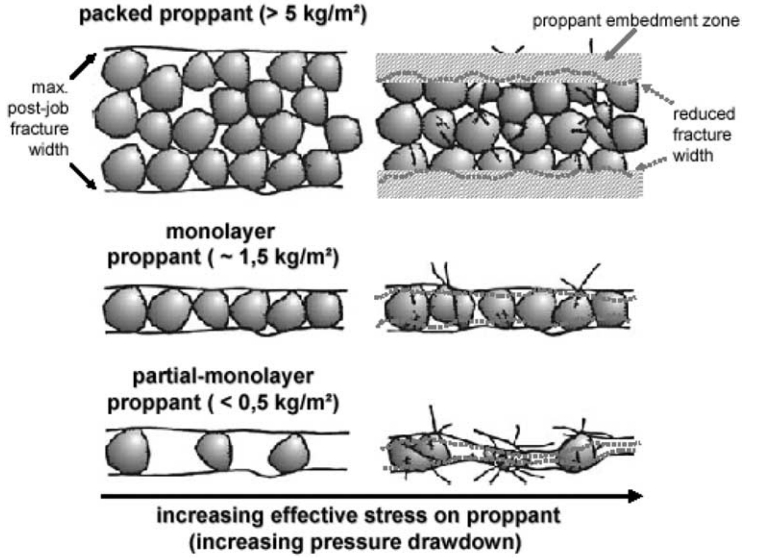

Fig. 6. Potential post-job proppant pack damage due to proppant crushing and embedment for different proppant concentrations with increasing effective stresses during drawdown (proppant pack classifications after Sato and Ichikawa, 1998).

The lower the concentration of proppants in the fracture, the more severe these effects are likely to be, especially when dealing with partial, monolayer proppants: in this case the stress concentration on one grain is maximised (punctual loading). The three-dimensional modelling of these fracture treatments showed a maximum post-job proppant concentration of only about 1.9 kg/m^2 (Fig. 5). This value is slightly higher than the monolayer criterion (Sato and Ichikawa, 1998) (Fig. 6) and consequently does represent an undersized packed frac for this reservoir. The conductivity of the frac is strongly limited and potential inflow restrictions are not completely by-passed. Proppant flow-back also occurred during the production tests, further diminishing the proppant concentration in the vicinity of the well-bore. Leaving the fracture-end inadequately propped (partial-monolayer) or unpropped can result in partial closure of the frac and further production impairment.

4. Conclusions

The open-hole hydraulic proppant fracture treatment was successful. The technical feasibility of the fracturing concept was proven, propped fractures were created and the inflow performance of the well was enhanced, although the stimulation ratio and post-frac productivity achieved were not as good as expected. Probably the fracs were undersized and did not properly connect existing productive reservoir zones to the well. The main reason for the inadequacy of the fracture dimensions is the initial, modest fracture design that was oriented towards risk reduction. For an effective productivity enhancement additional hydraulic proppant fracture treatments are needed in the Rotliegend sandstones, with increased proppant loading to create long-term conductive fractures. Post-frac production tests should also be performed moderately at lower pressures to mitigate any further proppant pack damage resulting in fracture conductivity reduction and production impairment. The stimulation potential of the Rotliegend sandstone reservoir has therefore not yet been depleted, and maximum productivity values have still to be achieved. Further work is needed to integrate the results already obtained and to consider additional technologic advancement.

Acknowledgements

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