Hydraulic Characteristics of the Basel 1 Enhanced Geothermal System

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Keywords

Geothermal, enhanced geothermal systems, temperature log, hydraulic well testing, flow regime

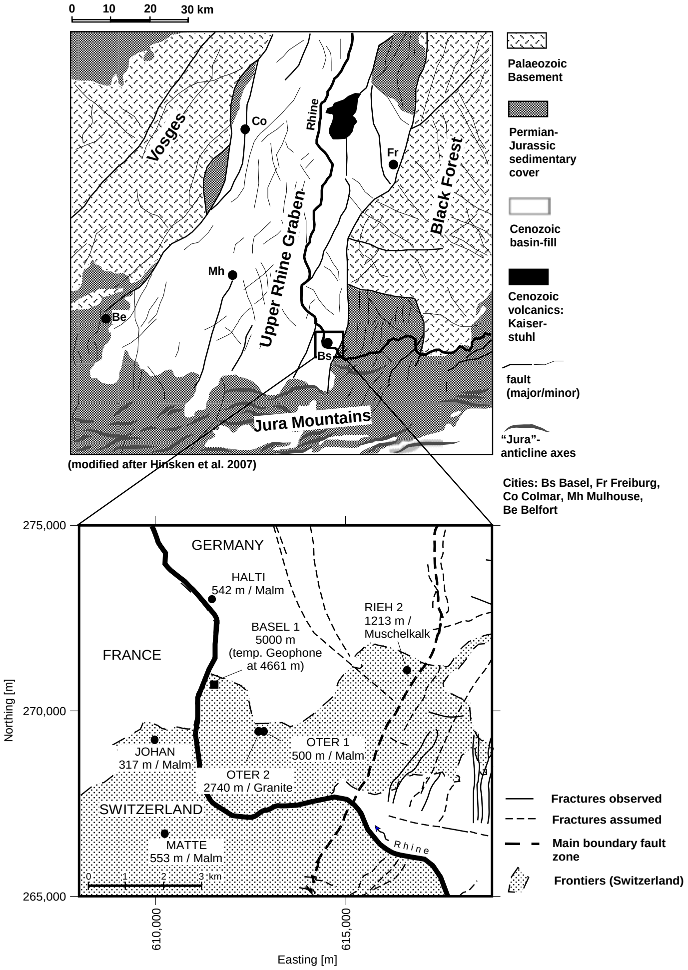
ABSTRACT

This paper characterizes the hydraulic properties of the Basel 1 enhanced geothermal system. The increase in reservoir permeability and the change of the dominant flow regime due to the massive stimulation in 2006 are evaluated with temperature measurements and low pressure hydraulic tests. The reservoir permeability was found to be increased by two orders of magnitude and the dominant flow regime changed from bilinear to linear flow. The findings from hydraulic well testing are supported by microseismic data analysis indicating a stimulated reservoir that evolved along a distinctive fracture zone.

Introduction

The EGS project Deep Heat Mining was initiated in order to develop a geothermal cogeneration plant in the city of Basel, Switzerland (Figure 1). In December 2006 a massive hydraulic stimulation into a 5 km deep granitic target zone was performed which led to perceivable induced seismicity exceeding acceptable levels in an urban area (Häring et al. 2008). Within six days 12000 m^3 of water were injected at wellhead pressures up to 300 bar (Figure 2, overleaf). The seismic activity – recorded by a sophisticated microseismic monitoring system (Dyer et al. 2008) – increased during the process up to a local event magnitude of M_L 2.7 after which the injection was aborted and the well shut in. Only a few hours later it was followed by an event of M_L 3.4. The well was bled-off and the pressure dropped to hydrostatic conditions within a few days. After the well bleed-off the seismic event rate declined gradually. In the post-injection phase over a period of 10 month, the seismic cloud grew by 75% of the size achieved during stimulation. The microseismic monitoring has been maintained over more than two years. After two years the microseismicity has virtually ceased (Figure 3, overleaf).

The project is still suspended awaiting an independent analysis on seismic risk of the Deep Heat Mining project. The risk analysis is expected to be finished by the end of 2009. Based on its conclusions the local authorities will decide whether the project can



(modified after Hinsken et al. 2007)

Figure 1. Schematic tectonic map of the Upper Rhine Graben. Basel is situated at the south-eastern margin of the Rhine Graben. Lower panel: microseismic network; seismic stations marked by black circles.

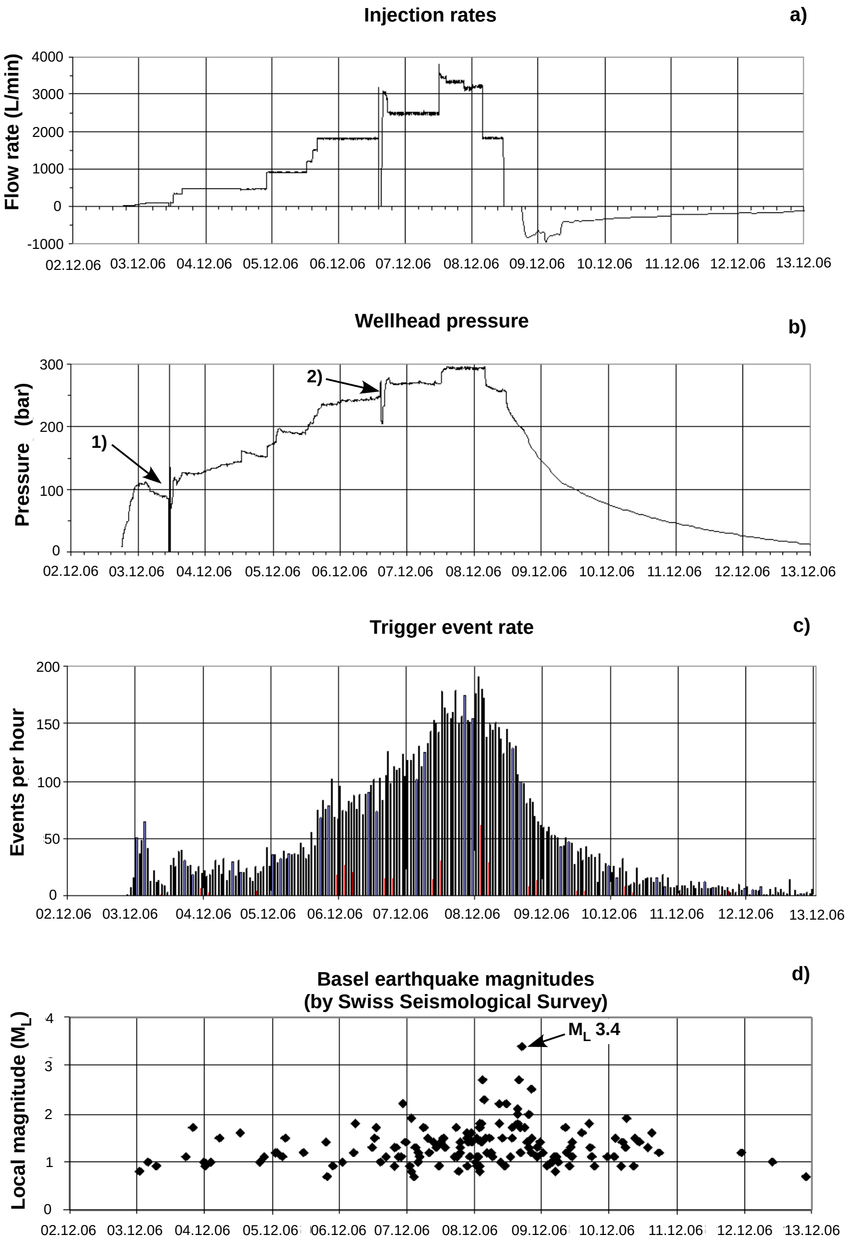


Figure 2. Data on the hydraulic stimulation of well Basel 1. History of a) injection rates, b) wellhead pressure, c) trigger event rates and d) Basel earthquake magnitudes as determined by Swiss Seismological Survey. In panel b) transient 1 is due a change in injection pump and transient 2 is due to the repair of a leaking wireline blowout preventer.

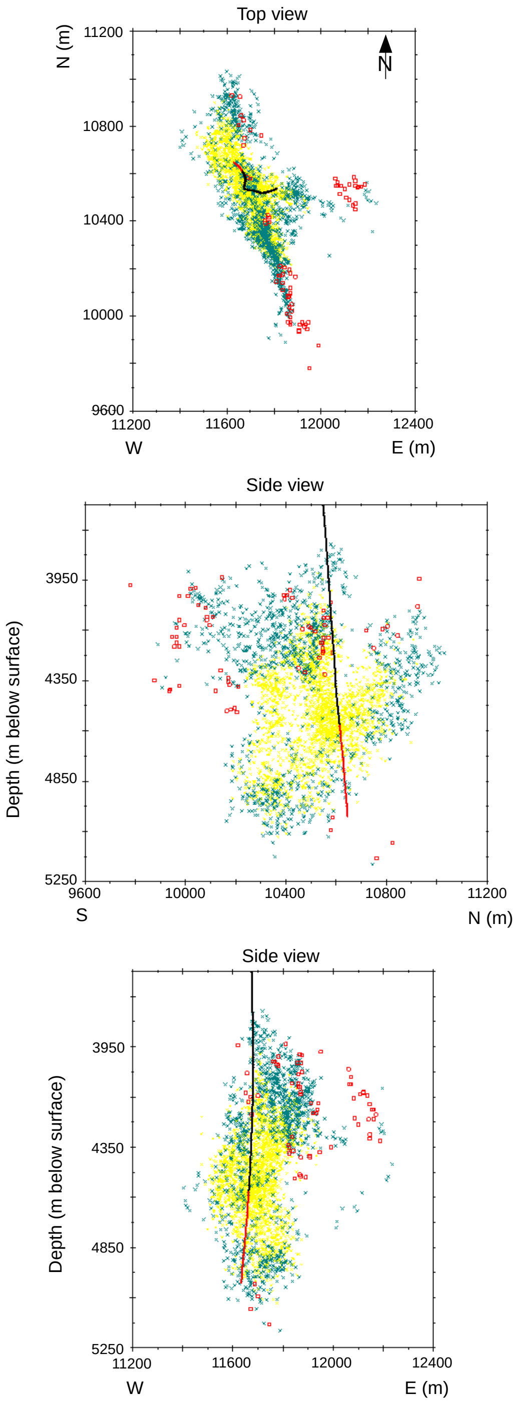


Figure 3. Absolute locations of seismic events from the active injection phase: 2-8 December 2006 (yellow crosses); from the early post-stimulation phase: 8 December 2006 – 2 May 2007 (green corsses); and from the later post-stimulation phase: 3 May 2007 – 30 April 2009 (red cubes). The black line represents the cased and the red line represents the open hole section.

continue in its original concept or has to adjusted to alternative targets or has to be aborted altogether.

New hydraulic and temperature data are available which characterize the reservoir prior, during and after the stimulation. In this paper we present the results of these measurements and the effect of the hydraulic stimulation on the reservoir is discussed in terms of permeability and fluid flow behavior.

Hydraulic Reservoir Characterization Prior to Stimulation

In November 2006, a pre-stimulation pressure test was carried out to characterize pre-existing hydraulic properties of the open hole section of Basel 1 well (Figure 4 and Figure 5 left panel for well completion). The recorded pressure curves suggest artesian conditions of up to 20 bar if the wellbore was filled with fresh water. However, the extrapolation of pressure trends can be mis-

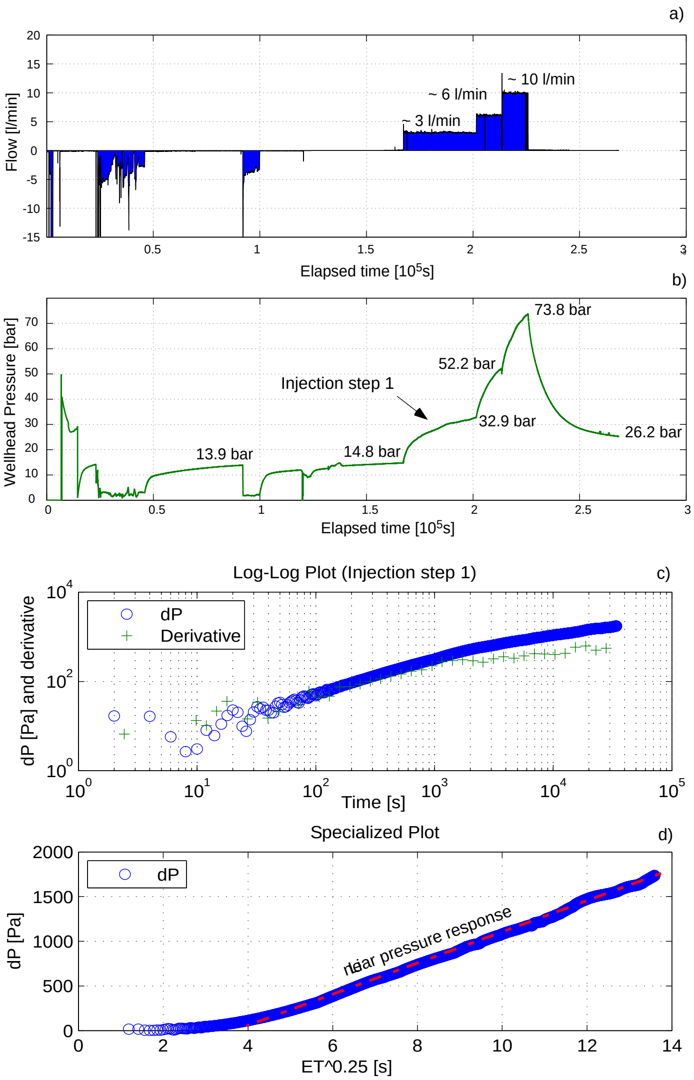


Figure 4. Hydraulic pre-stimulation test in the open hole section of Basel 1 in 2006. History of a) flow rates, b) wellhead pressure, c) log-log plot of the first injection step and d) specialized plot Δp vs. the fourth root of elapsed time indicating bilinear flow.

leading because other important factors such as temperature effects and borehole history effects were not taken into account.

The effective permeability was derived from the first injection step using the equation (1):

$$k = \frac{T}{h} \approx \frac{\mu \cdot \Delta Q}{h \cdot \Delta p} \qquad (1)$$

k	*Permeability* $[m^2]$
T	*Transmissibility* $[m^3]$
μ	*Viscosity of water at 174°C =* $1.75 \cdot 10^{-4}$ *Pa*s*
h	*Open hole section = 371m*
ΔQ	*Differential flow rate =* $5 \cdot 10^{-5}\ m^3/s$
Δp	*Differential pressure =* $18.1 \cdot 10^{5}$ *Pa*

The equation (1) yields an estimate for effective permeability of ~ $1 \cdot 10^{-17} m^2$. Further analysis using a plot of Δp versus the fourth root of elapsed time shows a linear pressure response indicating a bilinear flow regime (Figure 4). Bilinear flow occurs in fractured wells when the pressure drop in the fracture plane is not negligible and a second linear flow regime is established along the fracture extension (Bourdet, 2002). The undisturbed Basel 1 reservoir therefore can be described as a very low permeable granitic rock matrix containing few fractures with low fracture permeability causing bilinear flow.

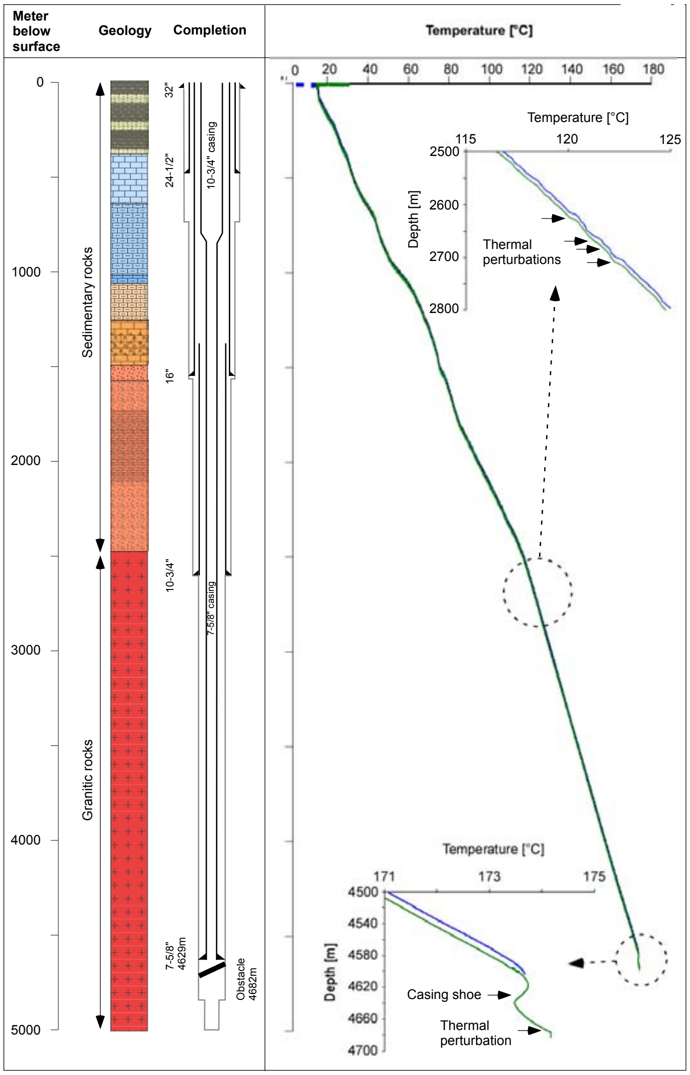


Figure 5. Left panel. Schematic geology and well completion of the Basel 1 well. The open hole section (OH) extends from 4629 – 5000m depth below surface. Right panel. Temperature logs from December 2008 (blue line) and June 2009 (green line). Interesting features in the temperature profile are highlighted.

Hydraulic Reservoir Characterization During the Stimulation

The stimulation in December 2006 was monitored in the initial phase downhole with a pressure-temperature-spinner flowmeter tool (PTS-tool) to detect hydraulically active fractures. Unfortunately the tool could not run to total depth due to an obstacle at 4682m depth. Nevertheless one permeable fracture at 4671m depth could be detected by repeated PTS-logging. This fracture took up to 50% of the injected flow. At the same depth

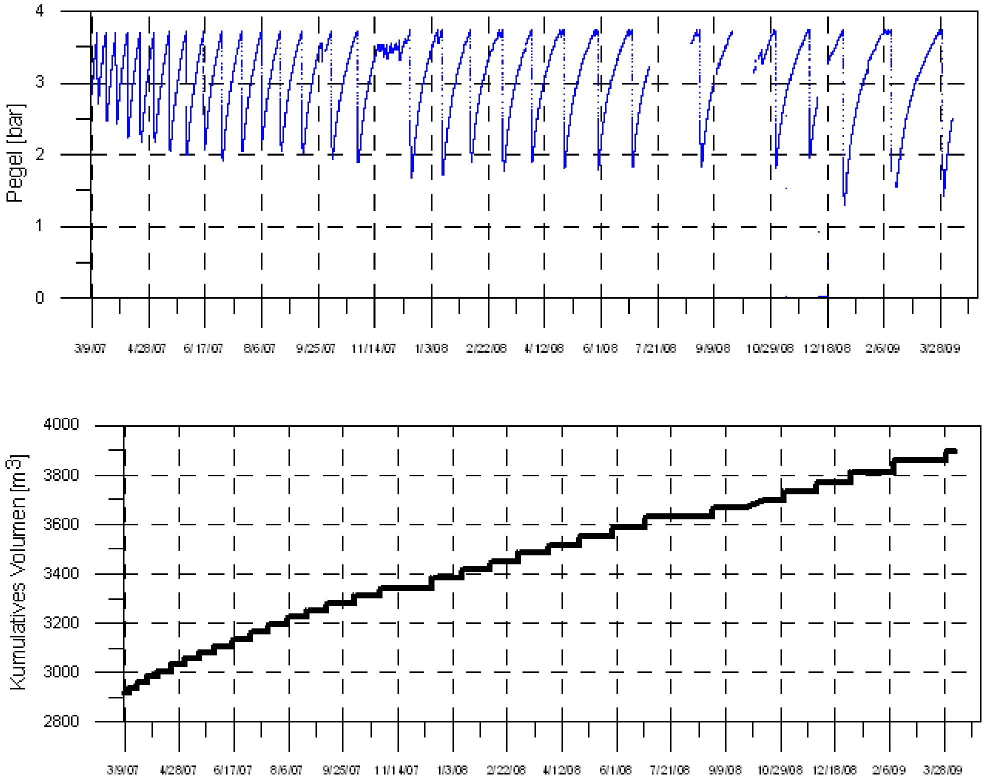


Figure 6. Upper panel. Water level variations expressed as pressure changes recorded by a downhole probe at 35 m depth below reference versus time (MM/DD/YY). Lower panel. Recorded cumulative backflow from Basel 1.

a steeply dipping fracture was observed in the acoustic borehole televiewer log.

A first estimate of the extent of reservoir permeability enhancement could be derived from pressure changes under varied backflow controlled with the choke manifold during the bleed-off phase (Häring et al. 2008). It showed that the reservoir permeability had increased by a factor of approximately 400 and that the enhancement proved irreversible through-out the bleed-off phase.

Hydraulic Reservoir Characterization After the Stimulation

Since the stimulation in 2006 the well was kept open and the water level in Basel 1 was monitored using a pressure probe installed at 35m below reference (= top x-mas tree). The pressure versus time-variation graph shows a dynamic behavior of the water level (Figure 6). After a build-up phase, the water level reaches the well head and produces a kind of a “blow out” where 20 - 40m^3 of water are ejected within a few hours. Afterwards the water level falls back and the next cycle starts. Just after the stimulation the time period of the “blow-outs”, the amount of the ejected water volume as well as the drawdown of the water level increased with time and stabilized in 2008. Due to the periodic pulses a total amount of ~ 3900m^3 of water was produced back from the reservoir since December 2006. The uncommon behavior of the water level is supposed to be caused by a minimal gas flow of nitrogen (98%, and traces of CH_4 and CO_2) in conjunction with a artesian reservoir pressure. In water dissolved gas is transported upwards in the well until it reaches the bubble point at which gas comes out of solution. When the internal pressure of the accumulated gas bubbles exceeds the pressure of the overlaying water column, water is expelled from the well.

In January and February 2009 several low rate injection and production tests were carried out in order to confirm the reservoir permeability enhancement. The pressure data from the second low rate injection test are shown in Figure 6. The duration of the pressure build-up was too short to reach steady-state conditions and thus pressure-transient analysis was used to get an estimate of effective reservoir permeability and transmissibility (Figure 7). The analysis yields a reservoir permeability of ~ $6*10^{-15}$ m^2 indicating an improvement of two orders of magnitude.

The build-up phase was analyzed by plotting Δp versus the square root of elapsed time. It shows a linear pressure response indicating a linear flow regime (Figure 7). Linear flow occurs in fractured wells when the fluid flows along the fracture without any pressure drop (Bourdet, 2002).

Temperature Logs After the Stimulation

The first temperature log was run in December 2008. This was the first operation since well suspension in December 2006 and thus the borehole is assumed to have attained thermal equilibrium. The temperature was logged down to 4600 m depth below surface just above the 7-5/8” casing shoe, where a maximum temperature of 174°C was measured. A second temperature log was run in June 2009. The tool passed the casing shoe at 4629 m depth and ran into the open hole where it stood up at 4682m depth on an already previously noted obstacle. The results form both temperature logs are shown in Figure 5 (left panel). The maximum measured temperature at 4682m depth was 174°C.

The shape of the temperature log in the sedimentary section is non-linear, indicating variations in rock thermal conductivity and water circulation in individual fractures and/or layers . The mean geothermal gradient in the sedimentary section was calculated to 4.1°C / 100m.

The temperature profile within the crystalline basement follows a linear trend showing a mean geothermal gradient of 2.7°C / 100m. An interesting feature was observed in the upper part of the crystalline basement where perturbations in the temperature profile are indicating the occurrence of water circulation.

The temperature profile in the accessible open hole is characterized by thermal perturbations in the vicinity of the casing shoe and another perturbation at 4677m depth suggesting a permeable fracture (Figure 5).

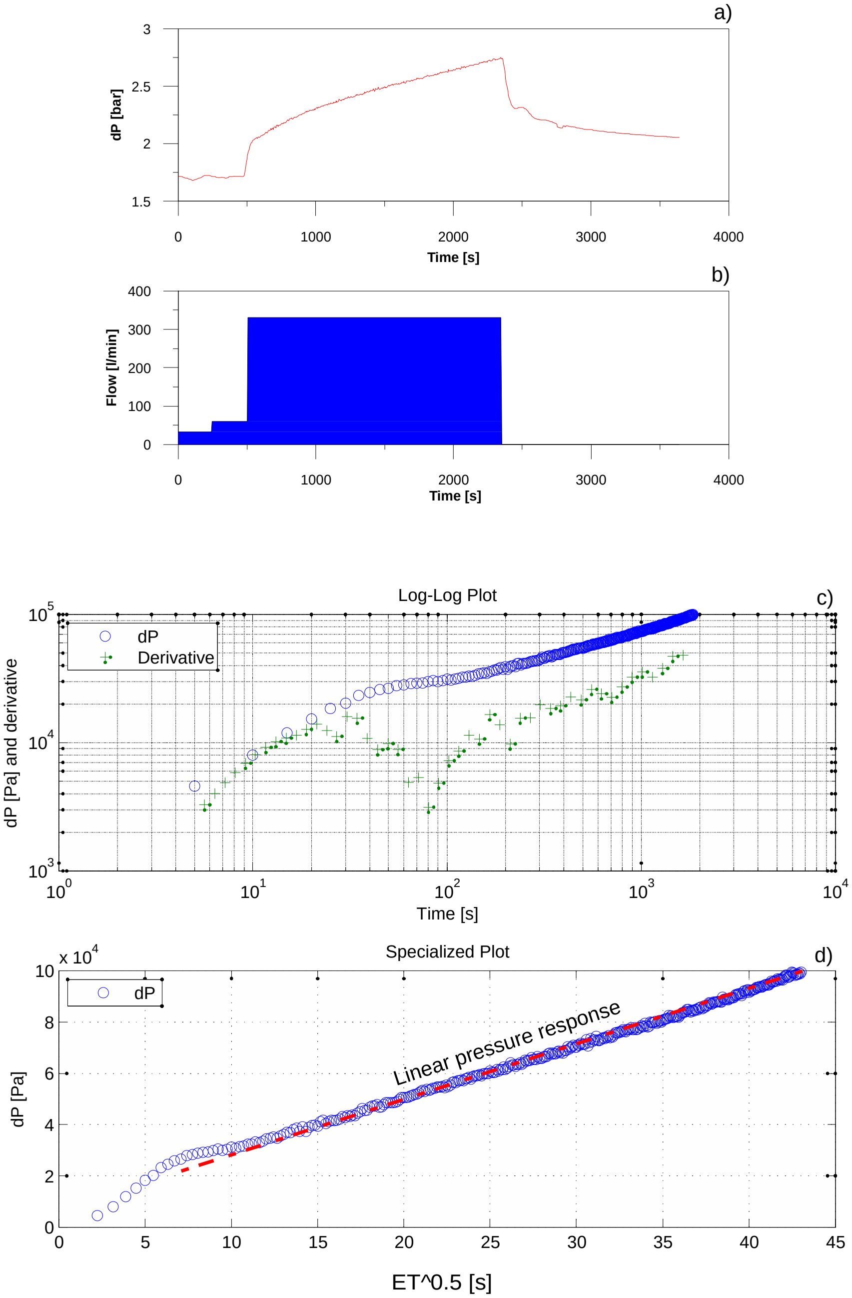


Figure 7. Hydraulic post-stimulation test in the open hole section of Basel 1 in 2009. History of a) wellhead pressure, b) flow rates, c) log-log plot and d) specialized plot Δp vs. the square root of elapsed time indicating linear flow.

Summary and Conclusions

The hydraulic stimulation in 2006 had a significant impact on the Basel 1 reservoir. The analysis of hydraulic data during and two years after the stimulation confirmed an irreversible permeability improvement of the Basel 1 reservoir by two orders of magnitude. In consequence of the hydraulic stimulation the flow regime is found to have changed from bilinear to linear flow indicating that fluid flow in the stimulated reservoir Basel 1 is dominated by few water-conductive fractures. This observation is supported by microseismic analysis suggesting that the main part of the reservoir has evolved along a distinctive fracture zone confined to a relatively narrow plane of few tens of meters (Häring et al. 2008). Therefore the original EGS-concept of generating a network of densely distributed fractures that are efficiently hydraulically interlinked over a large rock volume with one massive hydraulic injection has to be reviewed. New stimulation concepts such as multi zone stimulations have to be considered where a sequence of parallel-trending reservoir disks at different levels are developed in order to create a larger "heat exchanger" volume in the subsurface.

References

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