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STEPS TOWARDS A COMPREHENSIVE THERMO-HYDRAULIC ANALYSIS OF THE HDR TEST SITE SOULTZ-SOUS-FORÊTS

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ABSTRACT

During the exploration of the HDR test site Soultz-sous-Forêts (France) numerous unexpected thermal and hydraulic features have been encountered. The HDR reservoir at the Soultz-sous-Forêts site is targeted in a granitic horst zone bounded by subvertical N-S trending normal faults. The high surface heat flow at HDR test site, Soultz-sous-Forêts, being a main reason for its selection dropped from nearly 150 mW m^{-2} at surface to <25 mW m^{-2} in 2-3 km depth and recovers at greater depth to ~70 mW m^{-2}. In the depth range between 2-3.8 km (i.e. the range with low heat flow) numerous hydraulic experiments have been performed which highlighted the importance of far field drainage systems. The analysis of these features, jointly investigated by numerical models, elucidate that the local temperature field can be explained by a convective flow pattern which develops in the domain with the highest degree of fracturation. The convection cell can be localised between the top of the Buntsandstein at ~1000 m and a depth of ~3700 m in the Granitic basement. Another clue to the dominant role of the ambient fracture system is provided by investigations of numerous multiple level flow rate experiments performed in the GPK1 and GPK2 boreholes. These short time (t<20 days) tests have highlighted the importance of turbulent-like hydraulic behaviour and could be accurately fitted by transient models of simple geometry. Herein, particular attention to the influence of geometry and of far field fault systems was paid. Another effect of the dominant role of natural faults and fractures in the realm of the boreholes are thermo-elastic stresses developing during the 4 month circulation test from 1997 which cause dilation of the fracture voids.

These results allow to derive a conceptual model of the upper reservoir (3000-3800 m) at Soultz with a dominance of the natural fracturation and fault system. It is especially demonstrated that numerical simulation of hydraulic and thermal data can yield a recognition of flow processes and of flow geometries and provides the necessary basis for more elaborated 3-D models which then will allow to predict future HDR performance.

1 INTRODUCTION

The European HDR test site at the Soultz-sous-Forêts is located in a nearly NNE-SSW striking Graben structure between the Vosges and Black Forest mountains to the East and West. The targeted heat exchanger is a granitic rock matrix with a top at 1400 m, covered by Triassic and Tertiary sedimentary formations (e.g. Gérard & Kappelmeyer 1991). The Graben system has been formed in a period of strong extension in Late Eocene and Oligocene times. Locally at the Soultz site smaller subsidence took place and resulted in a horst structure of the granite (Genter & Traineau 1996) with a lateral elevation of ~500 m. The topmost part of the horst and its Triassic cover (Buntsandstein) are traversed by several large fault systems (referenced herein as "Graben faults") parallel to the Graben shoulder which are well known by oil exploration wells and partly even visible on the surface morphology. The most dominant Graben faults at surface in the area of Soultz are the Kutzenhausen Fault which delimits the western part of the horst and the Soultz Fault which crosses the GPK1 borehole in the Buntsandstein unit between 1000 and 1400 m (see also Fig. 1). A major fault was drilled in 2000 m by the GPK2 borehole situated 450 m to the South of GPK1. This event led to an immediate loss of the drilling mud column which indicates its huge transmissivity and storage capacity. Further implications on the role of the various faults zones have been emphasised by Elsass et al. (1992). They especially provide indications on fluid exchange between the sedimentary cover and the crystalline rock by geochemical analysis and also question the relation between near surface heat flow anomalies and fault systems. Within a few km distance surface heat flow can vary over several tenth of mW m^{-2} (LeCarlier et al 1994). In the two deep Soultz boreholes, GPK1 and GPK2, also a strong variation of vertical heat flow has been measured. It drops from nearly 150 mW m^{-2} at surface to <25 mW m^{-2} in 2-3 km depth and recovers at greater depth (z>4000 m) to ~70 mW m^{-2} (Pribnow et al. 1999).

Additional impact of the fracture systems to hydraulic experiments has been established by Kohl et al. (1996) and Bruel (1997). On the basis of numerical simulations of the multiple level flow rate experiments performed in GPK1 in 1994 Kohl et al. (1996) could establish a non-laminar flow model which requires as key feature large, high capacity drainage systems.

This study aims to characterise the unusual thermal and hydraulic features of the Soultz reservoir by highlighting their common characteristics derived from independent measurements. It will especially focus on the data collected so far by temperature logging and on hydraulic experiments. These findings based on completely independent data are quantified in order to characterise the subsurface fault system in the Soultz reservoir. The analysis is directed towards a general optimisation of HDR operation parameters and especially to explain data collected from the Soultz site.

2 DATA AND ANALYSIS METHODS

2.1 Numerical tool

The thermal and hydraulic data analysis is performed with the finite element (FE) code FRACTure (Kohl & Hopkirk 1995). This code is suited for three-dimensional coupled simulations for hydraulic, thermal and elastic processes. Besides the full hydro-thermal coupling further mechanisms such as non-linear stress dependent joint aperture laws or linear elastic effects of temperature and pore pressure perturbations on the stress field developing in the bulk rock can be treated. The numerical investigation is performed by a graphical mesh generator which allows to generate semi-automatically irregular 2D or 3D FE meshes which represent geological or hydrogeological structures such as fault zones or lithological units. An example of the FE mesh can be recognised in Fig. 1 with the rough mesh placed exactly on the boundaries of different lithologies. The 2-D model was most refined at the reservoir with typical spacing of less than 50 m and comprised over 5000 nodes.

2.2 Thermal investigations

Only in 1999 the GPK2 borehole has been deepened from ~3800 m to ~5000 m. Recent temperature measurements indicate temperatures around 200°C at bottom hole (Pribnow, 1999). Earlier temperature measurements in GPK1 and GPK2 show a nearly identical temperature profile in the undisturbed depth ranges (deviations < 10°C) for both wells with little variations probably due to different standing times after drilling. The simulated temperature data are compared to a composite temperature log. Since different depth intervals have been disturbed at different logging times and partly only limited, individual depth ranges have been logged a combination of different GPK2 logs (marked as "*T-Log GPK2*" in Fig. 2) had to be taken as basis for comparison. Thus, the temperature in the topmost 2000m is derived from log JUN97, in the depth interval 2000-3800m from log JUN95, in the lowermost part below 3800 m from log JUL99. Also illustrated in Fig. 2 is the GPK2 log JAN95 registered shortly after drilling completion and the GPK1 log MAY93 which shows only little difference to the combined GPK2 log.

The two-dimensional model investigates basically effects of forced convection due to the inflow of cold near surface fluids from the Vosges mountains and to free convection developing near the Soultz reservoir. Since lateral permeability variations remain speculative at the depth of the granite the permeability values have been increased only at places when it is absolutely required by the fitting procedure. Main fitting objective was to reproduce the temperature profile from GPK2 by a model which contains the main lithological and hydrogeological features but which reduces the number of units as much as possible. The model extends laterally from the Vosges mountain to the Black Forest and vertically to 20 km depth. The analysis is based on a geological WNW-ESE striking cross section (Garnish et al. 1994) perpendicular to the Graben structure. The following material sets have been considered: Sedimentary cover (Triassic, Oligocene), Buntsandstein (Triassic), Granite and deep basement (below 8 km). In Fig. 1 a detail of the geometry near the Soultz reservoir with a rough discretization can be recognised. Thus, besides the thermal properties, especially the Darcy flow velocity, v_D, is the dominant parameter for analysing the subsurface temperature field:

$$\mathbf{v}_{\mathrm{D}} = \frac{\rho_{\mathrm{f0}} \cdot g \cdot k}{\mu} \cdot \left[\nabla h - \rho_{\mathrm{R}} \cdot \nabla \mathrm{z}\right] \qquad [1]$$

with μ the dynamic fluid viscosity, k the matrix permeability, ρ_{f0} the reference fluid density (generally 1000 kg m^{-3}), g the gravity, ∇z the vertical component of the unity vector and h the hydraulic head. The term $\rho_R \nabla z$ describes the effect due to the density difference between reference density and in-situ density (Smith and Chapman, 1983).

2.3 Hydraulic experiments and non-Darcian flow

The open hole sections of GPK1 and GPK2 were extensively investigated between 1992 and 1997 by numerous multiple level flow rate injection or production experiments (Baria et al. 1995, Baria et al. 1997). These experiments extended over a relatively short time (t<20 days) and have been performed with maximum flow rates of <25 l s^{-1}. Since no circulation conditions were used only one borehole has been affected. Pressure was continuously measured downhole and flow rate at wellhead.

Already by analytical investigations of the quasi steady state pressure / flow data from these experiments the non-Darcian nature of the flow regime became obvious. More importantly, the hydraulic behaviour of the Soultz reservoir could be excellently explained by transient numerical simulations assuming non-Darcian flow along the fracture conduits (Evans et al. 1996, Kohl et al. 1997). Non-Darcian flow regimes can be detected as parabolic curve when plotting the steady-state values of differential pressure (ΔP) versus flow rate at different flow levels.

When substituting the empirical laws for non-laminar flow derived by Louis (1967) into the continuity equation for mass transport the transient hydraulic field can be described with (Kohl et al., 1997):

$$S_S \cdot \frac{\partial P}{\partial t} = \nabla \cdot \left(\widetilde{K} \cdot \sqrt{\nabla P}\right) \qquad [2]$$

with P the pressure, S_s the specific storage coefficient and t the time. The modified hydraulic conductivity $\widetilde{K}$ is defined as:

$$\widetilde{K} = 4 \cdot \log\left(\frac{1.9}{\varepsilon / D_h}\right) \cdot \sqrt{\frac{a}{\rho}} \qquad [3]$$

with a being the aperture of a fracture and ρ the fluid density and (ε/D_h) the relative roughness being defined as the ratio between the mean absolute height of asperities, ε, and the hydraulic diameter, D_h. These flow regimes have been successfully implemented in FRACTure using a Piccard iteration scheme.

The Soultz data show a nearly perfect parabolic relationship with the differential pressure, ΔP (i.e. difference between the measured downhole pressure and the natural formation pressure) proportional to the square of the flow rate (Kohl et al., 1997). The investigated material properties designate so-called "representative elementary volumes" (REV's) being abstractions of the true fractured medium but allow to estimate flow conditions, extensions and boundary conditions. The three REV's applied were (1) the borehole, (2) the single conduit characterised by a non-Darcian flow regime, and (3) the rock matrix with Darcian flow regime. A key feature in these models is the inclusion of reservoir faults with high transmissivity and storage which are connected to the borehole by the conduit. These faults act as fixed pressure boundary conditions and can be considered to be the large scale Graben faults which limit the lateral extensions of the hydraulic reservoir model.

3 SIMULATION RESULTS

3.1 Hydro-thermal models at regional size

Different model assumption, from pure diffusive thermal transport to strongly convectively dominated fluid flow, were taken to simulate the large-scale ambient thermal-hydraulic field around the reservoir. Although the horst situation is a promising structure to explain the vertical variation of heat flow by pure thermal diffusion due to lateral thermal conductivity variations, none of the pure diffusive models was able to reproduce the measured profile. On the other hand a highly convective fluid flow can easily reproduce the trend of the data. During the model fitting procedure it was intended to limit the convection cell to the smallest size possible which is in agreement with the observation of distinct fault structures.

A best fitting model (Fig. 2) could be found which limits the strong convective movement on the realm of the fault zones in the Buntsandstein and the topmost part of the granitic horst. The low heat flow between 2000-3800 m is supposed to be in an upwards directed branch of a convection cell which starts to develop at approximately 3700 m and extends up to 1000 m depth (Fig. 3). The basal heat flow in 20 km depth is taken as 40 mW m^{-2}. Table 1 presents all major parameters for the lithological units necessary to achieve this fit. Here, also the values of the highly fractured zone are stated which is responsible for the development of the dominant convection cell. The procedure to simplify the model by adopting identical thermal parameters for the granite and the fractured zone does not influence the model results since thermal transport in the fractured zone is purely due to convection and not to diffusion. It also needs to be stated that the permeability values in the strongly fractured zone of up to $3x10^{-14}m^2$ depend on the assumption for the basal heat flow value. Sensitivity analysis has shown that an increase by one order of magnitude for the permeability in the sedimentary layers does not change the temperature profile. This model shows somewhat similar results like the model elaborated by LeCarlier et al. (1994) with the difference that now, the depth extent of the convective circulation can be better resolved, constrained principally by temperature measurements. Also, this model focuses especially on the implications from the Graben fault systems. Thus, in agreement with the hydraulic observations, the same units which are traversed by fault zones are responsible for the low heat flow. This indicates that different, independent observations can be used for constraining comprehensively the deeper subsurface.

3.2 Hydraulic flow experiments at reservoir size

The numerical simulations resulted in accurate matches of the pressure transient data by models which assume non-Darcian flow in a single plane fracture (see as example the 95JUL01 experiment on Fig. 4). More specifically, the elaborated procedure allowed to estimate the geometrical extension of this fracture (hereafter called "conduit"), and to calculate the transient effects (Kohl et al., 1997). Although the analysis is non-unique by its nature, the geometrical extent can be estimated by placing physical reasonable bounds to the values of specific storage coefficient and to the Darcian permeability of the rock matrix. In this analysis the specific storage coefficient has been estimated to vary between 10^{-11} and $10^{-10}Pa^{-1}$, the permeability of the rock matrix near the reservoir to vary between 10^{-14} and $10^{-16}m^2$.

For an assumed conduit length of 1000 m and height of 100 m Table 2 illustrates the different parameters which allowed excellent fits of the injection tests 94JUL04 in GPK1, 95JUL01, 96SEP29 in GPK2 and production tests 94JUN16 in GPK1.

Another important characteristic of non-Darcian flow which can be recognised in the 95JUL01 data on Fig. 4 (see also Kohl et al. 1996) is the fact that the time required to approach steady-state increases significantly for higher flow rates (Kohl et al., 1997). The influence of the far field (Graben) faults becomes obvious by the fact that steady–state conditions in these single borehole experiments are reached already after a few days. It should be emphasised that the existence of these Graben faults agrees with the assumed physical flow behaviour since they imply a direct, non-divergent flow pattern in the conduit so that turbulent flow can persist over long distances. In a divergent flow field, flow would tend to switch into Darcian flow at some distance from the borehole.

3.3 Hydraulic Circulation Experiments

The 1994-1997 single borehole experiments provided useful calibration of the Soultz reservoir model. Additional data from short term and long term circulation experiments are however needed to study the heat exchanger's performance under operational conditions. Therefore, data from the four-month circulation test (Fig. 5) performed between August and November 1997 with flow rates of approx. 25 l s^{-1}were investigated. Throughout the experiment, the hydraulic impedance of GPK1, the injection borehole, reduced continuously and the impedance at GPK2, the production hole, increased. These observation can be attributed to thermal stresses: At GPK1, the injection of cold fluid tends to create tensile stresses in the rock matrix and potentially may enlarge existing fracture apertures. At GPK2, however, the rock mass was still cooled from earlier stimulation tests (large temperature perturbations at 3000-3800 m depth of GPK2) and production temperature increased continuously during circulation which induces compressive stresses and thus may potentially causes the closure of existing fractures which has been theoretically demonstrated by Kohl et al (1995).

These observations of thermo-elastic coupling have been confirmed by numerical simulations. The aim of these still preliminary models was to apply parameters derived from short term experiments to this long term test. At the initial state of the experiment, these parameters nearly perfectly represent the observed situation at GPK1 (deviation ~10%). With continuous circulation, however, this deviation increases up to a factor of 2.4 (see top bar of Fig. 5). At GPK2, the initial state was not well represented at the beginning (deviation ~22%). Again, the factor describing the mismatch between model (or equivalent to the change hydraulic impedance) and data continued decreasing down to a factor of 0.45. This behaviour is in perfect agreement with the above described temperature data. Thus, these FE simulations could explain quantitatively the behaviour of the long term circulation experiment and highlight the importance of the thermo-elastic mechanisms which modify the system behaviour over time.

4 CONCLUSIONS

The investigated Soultz HDR reservoir between 2000 and 3800 m is clearly dominated by large fault zones. Both, the unperturbed steady state temperature field and the hydraulic perturbations can only be explained quantitatively by accounting for strong hydraulic heterogeneities. Models assuming unfractured rock can be clearly discarded for the Soultz reservoir, even under ambient (i.e. not hydraulically stimulated) conditions. The combined investigations of the ambient temperature field and of the hydraulic experiments are complementary since they require the existence of high permeable features. The non-Darcian flow regime which represents one of the most interesting physical findings linked to the hydraulic behaviour in fractured rock manifests potentially only due to the fact that these Graben faults extend vertically from surface to the reservoir depth but need also to extend laterally over large distances to provide their huge storage capacity. The models for the ambient thermo-hydraulic fields predict a less developed connection to the surface but a high permeable zone seeming limited to the Buntsandstein and topmost granitic units. On the basis of the newly deepened GPK2 measurements, this model predicts especially a lower natural permeability of the rock matrix at greater depth. The future hydraulic experiments in this deepened section tests will show whether the non-Darcian flow behaviour continues to dominate the hydraulic flow behaviour (which would indicate the presence of these Graben faults at this depth) or if significant laminar components can be detected (which would indicate a lateral flow without the presence of a local drainage system).

This reservoir structure offers many advantages for commercial HDR techniques since operational concepts can be developed which modify the conventional dipole layout. The high capacity Graben fault zones in Soultz represent an integral part of the total reservoir and may be strongly beneficial for operational conditions. Fluid losses can be ignored, since these faults potentially provide the necessary amount of fluid through connections to distant, natural reservoirs. Under extreme conditions the injection leg of the future HDR plant thus would act only as an additional source which equilibrates the large scale fluid balance.

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TABLE

Table 1: Parameters required for the interpretation of the temperature data

	Th. conduct. [W m^{-1}K^{-1}]	**Permeability [m^2]**	**Heat prod. [W m^{-3}]**
Sediment. cover	2.0	$5x10^{-18}$	$1x10^{-07}$
Buntsand-stein	4.0	$1x10^{-16}$	$1x10^{-06}$
Granite	3.1	$5x10^{-17}$	$5x10^{-06}$
fractured zone	3.1	$3x10^{-14}$	$5x10^{-06}$
Basement (>8km)	2.0	$1x10^{-20}$	$2x10^{-06}$

Table 2: Parameters required for the interpretation of the 1994-1996 experiments

	94JUL04 94JUN16	**95JUL01**	**96SEP29**
Conduit GPK1			
Aperture [m]	$3.8x10^{-4}$		
Conduit GPK2			
Aperture [m]		$3.2x10^{-4}$	$4.7x10^{-4}$
Rock Matrix			
permeability [m^2]	$1x10^{-15}$	$1x10^{-16}$	$1x10^{-16}$
Spec. storage coeff. [Pa^{-1}]	$8x10^{-11}$	$5x10^{-11}$	$8x10^{-11}$

FIGURE

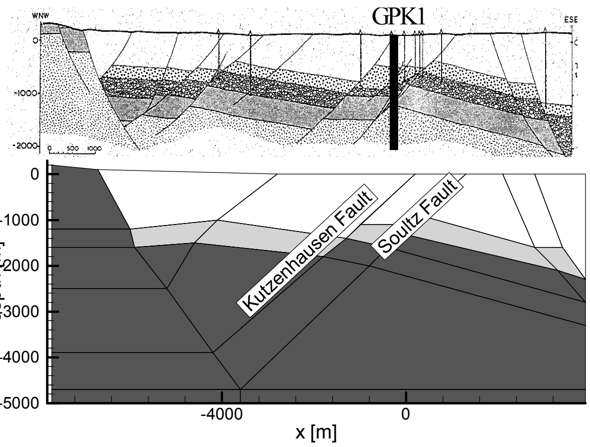

Fig. 1: Geological cross section (modified after Garnish et al. 1994) and detail of a rough FE mesh near the Soultz location. The total mesh extends from the Vosges in the East to the Black Forest in the West. The dark shaded area represents granitic rock, the grey shaded area the Buntsandstein and the bright area near the surface represent the sedimentary cover.

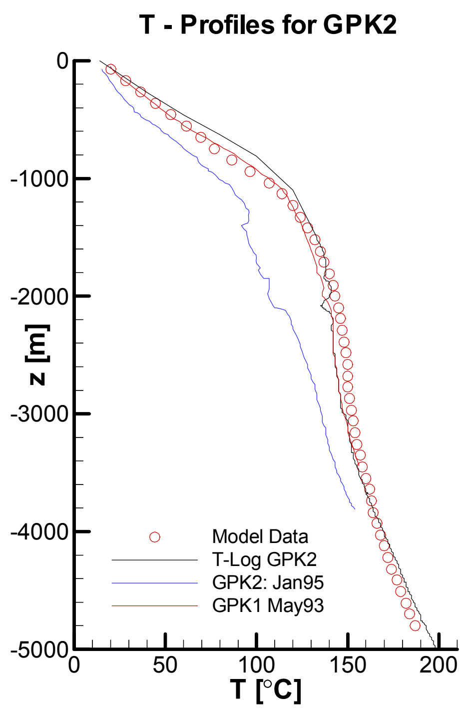

Fig. 2: Comparison of temperature logs and model results. The composite log is denoted by "T-Log GPK2".

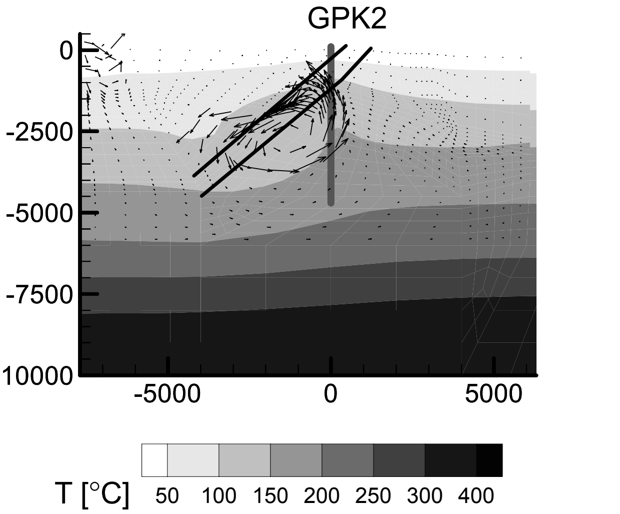

Fig. 3: Detail of the temperature and fluid flow field in subsurface. The flow velocities in the central model domain have been scaled down by a factor of 20 in order to represent even smaller components. The maximum fluid velocities near the two Graben faults exceed several cm / year.

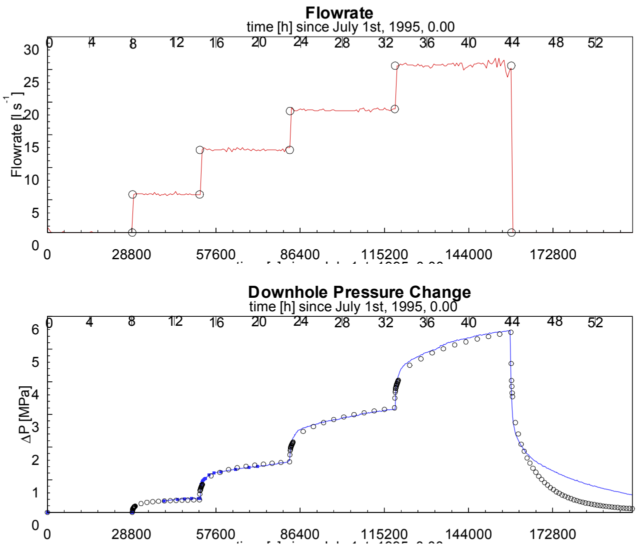

Fig. 4: Flow rate (upper frame) and downhole differential pressure in the GPK2 borehole of the 95JUL01 injection test (Upper x – axis: scaled in hours). Measurements are indicated by continuous lines and simulation results by open circles.

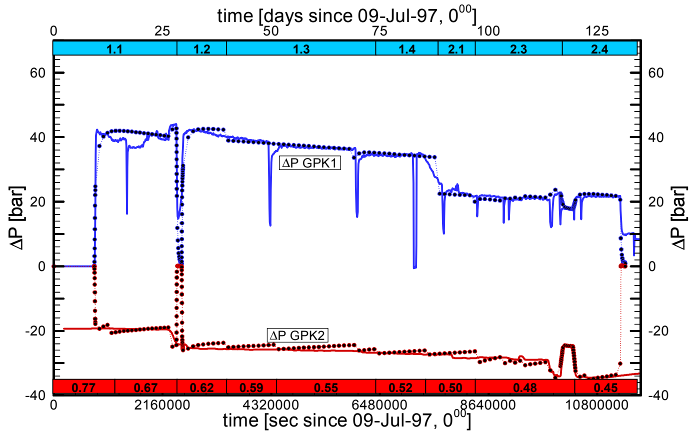

Fig. 5: Segmental fit of the measured and simulated pressure histories of a 4 month circulation test (Upper x – axis: scaled in days). The upper row of factors indicates the ratio between measured and simulated injection (GPK1) and the lower factor row indicates the ratio between measured and simulated production (GPK2) differential pressure.