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Combined analyses of hydraulic and thermal data at 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 results have been obtained. This study aims to characterise several findings by highlighting their common characteristics derived from independent measurements. It will especially focus on the data collected so far from temperature logging and on hydraulic experiments. These findings will be related to data from logging techniques and tracer tests as well as to the tectonic situation at Soultz.

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. In this analysis these features will be jointly investigated by numerical models. The results elucidate that the local temperature field can be explained by a convective flow pattern which develops in the area 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. Another clue to the dominant role of the ambient fracture system are provided by the numerical simulations of the numerous multiple level flow rate experiments performed in the GPK1 and GPK2 borehole. 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.

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

more elaborated 3-D models which then will allow to predict future HDR performance. This analysis is directed towards a general optimisation of HDR operation parameters and especially to explain data collected from the Soultz site.

KEYWORDS

Heat flow, non-Darcian flow, HDR, numerical modelling, fractured rock, Soultz-sous-Forêts

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 parallel to the Graben shoulder which are well known by oil exploration wells and partly even visible on the surface morphology. The most dominant faults 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 (***Figure 1***). A major fault which 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 with an estimated permeability of 100 Darcy-m (Baria et al., 1994). Further implications on the role of the 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 on several tenth of $mW\ m^{-2}$ (LeCarlier et al 1994). In the two deep Soultz boreholes, GPK1 and GPK2, also a strong vertical variation of 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 $mW\ m^{-2}$.

Additional impact of the fracture systems to hydraulic experiments has been established by Kohl et al. (1996). On the basis of numerical simulations of the multiple level flow rate experiments performed in GPK1 in 1994 a non-laminar flow model could be established which requires as key feature large, high capacity drainage systems. In this paper we will compare these findings based on completely independent data in order to characterise the subsurface fault system in the Soultz reservoir.

2. Data and Analysis Methods

2.1 Numerical tool

The 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 are represent geological or hydrogeological structures such as fault zones or lithological units. An example of the FE mesh can be recognised in Figure 1 with the rough mesh placed exactly on the boundaries of different lithologies.

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 GPKl and GPK2 show a nearly identical temperature profile for both wells with little variations probably due to different standing times after drilling. For the comparison of the simulated temperature data to the measurements major temperature logs will be provided. Since different depth intervals have been disturbed at different logging times and partly only individual depth ranges have been logged a combination of different GPK2 logs (marked as *"T-Log GPK2"* in *Figure* 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 *Figure* 2 is the GPK2 log JAN95 registered shortly after drilling completion and the GPKl 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 from cold near surface fluids from the Vosges mountains and of free convection developing near the Soultz reservoir. Since lateral permeability variations remain speculative in the depth of the granite permeability has 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 low 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 assumed Sedimentary cover (Triassic, Oligocene), Buntsandstein (Triassic),

Granite and deep basement (below 8 km). In ***Figure*** **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:

$$\mathbf{v}_D = \nabla\left(\frac{\rho_f \cdot g \cdot k}{\mu}\cdot\left[\nabla h - \rho_R \cdot \nabla z\right]\right) \qquad [1]$$

with μ the dynamic fluid viscosity, k the matrix permeability, ρ_{f0} the reference fluid density (generally 1000 kg m^{-3}), g the gravity, Vz the vertical component of the unity vector and hthe 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 GPKl and GPK2 were extensively investigated in between 1992 and 1997 by numerous multiple level flow rate injection or production experiments. These experiments extended over a relatively short time (t<20 days) and have been performed with maximum flow rates of <25 $1s^{-1}$. Since no circulation conditions were used only one borehole has been affected. Pressure was continuously measured downhole and flow rate at the borehole head.

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 in this 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 (AP) versus flow rate at different flow levels. These flow regimes have been also numerically analysed by FRACTure in a Piccard iteration scheme when substituting the empirical constitutive flow laws derived by Louis (1967) into the continuity equation for mass transport (Kohl et al., 1997):

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

with P the pressure, S_s the specific storage coefficient and t the time The modified hydraulic conductivity has to be defined as:

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

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.

The Soultz data show a nearly perfect parabolic relationship with the differential pressure, **AP** (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). For constraining the basic material properties, the numerical models consisted of the smallest possible number of material sets which designate so-called "representative elementary volumes" (REVs). The three REVs 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 are referred to herein as "far-field faults" since they constitute constant potential boundaries in our models.

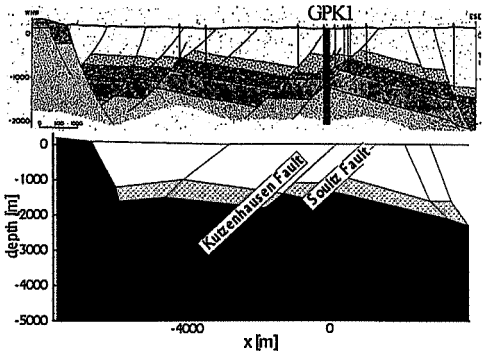

Figure 1: Geological cross section (modified after Garnish et al. 1994) and detail of a rough FE mesh near the Soultz location. The total mesh extends from the Vosges in the East to the Black Forest in the West. The dark shaded area represents granitic rock, the grey shaded area the Buntsandstein and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

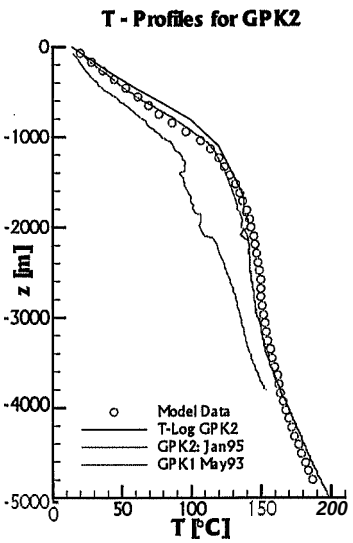

Figure 2: Comparison of temperature logs and model results.

3. Simulation Results

3.1 Hydro-thermal models at regional size

Different model assumption were taken from pure diffusive thermal transport to strongly convectively dominated fluid flow. Although the horst situation is promising for a purely diffusive driven vertical variation of heat flow, neither of the pure diffusive models was able to reproduce the measured profile. On the other hand the high convective driven 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.

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

Parameters	Sedimentary cover	**Buntsandstein**	**Granite**	**Basement**
Thermal conductivity [$W m^{-1}K^{-1}$]	2.0	4.0	3.1	2.0
Permeability [m^2]	$5x10^{-18}$	$1x10^{-16}$	$5x10^{-15}$	$1x10^{-20}$
Heat productivity [$W m^{-3}$]	$1x10^{-07}$	$1x10^{-06}$	$5x10^{-06}$	$2x10^{-06}$

A best fitting model (Figure 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 (Figure 3). The basal heat flow in 20 km depth is taken as 40 $mW m^{-2}$. Table 1 presents all major parameters for the unfractured lithology necessary to achieve this fit. In the strongly fractured zone permeability values up to $3x10^{-15} m^2$ had to be taken. It needs to be stated however that slightly different results can be also attained by a variation of the basal heat flux and the high permeability value responsible for the convection cells. The model shows somewhat similar results like the model elaborated by LeCarlier et al. (1994) with the difference that now, the depth extend of the convective circulation can be better resolved, constrained principally by temperature measurements. Also, this model focuses especially on the implications from the large 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.

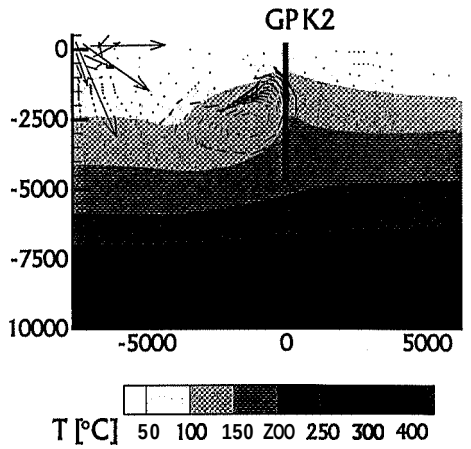

Figure 3: Detail of the temperature and fluid flow field in subsurface. The flow velocities in the central model domain have been scaled down by a factor of 20 in order to represent even smaller components.

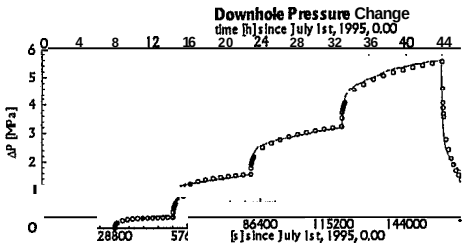

Figure 4: Downhole differential pressure in the GPK2 borehole of the 95JUL01 injection test. Measurements are indicated by continuous lines and simulation results by open circles.

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 Figure 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 (Figure 4) 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 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 reservoir 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.

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

	94JUL04 94JUN16	95JUL01	96SEP29
Conduit GPK1			
Aperture [m]	3.8×10^{-4}		
Conduit GPK2			
Aperture [m]		3.2×10^{-4}	4.7×10^{-4}
Rock Matrix			
Permeability [m^2]	1×10^{-15}	1×10^{-16}	1×10^{-16}
Specific storage coefficient [Pa^{-1}]	8×10^{-11}	5×10^{-11}	8×10^{-11}

4. Conclusions

The presently investigated Soultz HDR reservoirs between 2000 and 3800 m are 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 both 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 fault zones extend not only from surface to the reservoir depth but also laterally along large distances and therewith have a large storage capacity. From the thermal models a less developed connection to the surface is predicted and the high permeable zone seems to be limited on the topmost granitic and Buntsandstein units. On the basis of the newly deepened GPK2 measurements, the temperature model predicts especially a lower natural permeability of the rock matrix at greater depth. It needs to be investigated by future hydraulic tests whether the non-Darcian flow behaviour continues to dominate the hydraulic flow behaviour or if larger laminar components can be detected. The latter would indicate a stronger radial flow field.

This environment offers many advantages for commercial HDR techniques since operational concepts can be developed which modify the conventional dipole layout. The high capacity 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 based on the connection to distant,

natural reservoirs. The injection process represents only an additional source which equilibrates the large scale fluid balance.

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