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Determining the impact of massive hydraulic stimulation on local microseismicity

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ABSTRACT

The paper presents the adopted strategy and the perspective for forecasting the success of cost-intensive hydraulic stimulations. These models serve as basis for a further evaluation combining stochastic networks to the juvenile rock matrix.

The data suggest that “focused” stimulation may have a significant advantage compared to the single well stimulation technique and may be an important step towards efficient reservoir stimulation at larger separations between wells, thus improving the economic viability and acceptance of EGS systems.

1. INTRODUCTION

The research at the European HDR site at Soultz started in 1988 following the encouragement of the European Commission to pool the limited available national funds to form a coordinated multi-national team. The main task was to develop the technology needed to access the vast environmentally-friendly HDR energy resource. The European HDR research site is situated at Soultz-sous-Forêts at the western edge of the Rhine Graben, about 50 km north of Strasbourg (Fig 1). Baria et al (1993), Garnish et al (1994), Baria et al (1995), Baumgärtner et al (1995), & Baumgärtner et al (1998), Baria et al (2000) give brief summaries of the various stages of the development of this technology at Soultz since 1987.

The present "Scientific Pilot Plant Phase" started in April 2001. It accomplished two additional deviated 5000 m deep wells to form a three-well system and an enhanced permeability fractured rock reservoir by hydraulic stimulations. It also includes the use of various diagnostic techniques to understand and quantify various properties of the stimulated reservoir. The program also includes the establishment of a database of the potential HDR resource in the Western Europe.

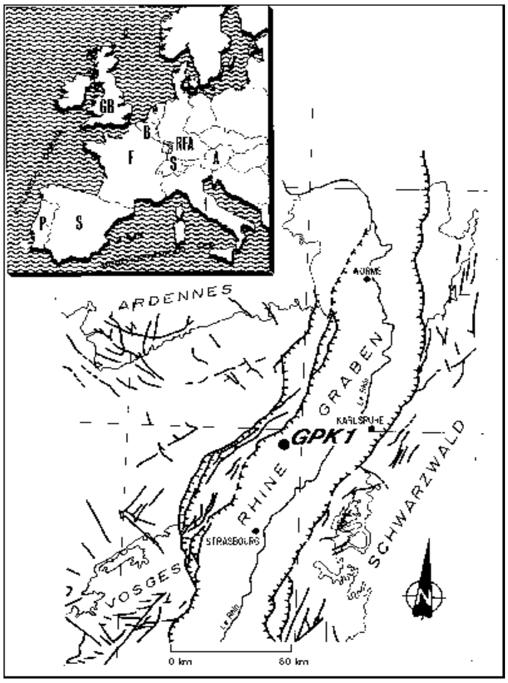

Fig. 1: The location of the European HDR site at Soultz-sous-Forêts

The first well GPK-2 was drilled to 5000 m in 1999 and stimulated in 2000. The well GPK-3 (the injector) was drilled in 2002 and targeted using microseismic and other data. The bottom hole temperature was 200.6 ºC and separation between the two wells at the bottom is around 600 m. GPK3 was then stimulated to enhance the permeability between the wells. A number of stimulation techniques have been tested including “focused” stimulation, a novel method of injecting simultaneously in two wells. Microseismic monitoring, flow logging and other diagnostic methods were used during these injections. Actually GPK4 is near completion at 5150 m measured depth (see Fig 2).

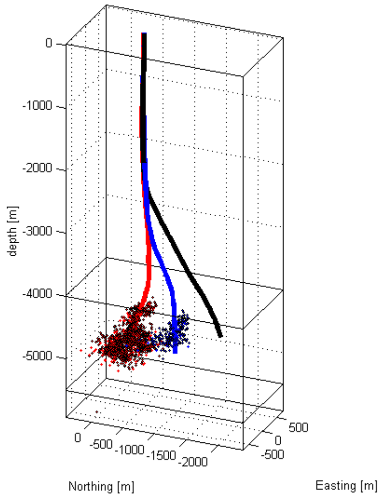

Fig. 2: Orientation and location of GPK2 (left), GPK3 (center) and GPK4 (right).

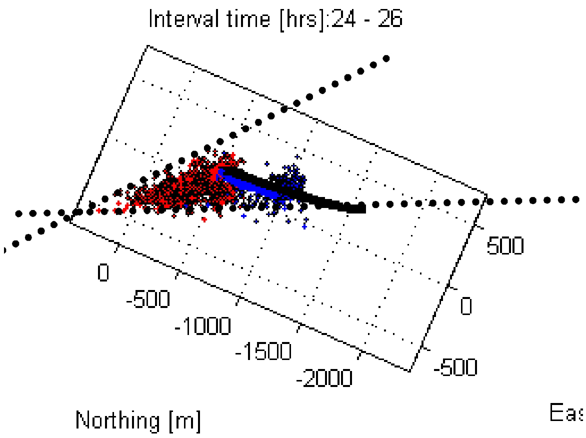

Fig. 3: Plane view on microseismic events occurring after 24h of injection into GPK2 and GPK3. Events from stimulating GPK2 are shown in red, from GPK3 in blue. Also shown are the trajectories of the boreholes (black) – see Fig. 2. for location of the boreholes.

The "sparse" microseismic network at the Soultz site consists of a number of seismic sensors deployed in five wells between 1500 m and 3600 m depth with bottom hole temperatures of 130-160 ºC. A 48 channel, 22 bit data digitizing unit was used for data acquisition in conjunction with proprietary software to carry out automatic timing and location of microseismic events due to stimulation in real time. This gave a decision-making possibility and control of the reservoir development in real time. This was the first time that such an interactive method had been carried out at this site.

Around 90'000 micro-earthquakes were triggered during these injections and about 9'000 events were automatically timed and located in real time. These stimulations created a total reservoir volume in excess of 3 km^3. This is the largest stimulated volume in the development of HDR technology to date.

2. HYDRAULIC MODELING CONCEPT

General

During the 2002-2004 hydraulic stimulations at the European HDR/EGS site in Soultz-sous-Forêts the interconnection of the microseismic cloud and the hydraulic flow field should be assessed. The observations of the transient development of the clouds indicate clear structures that are likely to represent either hydraulic barriers or well-conducting features. From a first purely visual, qualitative interpretation, micro-earthquakes generally occur in a well-bounded domain during a given time interval, before they start developing within "juvenile" areas. Fig 3 illustrates such a situation after a stimulation period of 24hrs, both at GPK2 and GPK3. Towards the bottom of Fig. 3 (South-West) it can be clearly seen, that the same features bound both seismic clouds. It should be noted that the GPK3 cloud was created 2 years after the GPK2 stimulation.

Baria et al. (2004) have shown that seismic signals were correlated to a ~3 MPa fluid overpressure threshold.

2.1 Numerical procedure / Stochastic Fracture Network

In order to simulate and map these features, a new approach was taken to merge deterministic and stochastic fracture zones from a fracture network model with continuous numerical FE models. The new procedure takes advantage of two well-experienced programs: FracSim3D and FRACTure.

The FracSim3D code has been developed in several stages. Originally written by Willis-Richards et al. (1996) in 2D, it was extended in 3D by Jing et al. (1998). Since then it was continuously improved (Bächler et al. 2001), modified and integrated into the HEX-S package that has now a GUI interface allowing for the definition of various fracture sets with their physical parameters and the visualizing of the imposed shear events. The 3D fracture network simulator especially addresses the problem of hydraulic stimulation by an approximation of the complex fracture mechanics behavior in a fractured reservoir. The effective normal stress $\sigma_{n,eff}$ and the effective shear stress τ_{eff} on the plane of each fracture are derived from the local principal stress components and the fluid pressure. Since the fractures are assumed to be well connected the fluid pressure P, although locally acting on the fracture wall, is isotropic. The normal stress $\sigma_{n,eff}$ and shear stress τ_{eff} acting on a planar fracture being the key stress parameters for the opening and shearing processes are calculated from the principle stress components. Originally only operational with a strongly simplified hydraulic solution, a major improvement is now realized in the HEX-S package by calculating the hydraulic pressure distribution, P, from accurate numerical 3D equations.

FRACTure is a versatile, 3-D finite element program for the simulation of various processes in geoscience (Kohl & Hopkirk 1995). It was designed with the specific aim of studying the coupling of different physical processes in the subsurface. Its flexible modular structure facilitates the addition of further processes and elements to the existing library and the handling of linear and non-linear constitutive laws and the calculation of their interactions. FRACTure can simulate individual hydraulic (laminar, turbulent), different transport (thermal, non reactive solute, radioactive solutes) and elastic processes as well as special coupled inter-actions between these processes. Hydraulic calculations can be performed as function of the Reynolds Number: hydraulic regimes may switch from laminar to turbulent-like and vice versa. The name FRACTure is an acronym for its functional capabilities (Flow, Rock And Coupled Temperature effects) whilst at the same time emphasizing the fracture as the dominant hydraulic structure in crystalline rock. Currently, the interaction only accounts for pure hydraulic effects – it is intended to activate density effects and poro-/ thermoelastic stress perturbations at a later stage.

Both codes treat numerous highly non-linear processes. In the present approach, both codes interact with each other through an iterative, explicit algorithm. Therefore, firstly the appropriate fracture sets are defined from deterministic observations and from stochastic parameters. Generally, sets of >20'000 single fractures are generated this way. If however, the later process only requires less, but more significant fracture sets, this number can be adapted accordingly. The intersection of these fractures with the continuous FE grid is performed by a special routine, that accounts for the current aperture, a Rock-to-Fracture volumetric index (RFVI). The mapping procedure results in individual FE volumes of strongly anisotropic properties that are adapted at every time-step. The degree of shear/normal compliance in the fracture network is predicted from the orientation of the fracture sets and from the change of hydraulic pressure. It results that the effective stress field will be strongly reduced at the injection boreholes, thus creating the most significant aperture changes. Generally, such hydraulic non-linear behavior is clearly observable at successful stimulation data, together with the transient extension of the microseismic cloud. At later interpretation, the modeled shearing events are compared to the location of the microseismic events.

2.2 Numerical Model

The numerical model used for the simulation of the hydraulically induced shearing events consists of ~450’000 nodes. The model is strongly refined towards its center, along the open hole sections of GPK2-GPK3 and GPK4 between 4500-5000m depth. Fig 4 illustrates this refinement in vertical and horizontal direction. Towards the boreholes, 25x25x25m^3 cubes have been implemented.

By a complex 3D, inverse numerical evaluation the interaction of microseismic events and hydraulic pressure field were evaluated for a typical Soultz situation. The applied numerical model included the three deep Soultz boreholes GPK2, GPK3 and GPK4 (Fig 4). In the present model a simulation of the GPK3 stimulation is intended. Therefore, the focus of the simulation is concentrated on the nearfield of GPK3 including measured deterministic and stochastic (derived from fracture distribution) fractures next to GPK3. The mapping of a stochastic/deterministic fracture network includes the measured GPK3 UBI log as well as further typical fracture parameters.

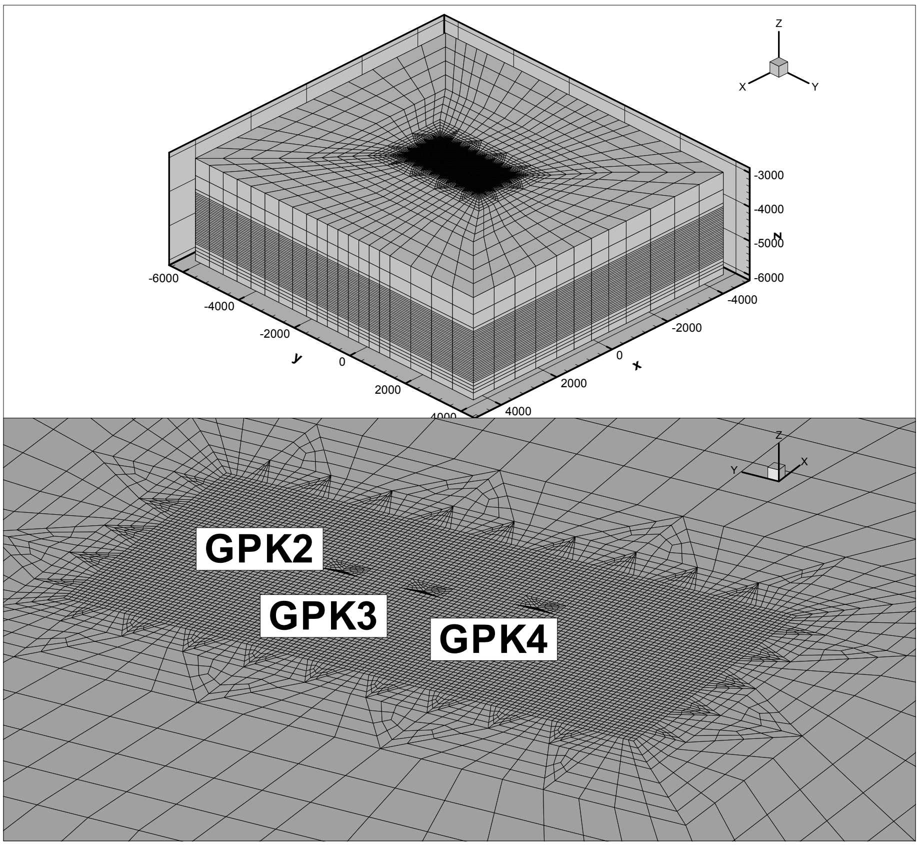

Fig. 4: Numerical finite element grid with open hole sections of GPK2, GPK3 and GPK4. A stochastic fracture network is mapped into the 3D elements.

Results and discussion

The simulation results highlight the strong complexity of non-linear processes occurring in the host rock. In the present paper, especially the initialization of shearing events and fracture dilatation will be discussed. The dependency of fracture aperture calculated from the current stress state is superimposed by the anisotropic distribution of fractures. Therefore the pressure field starts initiating along the N-S direction, perpendicular to the minimum horizontal stress. The transient development of the individual pressure isolines is not constant, but is strongly related to the individual fracture transmissivity. As a general pattern it can be observed that high-pressure zones develop as transient effects disappear after a certain time. Due to the spatially heterogeneous fracture distribution it can well happen that the pressure does not develop radially from the borehole (i.e. in horizontal direction) but vertically. In a horizontal slice through the 3D pressure field, such zones seem to be hydraulically disconnected from its neighborhood.

It has been carried out in our simulations that only a part of the pressure field is linked to seismic shearing events. A link between pressure and a shear event can be established for an over-pressure of 3 MPa. Lower overpressures penetrate into the host rock or adjacent fracture systems without any shearing effects. The calculated shear events align along major fracture zones. Clearly, many shearing events are simulated during a model run (>100'000 events during the first 10'000 sec). In comparison to the measured microseismic signals, it needs to be taken into account that not all shearing movements are locatable events, since they fall below a so-called "aseismic" threshold. In our analysis, we consider events below a shearing displacement of 1 cm to be aseismic.

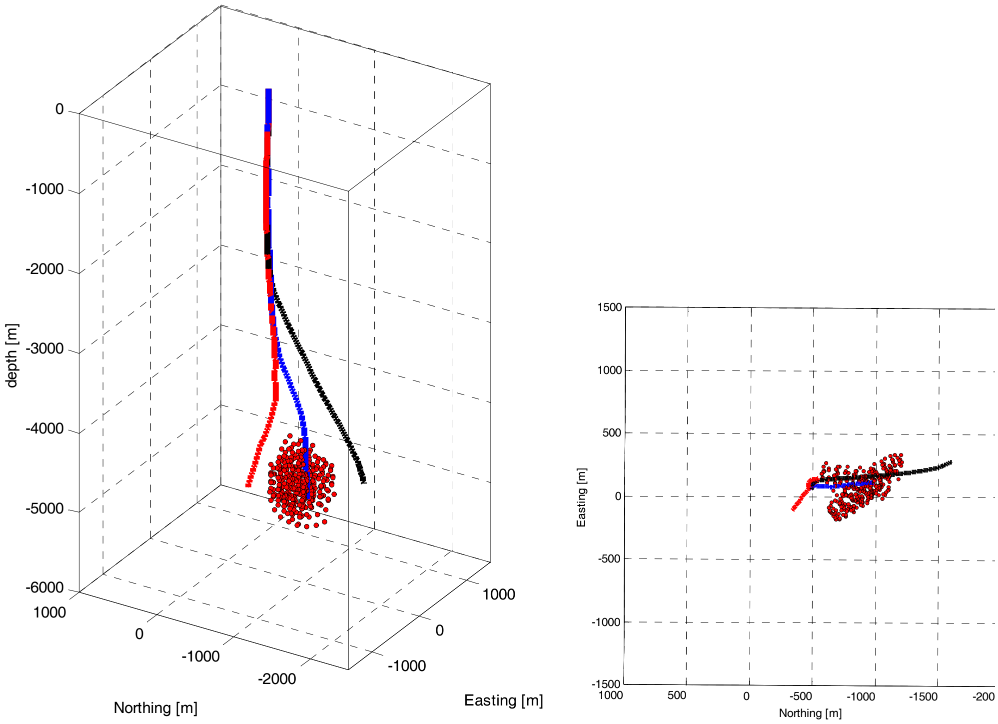

Fig. 5: Shearing events in the vicinity of GPK3, occurring in the first 10'000 sec after injection start.

The shearing events mostly group along the stimulation borehole (herein GPK3). On Fig 5 it can be clearly recognized that these events occur along the same features that also show up as high-pressure fluid zones. Within the shape of theses features, the seismic signals seem to strongly perturb the host rock. The increase of transmissivity is well simulated. Injectivity increase of a factor 5 or more can be forecasted, depending on the stimulation rate. Our analyses indicate that a sudden, strong high-rate stimulation (Heavyside step function) can induce more efficient stimulation results than slowly increasing flow rate.

CONCLUSIONS

A new simulation tool is now in operation that allows forecasting seismic events in space and time due to massive hydraulic injection into fractured rock. The interaction between the hydraulic pressure field and the shearing induced seismicity can now be demonstrated. This has a strong impact on the design of cost-intensive stimulation experiments. Now, it becomes possible to predict the shearing response and the evolution of microseismicity under given deterministic/stochastic fracture distributions and stress field.

Our analysis highlights the nature of seismic signals: they seem to correlate to fracture or fault zones that act as transient drainage system during stimulation. With increasing stimulation, these features can re-shear, however, the deeper penetrating pressure front activates more fractures at larger distance from the borehole. At a given stage, a nearly steady-state pressure field is reached and the extension of the microseismic cloud nearly stops.

In future, this concept will be further developed. While the present approach is well suited for the simulation of short-term effects, occurring in the first days, the simulation of the long-term response has to account for the effects of poro- and thermoelasticity in the host rock. Also, the application of our concept for sedimentary rock should be targeted in future.

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REFERENCES <HEADING 1 STYLE>

Baria, R., Baumgärtner, J., Gérard, A., Garnish, J., 2000, The European HDR programme: main targets and results of the deepening of the well GPK2 to 5000 m. In: Proc. World Geothermal Congress 2000, p. 3643-3652.

Baria R., Michelet S., J.Baumgaertner, B.Dyer, A.Gerard, J.Nicholls, T.Hettkamp, D.Teza, N.Soma, H.Asanuma, J. Garnish, T.Megel, 2004, Microseismic monitoring of the world's largest potential HDR reservoir, Proc. Twenty-Ninth Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, January 26-28, 2004

Baumgärtner, J., A. Gérard, R. Baria, R. Jung, T. Tran-Viet, T. Gandy, L Aquilina, and J. Garnish, 1998, Circulating the HDR reservoir at Soultz: maintaining production and injection flow in complete balance, Proceedings of the 23rd Workshop on Geothermal reservoir Engineering, Jan 26-28, 1998, Stanford University, 11-20.

Bächler D., Evans K., Hopkirk R., Kohl T., Mégel T., Rybach L., Data Analysis and controls towards understanding reservoir behaviour and the creation of a conceptual model, Final Report to the Bundesamt für Bildung und Wissenschaft, Projekt 98.0008-1 - EU Project No. JOR3-CT98-0313, Bern, Switzerland

Kohl, T. and Hopkirk, R.J., 1995. "FRACTure" a simulation code for forced fluid flow and transport in fractured porous rock. Geothermics, 24(3): 345-359.

Willis-Richards, J., Watanabe, K. and Takahashi, H., 1996. Progress toward a stochastic rock mechanics model of engineered geothermal systems. Journal of Geophysical Research, 101(B8): 17,481-17,496.