Characterization of fluid transport properties of the Hot Dry Rock reservoir Soultz-2000 using induced microseismicity

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ABSTRACT

Hydraulic stimulation is a procedure for increasing the permeability of a reservoir. At the geothermal site of Soultz (France) such experiments have been carried out since 1993 at different depths. During the Soultz-2000 hydraulic stimulation, about 7200 seismic events were located using borehole and free surface seismic network. We analyse the spatio-temporal distribution and the density of the events to estimate the large-scale permeability of the medium. We assume that the main triggering mechanism is a pore pressure diffusion process. Based on this idea, we apply different already developed methods for the Soultz-2000 hydraulic stimulation. We obtain two independent scalar permeability estimations, a permeability tensor and a heterogeneous reconstruction of the hydraulic diffusivity. The results agree very well with independent in-situ and laboratory tests.

INTRODUCTION

In July 2000, a hydraulic stimulation was carried out at the European Hot Dry Rock (HDR) research site at Soultz (France) in order to establish a new geothermal reservoir at a depth of 4500 - 5000 m (for an overview of the project see www.soultz.net). During six days, an injection of 23,400 m^3 of brine and water was carried out to increase hydrostatic pressure in the high-fractured granite basement (Figure 1). Such a modification of the pore pressure causes a decrease of the effective normal stress along preexisting cracks. These local modifications of the stress field induce microseismicity. During the experiment, about 31,000 seismic events were recorded. About 7,200 events were located by the seismologic team of L'Ecole et Observatoire des Sciences de la Terre (Strasbourg University, France) by using a seismic network consisting of downhole and surface stations. At the end of injection time, the cumulative seismic cloud was approximately 1500 m in length, 500 m in width, and 1500 m in height (Figure 2, for details about the experiment see Baria et al., 2001). This rock mass volume is generally called HDR reservoir (Murphy et al., 1999).

An approach called Seismicity Based Reservoir Characterization (SBRC) has been suggested to provide *in-situ* estimates of permeability characterizing a reservoir on a large spatial scale (for details and other case studies see Audigane et al., 2002; Shapiro et al., 1997, 1999, 2002, 2003a, 2003b). This approach uses the monitoring of microseismicity in order to characterize hydraulic properties of a geothermal or hydrocarbon reservoir.

Shapiro et al. (1997, 2002) assume that changes of pore pressure in space and in time are controlled by pore pressure diffusion. This relaxation process is the main mechanism of induced microseismicity. Based on this idea, different methods have been developed for estimating reservoir permeability.

In this study, SBRC methods are applied to the HDR reservoir established at Soultz in July 2000. The first two methods estimate hydraulic diffusivity in a homogeneous isotropic and anisotropic medium, respectively (see Shapiro et al., 1997, 1999; Audigane et al. 2002; discussion in Cornet, 2000; and reply in Shapiro et al., 2000). Considering a heterogeneous medium, a third method is suggested to reconstruct the

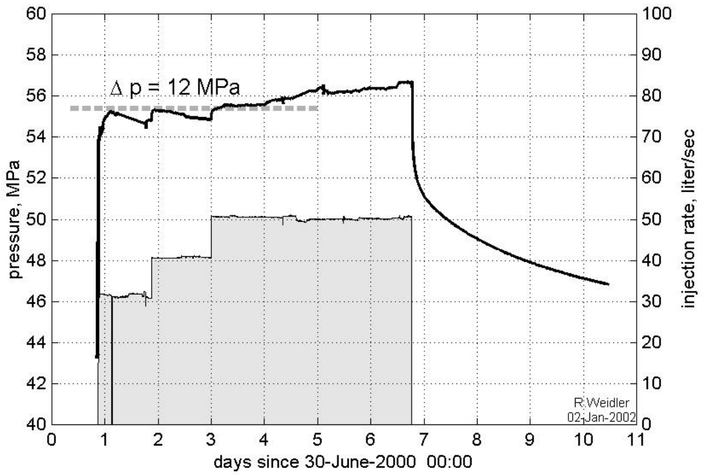

Figure 1: Downhole pressure in the open hole section of the well GPK-2 during the hydraulic stimulation Soultz-2000 after Weidler et al.(2002). During the first two injection steps, the maximum overpressure was limited to 12 MPa. During the 50 l/s step, the pressure increased to a maximum value of 13 MPa. Theses values were still far below the expected values that resulted from an extrapolation of the stress-field in the upper reservoir (3.5 km).

diffusivity distribution in space (Shapiro, 2000; Shapiro et al., 2002). Based on statistical considerations and using the density distribution of earthquakes, a fourth method is applied to provide a scalar diffusivity estimation (see Shapiro et al., 2003a; and Rentsch, 2003). The different methods complement each other and provide consistent estimations of hydraulic properties of the Soultz HDR reservoir.

DIFFUSIVITY ESTIMATES IN HOMOGENEOUS ISOTROPIC MEDIA

For a homogeneous, fractured, elastic, saturated medium, the linear dynamics of poroelastic deformation are described by the Biot equations (1962). The SBRC approach is based on the hypothesis that a pore-pressure perturbation propagates in the same manner as the low-frequency second-type compressional Biot wave. In the low-frequency limit of Biot equations, the propagation of the pore-pressure perturbation *p* can be approximated in the isotropic case by the following differential equation of diffusion (Shapiro et al., 1997):

$$\frac{\partial p}{\partial t} = D\nabla^2 p \tag{1}$$

where *D* and *t* are the diffusivity and the time respectively.
Considering a point source, Shapiro et al. (1997) approximated the time evolution of the pore pressure with a step function. According to the downhole pressure (Weidler, 2000), this approximation agrees well with observations at Soultz-2000. Then the pore-pressure perturbation can be described by the propagation of a triggering front as follows (for details about the triggering front see Shapiro et al. 2002, 2003b):

$$r = \sqrt{4\pi D t}, \tag{2}$$

where *t* is the time from the injection start, *D* is the scalar hydraulic diffusivity and *r* is the radial distance from the injection source to the hypocentre of events.
To estimate the isotropic diffusivity of the medium, we plot the minimum distance between the openhole section and the hypocentre to the source of each seismic event in a distance versus time diagram. For a correct hydraulic diffusivity value, the parabolic equation (2) corresponds to an upper bound for the majority of events in the r-t plot. According to the data (Figure 3), we suggest a value of *D* = 0.15 m^2/s as

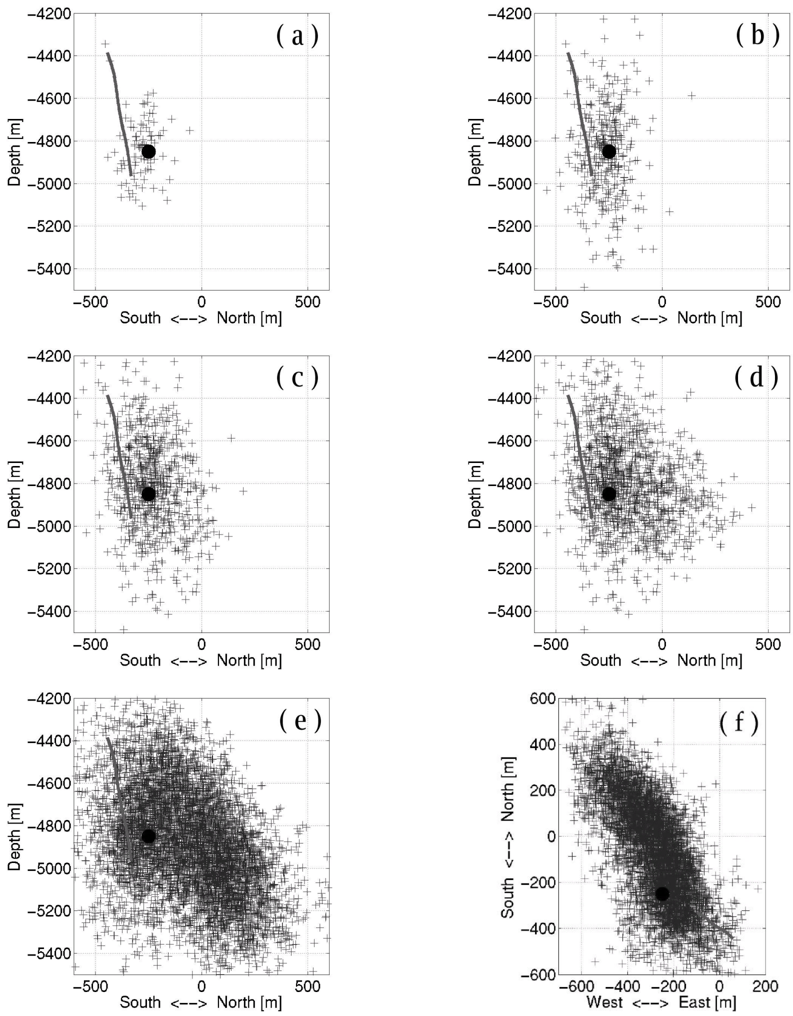

Figure 2: Evolution of the cloud of events with time during the hydraulic stimulation Soultz-2000. The line and the black dot denote the open hole section of the well GPK-2 and the point-like source. The snap shots (a),(b),(c),(d) represent the cumulative cloud of events at 3, 10, 20, 30 hours looking from the east. The snap shots (e) and (f) represent the seismic cloud at the end of the injection time (t=142.5 h) from the east and the top respectively.

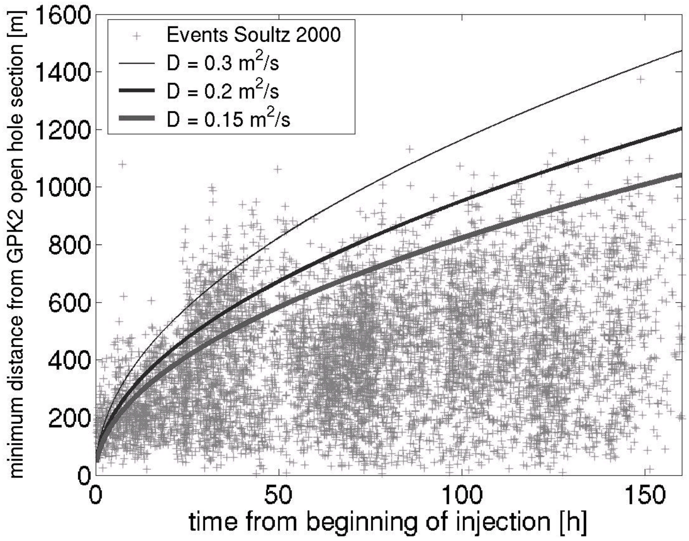

Figure 3: r-t plot of the hydraulic stimulation Soultz-2000. Possible estimations of the hydraulic diffusivity are: D=0.15 m^2/s, D=0.2 m^2/s, and D=0.3 m^2/s. The global estimation, D=0.15 m^2/s, seems to be more representative.

the most representative estimation.

DIFFUSIVITY ESTIMATES IN HOMOGENEOUS ANISOTROPIC MEDIA

Shapiro et al. (1999) assume a homogeneous anisotropic distribution of the hydraulic diffusivity, describing by tensor components in a fractured, fluid satured medium. The pore pressure is then determinated by the diffusion equation, with the following form:

$$\frac{\partial p}{\partial t} = D_{ij} \frac{\partial}{\partial x_i} \frac{\partial}{\partial x_j} p, \tag{3}$$

where D_{ij} are components of the tensor of hydraulic diffusivity.
The triggering front, equation (3), is described by (for details see Shapiro et al., 1999):

$$r = \sqrt{\frac{4\pi t}{\mathbf{n^T D^{-1} n}}}, \tag{4}$$

where $\mathbf{n^T}$ is the transposed vector of $\mathbf{n}$ = $\mathbf{r}$ / $|\vec{\mathbf{r}}|$ and $\mathbf{D}^{-1}$ is the inverse of the diffusivity tensor $\mathbf{D}$.
In the principal coordinate system, the diffusivity tensor becomes diagonal, the triggering front is described by the following equation (Shapiro et al., 2003b):

$$\frac{x_1^2}{D_{11}} + \frac{x_2^2}{D_{22}} + \frac{x_3^2}{D_{33}} = 4\pi t, \tag{5}$$

where x_i are the coordinates and D_{ii} (no summation over i) are the principal hydraulic diffusivities.
By scaling the x_i coordinates by $\sqrt{4\pi t}$, an ellipsoidal equation of the triggering front is obtained. The half axes of the ellipsoid represent the square roots of the principal diffusivity values. For determining the triggering front an ellipsoidal envelope must be defined for the majority of events in the scaled principal coordinate system (Figure 4). In order to apply the method, we approximate the openhole section with a point source in the centre of the cloud formed approximately three hours after the beginning of injection (see Figure 2; Discussion with Cornet, 2000 and Reply by Shapiro et al., 2000). This point source is close

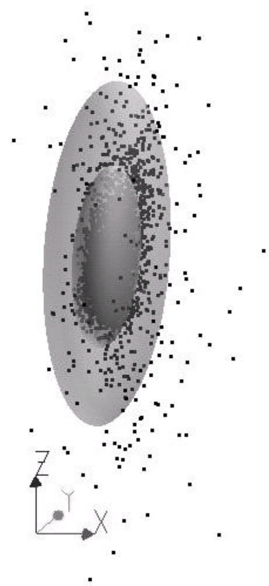

Figure 4: The ellipsoids representing different hydraulic diffusivity tensors shown together with the seismic cloud in the scaled coordinate system: $r_{si} = \frac{r_i}{\sqrt{4\pi t}}$ looking from the south.

to the middle of the part of the section where 90 % of the flow went through (Baria et al., 2001). At this depth more pore pressure perturbations have been caused in rocks. Applying the method, we determine a first fit which encloses a zone with a high-density area of events (the smallest ellipsoid, Figure 4) with the following diffusivity tensor estimation: D_{min}=diag(0.02; 0.08; 0.14) m^2/s.
Another fit is also suggested, which includes almost all the events (the largest ellipsoid, Figure 4) with the following estimation: D_{max}=diag(0.05; 0.21; 0.44) m^2/s.
The two tensors have different principal coordinate systems. However, the orientations of the principal axis are very close to each other. For the largest diffusivity component of the smallest ellipsoid, a strike and a dip of N$151°$E and $60°$ have been respectively estimated.

INVERSION FOR DIFFUSIVITY OF HETEROGENEOUS MEDIA

The method developed by Shapiro et al. (2000, 2002) is an inversion procedure to reconstruct the spatial distribution of the hydraulic diffusivity considering a heterogeneous medium. As in the previous section, we consider a step-function like pressure perturbation with the same point source.
In this case, the diffusive process and the evolution of the triggering front are described by the eikonal equation (for details see Shapiro et al., 2002, 2003a):

$$D = \frac{t}{\pi|\nabla t|^2}. \tag{6}$$

The equation (6) is used in the inversion procedure to reconstruct the hydraulic diffusivity distribution in space (Figure 5).

DIFFUSIVITY ESTIMATES USING DENSITY OF INDUCED MICROSEISMICITY

Another interpretation of microseismicity using the density distribution of earthquakes is suggested by Shapiro et al. (2003b). A point source of a fluid injection is considered in an infinite porous medium. The

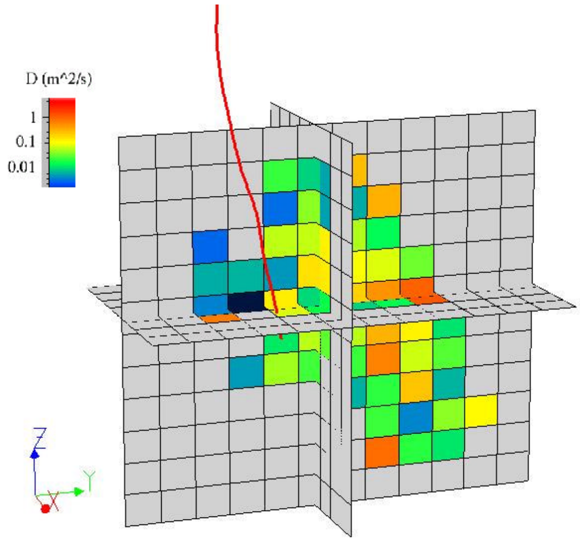

Figure 5: Hydraulic diffusivity reconstruction in three dimensions for the Soultz 2000 data set looking from the south-east. The X and Y coordinates represent strikes of N70°E, N340°E, respectively. The diffusivity is given on a logarithmic scale. It varies between 0.001 and 1 m^2/s. A cell has the following spatial dimension dx=110 m, dy=130 m, dz=120 m. The well GPK-2 is also represented in red.

probability that an earthquake occurs at a given time *t* and point *r* will be equal to:

$$\Pi(p_c(\mathbf{r}) \leq p(t,\mathbf{r})) = \int_0^{p(t,\mathbf{r})} f(p_c)dp_c, \tag{7}$$

where p_c***(r)*** is the critical pressure due to injection, ***p(t,r)*** is the pore pressure, and *f(*p_c*)* is the probability density function of the critical pressure.

The pore pressure ***p(t,r)*** is a solution of the diffusive equation describing the process of the pore pressure relaxation. An even distribution of the critical pore pressure is considered in an isotropic medium. The hydraulic diffusivity of a medium is usually anisotropic. To apply the method we have to transform the cloud obtained under conditions of a pore pressure in an anisotropic medium into the equivalent cloud, which would be obtained in an isotropic medium. For this, using the principal coordinate system of the section "Diffusivity estimates in homogeneous anisotropic media", the original cloud is scaled by the inverse square roots of the principal components of the hydraulic diffusivity tensor. In the scaled principal coordinate system, spherical shells centred on the source point with a radius proportional to r=120 m have been taken. In each shell, the number of events has been counted. A plot is produced with the normalized number of events versus distance (Figure 6). This plot must be fitted by the following equation (for details see Shapiro et al., 2003b; Rentsch, 2003):

$$p(r,t,D) = \frac{q}{4\pi Dr} erfc(\frac{r}{\sqrt{4Dt}}). \tag{8}$$

where *q* is the pore pressure perturbation, *erfc(x)* is the complimentary Gaussian error function and *t* is the duration of the injection.
A scalar diffusivity estimation of *D*=0.14 m^2/s is obtained.

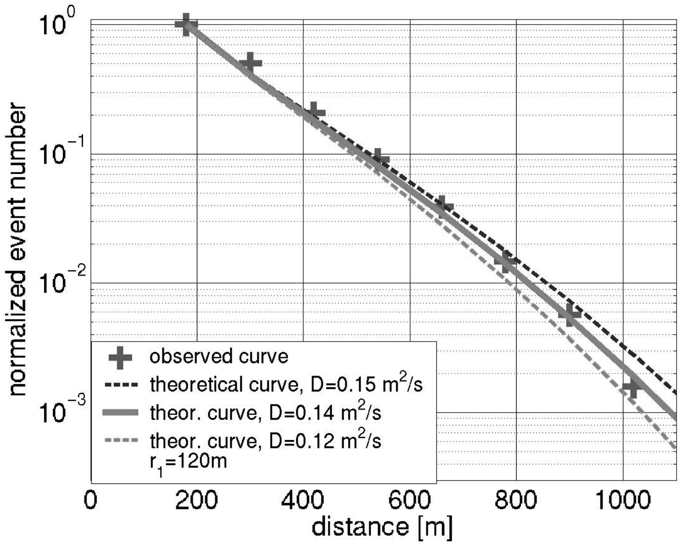

Figure 6: Spatial density of the microseismic cloud versus distance from the injection source for the microearthquakes induced during the hydraulic stimulation Soultz-2000. The best fit estimate of the hydraulic diffusivity is D=0.14 m^2/s. The two dashed curves (D=0.12 m^2/s and D=0.15 m^2/s) illustrate the accuracy of the method.

ESTIMATING PERMEABILITY FROM DIFFUSIVITY

The relationship between the hydraulic diffusivity tensor can be related to the permeability tensor according to the following equation (Shapiro et al., 2002):

$$\mathbf{D} = \frac{\mathrm{N}\mathbf{K}}{\eta}, \tag{9}$$

where **K** is the permeability tensor, η the pore-fluid dynamic viscosity and N is the poroelastic modulus. N can be approximated for the case of low-porosity crystalline rocks as follow:

$$\mathrm{N} = [\frac{\phi}{K_f} + \frac{\alpha}{K_g}]^{-1}, \tag{10}$$

with $\alpha = 1 - K_d/K_g$, ϕ the porosity and K_d, K_g and K_f the bulk moduli of the dry frame, the grain material and the fluid, respectively.
For the Soultz-2000 experiment, accepting the following estimates found in the literature for the cristallyne rocks at the depth of 5000 m: ϕ=0.003, η=2×10^{-4} Pa.s (an approximate value of the dynamic viscosity of salt water, Haar et al. 1984), K_d=49 GPa, K_g=75 GPa and K_f=2.2 GPa; we obtain N $\simeq$ 1.68×10^{11} Pa. Using equation (10), scalar permeability estimates of the methods using the spatio-temporal distribution and the event density are 18×10^{-17} m^2 and 17×10^{-17} m^2 respectively. In the anisotropic case, the two diffusivity tensor estimations (Section 3) correspond to the two following permeability tensors:
$K_{min} = diag(2.3; 5; 16.7) \times 10^{-17} m^2$,
and $K_{max} = diag(6.0; 25.0; 52.4) \times 10^{-17} m^2$.

DISCUSSION

We have applied four different methods based on the SBRC approach for estimating the permeability of the Soultz-2000 reservoir. Although the injection was not performed by a point source, we make such an approximation for three methods. The defined injection point is located as the centre of the cloud triggered by the first three hours (located approximately 100 m off the openhole section, Figure 2). Although the different methods are based on different signatures of the microseismicity, we obtain consistent results.

Diffusivity estimation in the isotropic case

Between 20 hours and 30 hours, Figure 3 shows a fast increase of the hypocenter distance of more than 400 m appears 24 hours after the start of stimulation. The corresponding events represent a step on the r-t plot above the parabola (D = 0.15 m^2/s, Figure 3). These events are located NNW from the well GPK-2 and are responsible of a horizontal extension of the cloud (Figure 2). This direction of extension is parallel to the maximum horizontal stress component in this part of the Rhine graben (Helm, 1996; Cuenot et al., 2003). These events appear shortly after the increase of the downhole overpressure from 12 to 13 MPa (second step of stimulation in Figure 1). It is possible that between 24 hours and 48 hours of the injection time, the events which have a hypocentre distance of more than 400 m are due to this increase of downhole pressure. According to the sudden increase of the hypocentral distance, we can also expect that the zone reached by the triggering front corresponds to a zone with higher diffusivity.
During the first 24 hours, in the r-t plot (Figure 3) events are partly triggered above the parabolic envelope. Nine hours before the beginning of the hydraulic stimulation, five pulse tests were carried out in the well GPK-2 (Figure 1). A first explanation is that the five pulse tests initiated a diffusive process. We can also expect a higher diffusivity zone near the openhole section established during hydraulic tests, like the low rate injection test in February 2000 (Baria, 2001).

Diffusivity estimation in the anisotropic case

In the anisotropic case, the maximal principal component of the minimum diffusivity tensor estimation is D=0.14 m^2/s. From the definition of the method, it results that the maximum diffusivity component should agree with the scalar estimation. This is in agreement with a scalar diffusivity estimation of D=0.15 m^2/s. The orientations of the two tensors are very closed to each other. The strike of the largest component of the permeability tensor (N$151°$E) coincides with the horizontal maximum stress orientation in the medium: N$160°$E (Helm, 1996; Cuenot et al., 2003). The analysis of cores shows that the orientation of cracks coincide with the maximum stress component (see results of logs in the well GPK-2 rose diagrams in Baria et al., 2001). The minimum and maximum estimations can be interpreted as the natural diffusivity of the medium and the diffusivity of the established reservoir, respectively. The last conclusion is due to the fact that events corresponding to the larger ellipsoid are located in the vicinity of the borehole and occurred during short time after the start of injection.

Diffusivity reconstruction in a heterogeneous medium

Strong variations of the diffusivity value in the reservoir (Figure 5) have been found by the eikonal-equation based inversion algorithm. A high diffusivity zone (D=0.1 - 1 m^2/s) in NNW appears over a quite homogeneous and low-diffusivity background (D $\leq$ 0.01 m^2/s). This agrees with Figure 2, which shows a number of early events (between t=20 h and t=30 h) also in NNW. Shapiro et al. (2002) already applied the method to the Soultz-1993 seismic cloud. They performed numerical tests to estimate the accuracy of the method (Rothert et al., 2003). The method gives at least semi-quantitatively diffusivity values to characterize the reservoir.

Comparaisons with independent results and with the Soultz-1993 stimulation

Hettkamp et al. (1998) estimate a permeability value of approximately 37×10^{-17} m^2 in the fracture direction for a granite sample with a 12 MPa fluid overpressure. Before the stimulation on the Soultz site, two slug tests have been conducted in the well GPK2 at a depth of 4500-5000 m (Weidler, 1999). For the

640 m openhole, the apparent permeability value determinated is about 5-13$\times 10^{-17}$ m^2. These independently estimated values agree with our results (2-17$\times 10^{-17}$ m^2).
Comparing to the 1993 experiment, our different diffusivity estimations for Soultz-2000 give three times higher values. In the anisotropic approximation, the direction of the Soultz-2000 maximal diffusivity component have approximately the same strike and dip values (N$151°$E, 2000 - N$171°$E, 1993 and $60°$, 2000 - $72°$, 1993 respectively).

CONCLUSION

We applied the SBRC approach which uses the induced microseismicity measured during the hydraulic stimulation at Soultz in 2000 to estimate the permeability of the crystalline medium.
The SBRC approach considers the microseismicity as signature of a pore pressure relaxation process. We estimated diffusivity values in a scalar approximation and a permeability tensor. The both estimates agree very well with independent experiements (slug tests and laboratory measurements).
In comparison to the Soultz-1993 stimulation at a depth of 2900-3500 m, we obtain 3 times higher permeability values with the same method.
A method of reconstructing the diffusivity distribution in 3-D has been also applied. The result images an high permeable zone.

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