Fluid induced seismicity guided by a continental fault: Injection experiment of 2004/2005 at the German Deep Drilling Site (KTB)

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[1] Recent hydraulic experiments at the KTB site have shown that seismicity induced by long-term fluid injection directly into a continental crustal fault remains guided by this fault. The seismicity is triggered by pressure perturbations as low as 0.01–1 bars at the hypocenters. A combination of sequential one-year fluid extraction (2002/2003) and one-year fluid injection (2004/2005) experiments has shown that only positive pore pressure perturbation (i.e., injections) was able to induce the seismicity. Moreover, the onset of seismicity roughly coincides with the time of compensation of the extracted fluid volume by the following injection. This confirms that the pressure diffusion is a dominant mechanism of seismicity triggering by fluid injections. The probed fault shows a significant anisotropy and non-linearity of its hydraulic behaviour. Its hydraulic diffusivity is up to one order of magnitude larger than that of surrounding rocks.
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1. Introduction

[2] A paradigm that fluids can cause seismicity is very well known and broadly discussed. Recently, efforts have been undertaken to quantify signatures of such a relationship [see *Shapiro et al.*, 1997, 2002]. For this aim, both, observations of natural earthquakes as well as experiments designed to trigger artificial seismicity are of importance. Two fluid injection experiments inducing microseismicity were conducted at the German Continental Deep Drilling Site (KTB) in 1994 and 2000 [*Zoback and Harjes*, 1997; *Baisch et al.*, 2002]. A long-term hydraulic experiment mainly designed for studying induced seismicity at a continental fault system at the KTB site was conducted in 2002–2005.

[3] The phenomenon of microseismicity triggered by fluid injections in boreholes is related to the energy transport process of pore pressure diffusion. The tectonic stress in the earth crust at some locations is close to a critical stress necessary for a brittle failure of rocks. Increasing fluid pressure in the pore and fracture space leads to an increase of the pore pressure at the critical locations also. Such an increase in the pore pressure causes a decrease of the effective normal stress and leads to sliding along preexisting subcritical cracks. Fluid induced seismicity typically shows several diffusion related features of the geometry of clouds of micro earthquake hypocenters, of the rate of spatial growth of these clouds and of their spatial density.

[4] The German KTB site is located in SE Germany near the western margin of the Bohemian Massif at the contact zone of the Saxo-Thuringian and the Moldanubian [*Wagner et al.*, 1997]. Between 1987 and 1994 two boreholes were drilled within a crustal segment mainly composed of metabasites and gneisses. The pilot hole reached a depth of 4 km whereas the main hole penetrated down to 9.1 km. In order to investigate fluid transport processes at the KTB and to study crustal stresses, a short-term fluid injection experiment was carried out in 1994 [*Zoback and Harjes*, 1997]. In 2000, a longer-term fluid-injection experiment of several months was performed [*Baisch et al.*, 2002].

[5] Features of particular interest of the new research program starting in 2002 are two dominant fault systems encountered at 7.2 and 4.0 km depths, hereafter called SE1 and SE2, respectively [see *Hirschmann*, 1994] (Figure 1). The first major experiment was a one-year fluid production test in the KTB pilot hole (June 2002–June 2003). A total volume of 22,300 m^3 of saline crustal fluids were produced from the open hole section (3850 m–4000 m, approx. 120°C). Final draw down was 605 m below surface - at fluid yield of 58 l/min. The KTB main hole was equipped with a seismometer installed at 4000 m depth and two water level sensors. Fluid level in the main hole - at 200 m distance from the pilot hole - steadily fell from zero to 50 m below surface, indicating (as already pointed out by *Baisch and Harjes* [2003]) some hydraulic connection between the pilot and the main hole. During the fluid production phase of the experiment induced seismicity was absent. Hydraulic permeability was estimated to be around 2×10^{-15} m^2 [*Stober and Bucher*, 2005; *Gräsle et al.*, 2006].

[6] After 12 months of hydraulic recovery, we have started a fluid injection test in the pilot hole (June 2004). Over ten months, 84,600 m^3 of water were injected into the open hole section at 4 km depth of the pilot hole, where the SE2 reflector intersects the borehole. Injection rate was 200 l/min on average, at about 100 bar well head injection pressure. The fluid level in the main hole clearly responded to the injection in the pilot hole. In October 2004, the main hole became artesian and produced some 1 m^3 of water per day. Significant induced seismicity started in September 2004 and increased slowly. In this paper, we describe the

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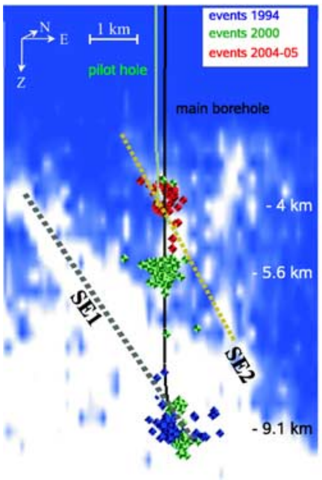

Figure 1. Depth migrated image ISO89-3D. The seismic reflection intensities are shown in blue-white colour on one vertical slice. Light colours correspond to large reflection intensities and darker colours to lower ones, respectively. The SE1 reflector is clearly visible as a steeply dipping event. Additionally, seismicity induced by injection experiments of years 1994 (blue), 2000 (green) and 2004/2005 (red) is shown. Also seen are locations of the main (black line) and pilot (green line) boreholes.

main features of this seismicity and interpret them in relation to hydraulic parameters of the injection.

2. Morphology of Induced Seismicity and Its Correlation to Seismic Reflectivity

[7] During the injection experiment about 3000 microseismic events were detected by the borehole sonde and about 140 events were localised using borehole sonde and surface station recordings. Horizontal projections of the events localised compose a NW-SE elongated zone. This zone is nearly parallel to the Franconian Lineament (referred to as FL in the following; see Figures 1 and 2).

[8] Before and during the drilling phase at the KTB site, intensive seismic studies were carried out. From a 2D seismic survey (KTB8502), a sharp northeast-dipping seismic reflector (SE1) was identified in seismic profiles [*Simon et al.*, 1996; *Harjes et al.*, 1997; *Buske*, 1999]. This reflector is regarded as the continuation of the FL through the upper crust. A pre-stack Kirchhoff depth migration of the KTB8502 profile as well as of a 3D seismic reflection survey (ISO89-3D) was presented by *Buske* [1999]. During this experiment, an area of about 21 km $\times$ 21 km with the main borehole located at the centre was investigated. Figure 1 shows the relevant parts of this data set after migration. Above the SE1 reflector and quasi parallel to it a slightly reflecting linear structure intersecting the boreholes approximately at the depth of 4 km can be also seen. This is the SE2 reflector. The induced seismicity of the 2004/2005 injection experiment is directly related to this reflector. This is even more evident in Figure 2 where a horizontal slice of the reflectivity at the depth of 4 km is shown. Considering Figures 1 and 2 we can conclude that the seismicity seems to be guided by the SE2 fault structure. A possible explanation is that the SE2 fault system is characterised by an enhanced permeability due to fracturing. Such a permeability is anisotropic. Pore pressure fluctuations due to the fluid injection propagate then mainly along the direction of the largest principal component of the permeability tensor. This component is directed along the fractures, i.e., along this fault. This portends to the phenomenon of guided induced seismicity. Moreover, Figures 1 and 2 indicate that the permeability along the SE2 fault into horizontal (strike) direction is larger than the permeability along its up-dip direction. This is possibly related to the geometry of fractures composing the SE2 fault system. *Bohnhoff et al.* [2004] discussed the relation of induced seismicity and major fault zones at the KTB based on data of the year 2000 experiment. They state that major fault zones act as pathways for the injected fluid but that seismic events occur on smaller nearby faults which are in correspondence with the present stress field. Our observations confirm that the major fault zones act as pathways for the migration of crustal fluids. However, we find seismicity also to be concentrated within the major fault zone SE2. Thus, we conclude that major fault zones can also be seismically active.

[9] *Rothert and Shapiro* [2003] have shown that at the KTB site the larger reflectivity zones tend to have larger hydraulic permeability. Figures 1 and 2 show that the SE1 zone is characterised by much larger reflectivity than the SE2 one. Thus, we expect that the SE2 fault system is less permeable than the SE1 one, but still more permeable than the surrounding rocks.

3. Microseismicity and Hydraulic Parameters

[10] One of the important observations of the 2002–2005 KTB hydraulic experiments was the absence of seismicity during the phase of fluid extraction. Moreover, the induced seismicity started during the injection phase approximately at the time when the fluid volume extracted during the previous phase of the experiment had been injected. It was approximately 110 days after the start of the injection (see Figure 3).

[11] An approach to estimate the hydraulic diffusivity of rocks using microseismicity (Seismicity Based Reservoir Characterisation, SBRC) uses a spatio-temporal analysis of the cloud of fluid-injection induced events [see, e.g.,

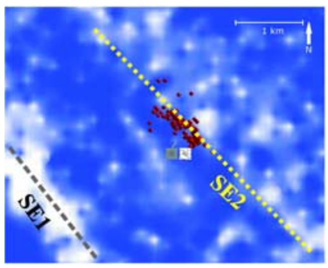

Figure 2. A 4 km depth horizontal slice over the depth migrated image ISO89-3D plotted along with the projections of seismic hypocenters induced by the injection experiment of 2004/2005 to this slice. The white and gray squares are locations of the main and pilot boreholes, respectively.

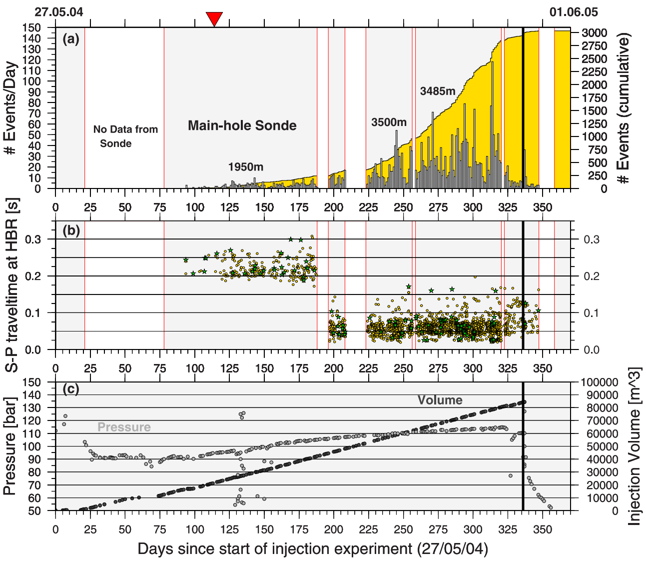

Figure 3. (a) Microseismicity during the 2004/2005 injection experiment as recorded by the surface stations. (b) Changes in the locations of the bore hole geophone are clearly seen from the plot of differences of the S- and P-waves arrival times. (c) The injection pressure along with the cumulative volume of the injected water. The time when the amount of previously extracted fluid was re-injected is marked in Figure 3a (red inverse triangle on the top).

Shapiro et al., 2002]. This approach has already been applied to the KTB site several times [see *Shapiro et al.*, 1997; *Rothert and Shapiro*, 2003]. Its simplest version uses an equation describing the spatial position r of the so-called triggering front in an effective isotropic homogeneous poroelastic medium with the scalar hydraulic diffusivity D at time t:

$$r = \sqrt{4\pi D t}. \tag{1}$$

This front is regarded as a spatial surface which approximately separates the regions of the relaxed and unrelaxed pore pressure. The distance of each single microseismic event r_i is plotted versus its occurrence time t_i. Fitting the cloud of events by a parabolic envelope (1) provides the effective scalar estimates of the hydraulic diffusivity.

[12] The data of the 1994 injection experiment provided estimates of the hydraulic diffusivity strongly influenced by the SE1 fault system. They were of the order of 0.3 to 2 m^2/s. The injection experiment of 2000 provided estimates of only 0.05 m^2/s to 0.2 m^2/s from more or less the same spatial zone in the depth of 9 km. Additionally, this injection experiment provided significantly smaller estimates of the order of 0.004 m^2/s to 0.01 m^2/s of the diffusivity for the depth interval of 5.4 km. This depth interval is also characterised by a low seismic reflectivity.

[13] We apply the SBRC approach also to the data set of the 2004/2005 injection experiment (see Figure 4). Because the injection started after a long fluid extraction phase, followed by a passive recovery phase, there are evident problems with a direct application of this approach. Indeed, the standard SBRC formulation requires an injection experiment without any preliminary fluid extraction; that is, the excess pore pressure build-up must start at time zero. Applying the envelope (1) fitting (red solid line) without taking into account the fluid extraction and recovery phase leads to underestimating hydraulic diffusivity. Analytical estimations of the pore pressure perturbation caused by the fluid extraction-injection signal of 2002–2005 experiment show, that the corresponding estimate of the diffusivity can be two to four times smaller than those one of an equivalent homogeneous isotropic porous medium approximating the real KTB rock. Another way for roughly estimating the hydraulic diffusivity is to use the onset of significant seismicity as time zero. This corresponds approximately to the time when the water volume extracted in the previous experimental phase was compensated by the injection. The obtained estimates of the hydraulic diffusivity are of the order of 0.01–0.02 m^2/s. It is higher then the diffusivity at the depth of 5.4km. This is also in good agreement with the slightly enhanced seismic reflectivity of the SE2 fault system in respect to the surrounding rocks.

4. Critical Pressure and Seismic Productivity

[14] The absence of seismicity during the fluid extraction phase clearly shows that a positive pore pressure perturbation is required for triggering microseismicity. Moreover, an approximate compensation for the induced pore pressure deficit was required for making the medium seismically active. The fact that most of the microseismic events occurred several hundred meters away from the injection borehole (Figures 1 and 2), and that the water level in the main hole at the start of seismic activity had increased by a few tenth of meters indicates that pressure perturbations less than a few bars at hypocenters are required to trigger seismic events at the KTB site. Computing the pore pressure perturbations at the hypocenters using the diffusion equa-

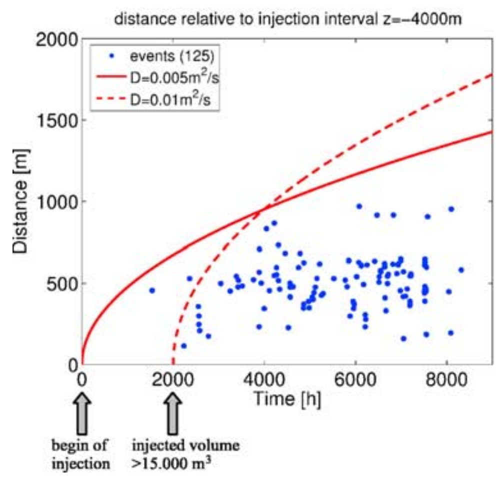

Figure 4. Estimates of the triggering front for microseismicity of 2004/2005 injection experiment. For comparison two curves of triggering front are fitted. One, assuming that the origin time coincides with the start of the injection. Another one, assuming that the origin time coincides with the time of compensation of the water volume extracted by the previous hydraulic experiment.

tion and the diffusivity estimates found above yields values of the order of 0.01 – 1 bars also. Furthermore, *Gräsle et al.* [2006] found pore pressure perturbations in this order of magnitude by numerical simulations of hydraulic observations at the KTB. Such small perturbations of pore pressure leading to brittle failure was already reported by *Zoback and Harjes* [1997].

[15] A product of the injected volume V and the average injection pressure P gives approximately the total fluid-injection energy: $E_{inj} = PV$. The energy of seismicity is usually several orders of magnitude lower [see, e.g., *Baisch and Harjes*, 2003]. A ratio of the induced events cumulative number N to the energy E_{inj} provides us with a measure of seismic productivity of the fluid injection: $I_s = N/E_{inj}$. Clearly, it is not an optimal characteristic because it is influenced by such factors as the hydraulic diffusivity of rocks, injection geometry, etc.. Still, for the KTB site it can be used as an indicator of real seismic productivity of rocks. Indeed, the KTB injection experiment of 2004/2005 was conducted for a rather long time and a much larger volume was injected (even if we count from the moment of the compensation of the extracted fluid volume) than during the short term experiments of 1994 and 2000. Still, the medium responded by lower seismic activity in comparison to the experiment of 1994 (several tenths events a day in contrast to several hundreds events a day, respectively). Also the experiment of 2000 was characterised by a somewhat larger average activity. The quantity I_s is equal to $7 \times 10^{-6}\ J^{-1}$, $2 \times 10^{-8}\ J^{-1}$ and to $5 \times 10^{-9}\ J^{-1}$ in the experiments of 1994, 2000 and 2004/2005, respectively. This indicates a low seismic productivity in the case of the last injection experiment.

[16] One possible explanation here could be that the stabilising influence of the fluid extraction from the first phase of the experiment had not yet been completely compensated by the injection. However, taking into account that the injected water volume was almost four times larger than the extracted one, another explanation appears to be more probable. Possibly this means that due to permanent natural pore pressure perturbations (e.g., of seasonal character or due to tectonic forcing) more critical pre-existing cracks (i.e., cracks requiring small increases of pore pressure for slipping) have already been largely triggered or are being permanently triggered during the fault life.

5. Conclusion

[17] The influence of the orientations of pre-existing natural fracture systems on the triggering of microseismicity is obvious. Recent (2002 – 2005) hydraulic experiments at the KTB indicated several unique features of microseismicity related to properties of the seismic SE2 reflector. Firstly, it seems that this fault is seismically more stable than rock volumes stimulated during previous (1994 and 2000) injections. It produces less seismicity for the same order of averaged injection pressure and much larger injection fluid volume. Still the seismicity has been triggered by surprisingly weak pore pressure perturbations, i.e., as low as 0.01 – 1 bars if estimated at hypocenters. The seismic reflectivity is positively correlated with the hydraulic permeability. The SE2 reflector is characterised by permeability up to one order of magnitude higher than that of surrounding rocks. For pressure perturbations in the order of tens of bars, this fault has non-linear hydraulic properties (permeability increasing with pore pressure, according to flow-pressure data of the last production and injection experiments). Possibly, these features are common for major continental fault systems. These findings motivate hydraulic injection experiments at the SE1 reflector, which is characterised by a much larger seismic reflectivity.

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