Seismicity Based Reservoir Characterization Case Study: Correlation of Microseismicity with Reflectivity at the KTB

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ABSTRACT

An approach for the interpretation of microseismic data was proposed to provide in-situ estimates of the hydraulic diffusivity characterizing a geothermal or hydrocarbon reservoir on the large spatial scale (on the order of $10^3 m$). This approach is called "Seismicity Based Reservoir Characterization" (SBRC, Shapiro et al. (1997-2002)). The SBRC is based on the hypothesis that the spatial propagation of hydraulically induced seismicity is caused mainly by the pore pressure relaxation process. According to this hypothesis the SBRC uses a spatio-temporal analysis of fluid-injection induced microseismicity to reconstruct the tensor of hydraulic diffusivity and to estimate the tensor of permeability in 3D. However, processes that can lead to triggering of microseismicity are not yet fully understood. A correlation of microseismic hypocenters with structural images obtained from reflection seismics can help to better understand the physics of microseismicity triggering and thus to test the main assumption of the SBRC.

The SBRC approach was successfully applied to real data several times. Recently, fluid injection induced microseismicity at the KTB site was analysed in terms of the SBRC method to reconstruct the tensor of permeability at the open hole section at 9.1 km depth. Using new data sets acquired in 2000 we are able to observe indications of the depth-dependency of hydraulic diffusivity at the KTB for the first time. The analysis of fluid-induced microseismicity leads to an estimation of the hydraulic diffusivity at the KTB at different depths. A lower value of hydraulic diffusivity was found in upper parts of the subsurface compared with the values at the open-hole section. Correlations with structural images were obtained. For example, we observe that rock volumes characterized by larger diffusivity also show larger reflectivity.

INTRODUCTION

The attention to microseismic monitoring during operation of geothermal or hydrocarbon reservoirs has grown considerably over the last several years. The observation of microseismicity occurring during borehole fluid injections or extractions has a large potential in characterizing rocks in terms of their hydraulic parameters at locations up to several kilometers from boreholes (Talwani and Acree (1985); Adushkin et al. (2000); Fehler et al. (2001)). The most common application has been hydraulic fracture imaging and growth characterization (e.g. Phillips et al., 1997; Urbancic et al., 1999). Longer-term microseismic monitoring has been used to map oil-producing, natural fractures (e.g., Rutledge et al., 1998) and also shows promise in tracking flood fronts in the case of enhanced oil recovery (e.g., Maxwell et al.,1998). Beyond delineating conductive fracture geometry and inferring fluid-flow paths, microseismic data could potentially be used to measure in-situ hydraulic properties of rocks at interwell scales, providing information that could further guide operations to optimize field production.

Recently, an approach for the interpretation of microseismic data was proposed to provide in-situ estimates of the hydraulic diffusivity characterizing a geothermal or hydrocarbon reservoir on the large spatial scale (of the order of 10^3m). This approach is called “Seismicity Based Reservoir Characterization“ (SBRC). It uses a spatio-temporal analysis of fluid-injection induced microseismicity to reconstruct the tensor of hydraulic diffusivity and to estimate the tensor of permeability (see Shapiro et al., 1997, 1999, 2000, 2002 and the discussion of the method in Cornet 2000). The approach assumes the following main hypothesis: Fluid injection in a borehole causes perturbations of the pore pressure in rocks. Such perturbations cause a change of the effective stress, which, if large enough, can trigger earthquakes along pre-existing zones of weakness. The SBRC approach considers that most of the seismicity is triggered along critically stressed, pre-existing fractures.

Furthermore, it assumes that the spatio-temporal evolution of the hydraulically-induced microseismicity is completely defined by the diffusion-like process of pore-pressure relaxation. The analysis of spatio-temporal features of the microseismicity then provides a possibility to invert for hydraulic diffusivity distributions in fluid-saturated rocks. The approach was successfully applied to real data several times (Shapiro et al. (2000); Rothert et al. (2001); Shapiro et al. (2002); Audigane et al. (2002)) and numerically verified (Rothert and Shapiro (2002a,b)).

In this paper, we present a case study from the German continental deep drilling site (KTB) where microseismic events were induced by fluid injection within various depth ranges. This enables us to analyse the depth-dependency of hydraulic parameters at one location for the first time. The results obtained are correlated with structural images. Spatio-temporal features of the evolution of microseismic clouds as well as the differences in the estimations of depth-dependent hydraulic diffusivity are quite well supported by reflection seismic results.

A SUMMARY OF THE CONCEPT OF SBRC

In the low-frequency limit of the Biot equations of poroelasticity (Biot 1962) the pore-pressure perturbation p can be approximately described by the following differential equation of diffusion:

$$\frac{\partial p}{\partial t} = \frac{\partial}{\partial x_i}\left[D_{ij}\frac{\partial}{\partial x_j}p\right]. \tag{1}$$

Here, D_{ij} are the components of the tensor of hydraulic diffusivity, x_j ($j = 1, 2, 3$) are the components of the radius vector from the injection point to an observation point and t is the time. Equation (1) corresponds to the second-type Biot wave (the slow P-wave) in the limit of the frequency being extremely low in comparison with the global-flow critical frequency (Biot 1962). The tensor of hydraulic diffusivity is directly proportional to the tensor of permeability (see Shapiro et al., 2002).

Considering the power spectrum of a step function injection signal, which can roughly approximate a real pore pressure perturbation, Shapiro et al. (1997) and Shapiro et al. (2000) introduced a heuristic concept of the *microseismic triggering front*. This front is regarded as a spatial surface which separates the regions of the relaxed and unrelaxed pore pressure perturbation. For example, in the case of a homogeneous and isotropic medium, Shapiro et al. (1997) obtained the following equation describing the spatial position of the triggering front in an effective isotropic homogeneous poroelastic medium with the scalar hydraulic diffusivity D:

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

Equation (2) is able to provide scalar, homogeneous estimates of the hydraulic diffusivity only. It does not provide orientations of the tensor. In order to obtain these orientations, an alternative method was proposed by Rindschwentner (2001). The transition to a new coordinate system by scaling the original data points by

$$x_{si} = \frac{x_j}{\sqrt{4\pi t}} \tag{3}$$

yields the triggering front as an equation of an ellipsoid:

$$\frac{x_{s1}^2}{D_{11}} + \frac{x_{s2}^2}{D_{22}} + \frac{x_{s3}^2}{D_{33}} = 1. \tag{4}$$

In order to determine the triggering front one needs to find an envelope ellipsoid for the majority of events. The main axes of such an ellipsoid are directly proportional to the square roots of hydraulic diffusivity. Details of the method can be found in Rindschwentner (2001).

For the case of heterogeneously distributed D and a step-function pressure perturbation, an eikonal-like equation has been derived which describes the triggering time $t(\mathbf{r})$ (see Shapiro et al., 2002) :

$$|\nabla t|^2 = \frac{t}{\pi D}. \tag{5}$$

This equation was derived using an approximation based on geometrical optics, which is a heuristic treatment of the diffusion equation with a heterogeneous diffusion coefficient. Equation (5) serves as a basis for the inversion procedure to reconstruct spatial distributions of the hydraulic diffusivity in heterogeneous media.

Because both equations (2) and (5) were derived in a quasi-heuristical way, a quantitative approach is required to verify the inversion algorithms based on them. A possible way of verification is to apply the inversion algorithm to numerically simulated microseismic data. For this approach a numerical simulation of microseismicity during borehole fluid injections is required. We developed numerical procedures to simulate the triggering of microseismicity due to borehole fluid injections. For details we refer to Rothert and Shapiro (2001) and Rothert and Shapiro (2002b).

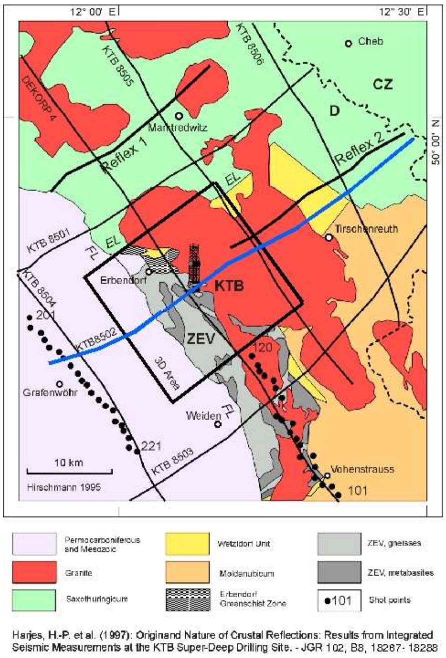
CASE STUDY: GERMAN KTB SITE

The KTB is located in SE Germany at the contact zone of the Saxothuringian and the Moldanubian. The area encompasses parts of these units of the Variscan fold belt. A NW-SE trending system of reverse faults, the Frankonian Lineament, separates this fold belt from up to 3 km thick Permo-Mesozoic foreland sediments. The KTB project was designed to study the properties and processes of the deeper continental crust by means of a superdeep borehole (Emmermann and Lauterjung (1997)). The two main areas of interest were the investigation of the crustal stress field and the brittle-ductile transition zone as well as crustal fluids and transport processes. The drill site itself lies within the zone of Erbendorf-Vohenstrauss, a smaller crustal segment, mainly composed of metabasites and gneisses (Pechnig et al. (1997)).

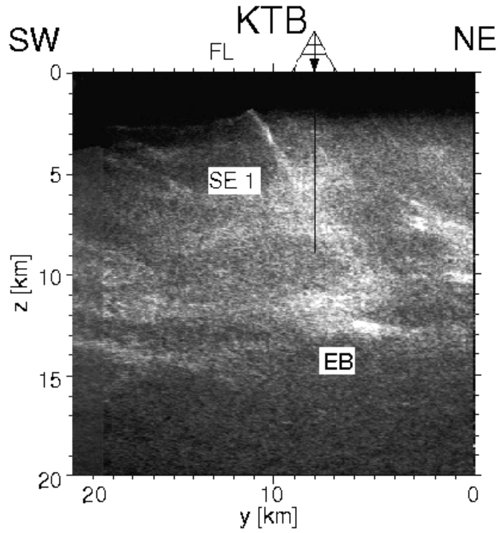
Until 1994, two boreholes were drilled at the KTB site. The main borehole has reached a final depth of 9101m and temperatures of about 270° C. Two prominent seismic reflectors (SE1 and SE2) were drilled at approx. 4000m and 7000m depth by the main borehole. The SE1 reflector was met at approximately 3500m depth by the pilot hole, which reached a final depth of 4100m and is located 185m NE of the main hole. For details of the drilling site see Harjes et al. (1997).

3D reflectivity

During the pre-drilling phase, intensive seismic reflection surveys were carried out in the vicinity of the KTB region (Fig. 1(a)). From 2-D surveys which were orientated perpendicular to the strike of the Franconian Lineament (FL), images of relatively sharp northeast-dipping seismic reflectors were obtained. The FL continues through the whole upper crust as the so-called SE1 reflector. In Figure 1(b) a part of the 2-D pre-stack migration of the profile KTB8502 is shown (Buske (1999b)). From this image, the dip angle of the SE1 reflector can be estimated to about 55°.



(a) Map of the german KTB region with main geological units and seismic surveys carried out during the pre-drilling phase. Picture taken from Harjes et al. (1997).



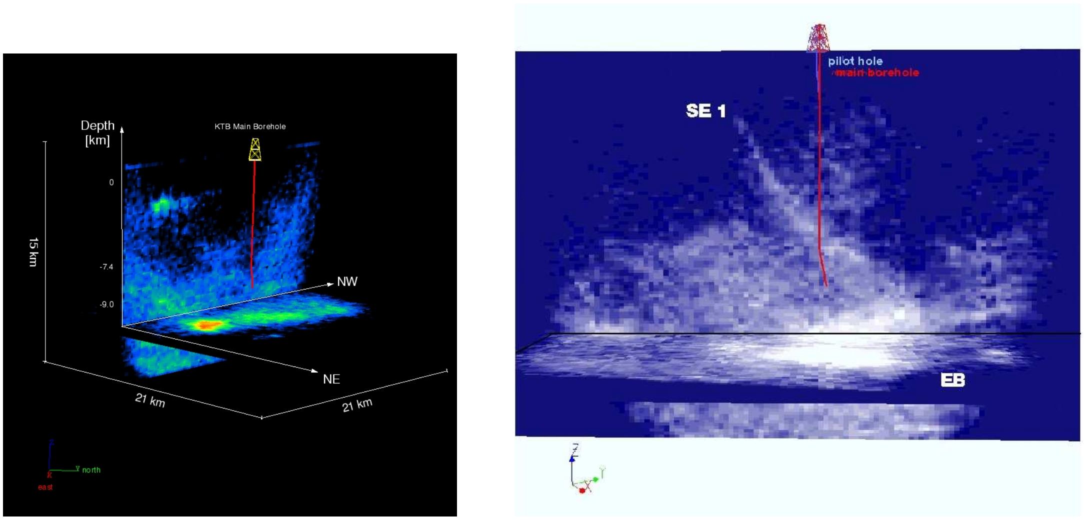
(b) Part of the 2D pre-stack Kirchhoff depth migration of the profile KTB8502. The profile is perpendicular to the strike of the Franconian Lineament (FL, compare Fig. 1(a)) and passes through the KTB location. The SE1 reflector is clearly visible as a steeply dipping event, the EB appears with strong reflectivity at a depth of 12-13 km. Taken from Buske (1999b).

Figure 1: KTB drilling location, seismic surveys and 2D migration results.

In 1989, a 3-D deep seismic reflection survey (ISO89-3D) was carried out in the vicinity of the KTB drill hole (black rectangle in Fig. 1(a)). This experiment was part of the program 'Integrated Seismics Oberpfalz (ISO)'. An area of about 21 km $\times$ 21 km was investigated using reflection seismics. The main borehole is located in the center of this region. At a depth of 12 to 14 km, directly beneath the SE1 reflector, a highly reflective zone known as the Erbendorf body (EB) can be observed (see Fig. 2). The ISO89-3D data set was processed by Buske (1999b) in terms of 3D pre-stack Kirchhoff depth migration (Fig. 2(a)). For details we refer to this publication. In spite of the low coverage, the migration of the ISO89-3D data set clearly shows the geometry and the shape of the dominant structures (SE1, EB) in the subsurface (see Fig. 2(b)).

Fluid induced microseismicity, injection experiments in 1994

In order to study the brittle ductile transition zone as well as crustal fluids and transport processes at the KTB, a fluid injection experiment was carried out at the end of the drilling. The injection experiment was designed with the following objectives: to obtain knowledge of crustal stress based on borehole measurements to the open hole section in 9.1 km depth, of in situ temperatures more closely approaching 300° and to test the hypothesis that the lithosphere is in failure equilibrium with respect to the state of stress. To test this hypothesis it was intended to inject fluids at the open hole section and to determine if small perturbations of pore pressure could lead to the triggering of microearthquakes at this particular depth and high temperature.



(a) Geometry of 3D migrated volume. The colors denote reflectivity, blue colors correspond to low reflectivity, red ones to higher reflectivity, respectively.

(b) Result of 3D migration, view from SE. Light colors correspond to higher, dark to lower reflectivity. The steeply dipping SE1 reflector is clearly visible as well as the high reflectivity of the EB.

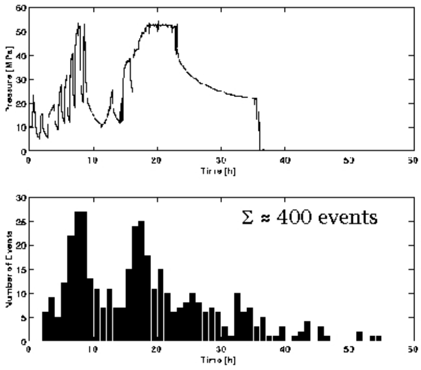
Figure 2: left: Geometry of 3D migration, right: 3D Kirchhoff migration of ISO89-3D data set (Buske (1999b))

During the fluid injection experiment in 1994 about 200 m^3 of KBr/KCl brine was injected in the open hole section between 9.03-9.1 km depth for a duration of 24 hours (Fig. 3(a) top). 73 surface seismometers and one borehole seismometer recorded approximately 400 microearthquakes within 60 hours (Fig. 3(a) bottom). 94 events were localized with precision high enough to analyse them in terms of the SBRC method (Fig. 4). The seismically active rock comprised a volume of approx. 0.35 km^3. Moreover, because of the small changes in injected pressure in this experiment, the seismically active volume of rock was not fractured at all (Zoback and Harjes (1997)).

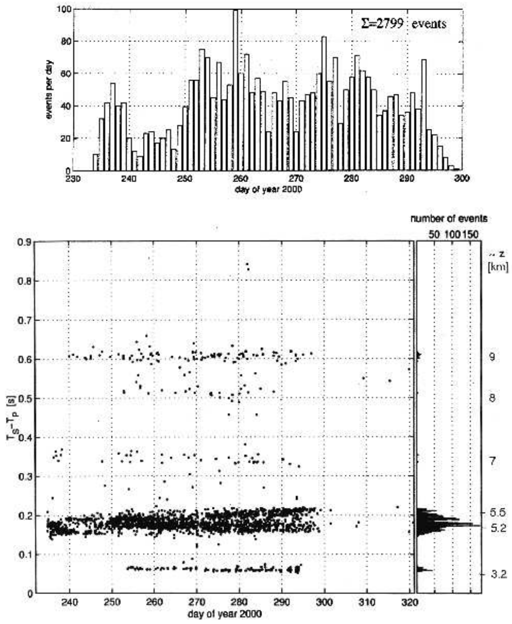
All recorded events were considered to be induced by the injection. Only a small increase in pore pressure ($<$ 1 MPa) was sufficient to trigger the earthquakes. Events only occurred above the bottom of the well 4(a)). Possible explanations were given by Zoback and Harjes (1997): either the encounter of the brittle-ductile transition zone at this depth (impermeable half-space) or, alternatively, a decreased stress level much smaller than the rock's frictional strength.

Fluid induced microseismicity, injection experiments in 2000

In order to further investigate whether the limitation of hypocentral depth to the upper 9.1 km during the injection experiments in 1994 reflects a rheological boundary or simply the limited range of pore pressure increase, a long-term fluid injection experiment was performed in 2000. The experiment was designed to enable fluid migration away from the injection interval and to cause pore pressure increase also at larger distances. Starting August 21st, 2000, the injection of 4000 m^3 of water into the wellhead of the main borehole started and lasted for 60 days (Baisch et al. (2002), see Fig. 3(b) top). Monitoring took place from a surface network and a downhole seismometer in the pilot hole. Since preceding hydraulic tests did not indicate any leaks in the casing, it was assumed that the main borehole was hydraulically closed at least down to 6 km depth. However, due to several leakages in the borhehole casing which were not known fluid loss into the rock occurred within various depth intervals. This was confirmed by the difference of phase traveltimes ($T_s - T_p$) of the recorded microseismic events (Fig. 3(b) bottom). About 2800



(a) Short term fluid injection experiment at the KTB 1994. The upper image shows the time-dependent pressures during the injection. In the lower part the microseismic event rate during the experiment is shown.



(b) Long term fluid injection experiment at the KTB 2000. In the upper part, the measured microseismic event rate during 70 days of the experiment is shown. The lower plot shows the measured $T_s - T_p$ times of the 2799 events and the corresponding depths where microseismicity occurred.

Figure 3: Fluid injection experiments at the KTB 1994 and 2000 (Baisch et al. (2002)).

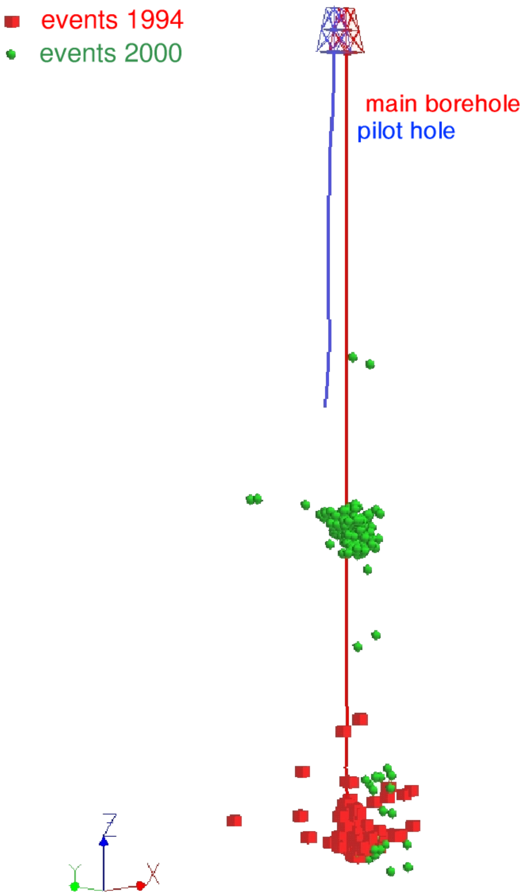
microearthquakes were recorded during the experiment. The main depth domains where microseismicity occurred were around 5.4 km and 9 km depth.

The events were processed by Baisch et al. (2002). Approximately 240 events were localized with precision high enough to analyse them in terms of the SBRC method. Unfortunately, only very few events could be used for the estimation of hydraulic diffusivity for a specific depth interval. In spite of the small event number the results (see following section) are significant in our opinion.

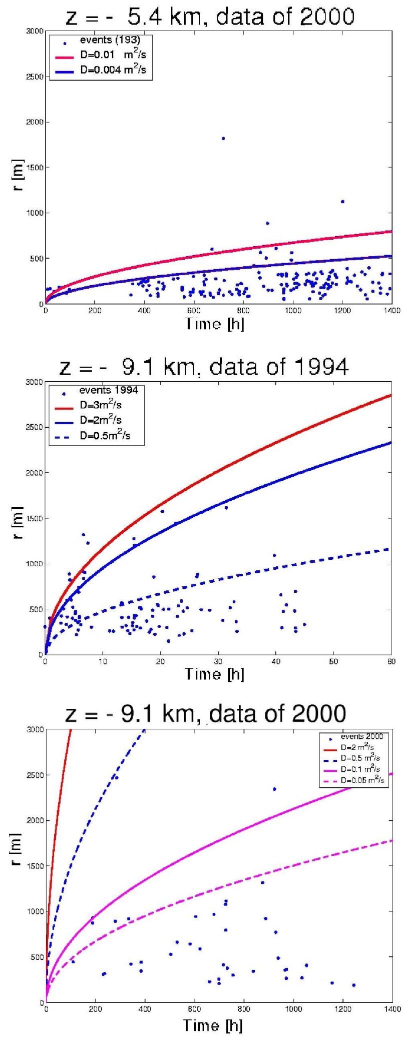
Analysis of fluid induced microseismicity at KTB, results of depth dependent hydraulic diffusivity

Rindschwentner (2001) already processed data of fluid injection induced microseismicity at the KTB from 1994. He obtained estimations of scalar hydraulic diffusivity based on equation (2) as well as magnitudes and orientations of the anisotropic diffusivity tensor based on equation (4). He found isotropic estimates of hydraulic diffusivity which ranges from 0.5 to 2.0 m^2/s for the open hole section at 9.1 km depth. A diffusivity tensor was found, whose orientation of the maximum component agrees well with the orientation of foliations which trend NW-SE and dip between 50° and 80°. This is also confirmed by the resulting stress orientations which are composed by a maximum horizontal stress orientation of N160° and a vertical stress of about the same magnitude (Emmermann and Lauterjung (1997)). Furthermore, the two major tensor components span a plane which is quasi-parallel to the seismic reflector SE1, which is regarded as the subsurface extension of the Franconian Lineament (Fig. 5).

Of course, one has to mention that the SBRC method requires a preferably large number of events for the estimation of hydraulic diffusivity. The event numer for the estimation of the tensor components from



(a) KTB-boreholes together with the hypocenters of the microseismic events of 1994 (red squares) and 2000 (green dots). During 1994 events occurred only at the open hole section at 9.1 km depth and up to approx. 8 km. Due to leakages in the borhehole casing, events in 2000 occurred mainly at 5.4 and 9 km depth.



(b) Estimation of scalar hydraulic diffusivity for the two main depth domains where microseismicity occurred. The plot at the top shows the estimation for the depth domain around 5.4 km, the middle and lower plot the estimation for 9.1 km from 1994 and 2000 data, respectively. In spite of the small event number, the magnitude of hydraulic diffusivity is found to be much lower in the upper part compared with the lower depth domain.

Figure 4: Fluid injection experiments at the KTB 1994 and 2000 and estimation of depth dependent scalar hydraulic diffusivity

the 1994 data set alone is not very high. Only 94 events were localized precisely enough in 1994 to use them for our analysis. In spite of the small event number, it is evident that the cloud of microseismicity in the lower part of the borehole coincides with the distribution of the hypocenters. However, the assumption that the orientations of pre-existing fracture systems may explain the feature of spatial evolution of event coordinates has to be proven in more detail.

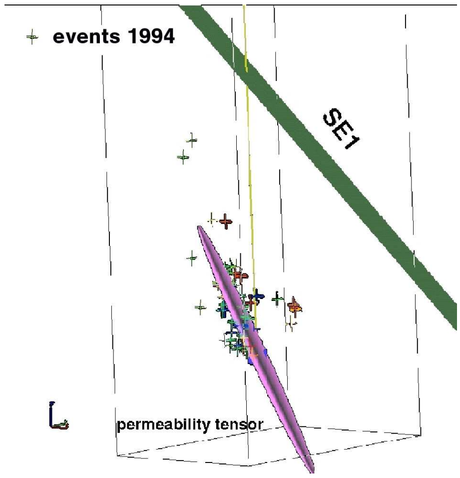


Figure 5: Estimation of the tensor of hydraulic diffusivity from the 1994 data set (Rindschwentner (2001)). The hypocenters are shown as crosses, the tensor is shown together with the schematical dipping of the SE1 reflector. The estimated main direction of the tensor is found to be quasi-parallel to the seismic reflector.

The aim of the analysis of the new data set created during the fluid injection experiments in 2000 were twofold: first, it should be tested if the values of hydraulic diffusivity/permeability found previously could be reconstructed for the depth domain around 9 km. Secondly, because microseismic events occurred within various depth intervals due to the unknown leakages in the borehole casing, the depth-dependency of hydraulic parameters should be studied. Therefore it is possible for the first time to obtain more insight into the depth-dependent behaviour of diffusivity at one single injection site.

We mainly analysed two major depth intervals where microseismicity occurred in the year 2000: the domain around 5.4 km depth where 193 events were used for the analysis and around the open hole section at 9.1 km depth where 42 localized events occurred. Two main results turned out from the analysis of hypocenter locations (see Fig. 4(a)): the upper cloud induced in 2000 seems to be characterized by a completely different evolution signature compared with the lower one: the seismically active volume is smaller compared with the volume where microseismicity occurred in 9.1 km depth. Moreover, the spatial shape of the cloud in the upper part of the borehole is more spherical whereas the lower one seems to show preferred directions of hypocenter locations and is more scattered.

The second result turns out by applying the SBRC algorithms in terms of equation (2). As coordinates for the injection source points for the two different clouds the known positions of the leakages were used. The estimation of scalar hydraulic diffusivity yields values in the order of 0.004 m^2/s $< D < 0.01$ m^2/s for the upper part of the rock. From the lower microseismicity cloud we obtained values of 0.05 m^2/s $< D < 1$ m^2/s which confirm the previous estimations of Rindschwentner (2001) and Shapiro et al. (1998) (Fig. 4(b)). Therefore we conclude, that the diffusivities found for the upper domain of the rock are by a factor of at least 100 smaller than those for the lower domain. A 3D reconstruction as well as an estimation of the hydraulic diffusivity tensor from the 2000 data set was not meaningful due to the small number of events.

In order to better understand the different signatures observed in the spatial-temporal evolution of the two main clouds induced in 2000 mentioned above, we compare the hypocenter locations with 3D migration results (Buske (1999b,a)). This could also help in understanding and the interpreting the great variance of magnitude of hydraulic diffusivity for the two different depth domains.

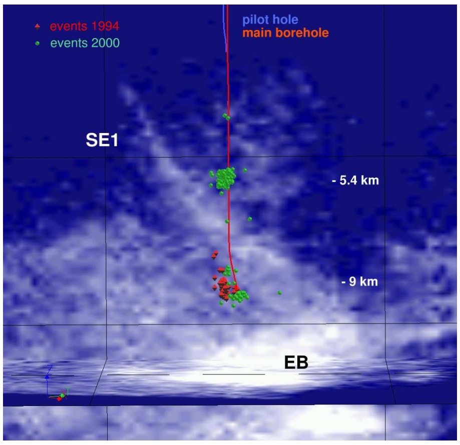


Figure 6: 3D migration together with the microseismic hypocenters of 1994 (red) and 2000 (green).

Correlation of microseismicity with reflectivity

The hypocenter locations of microseismicity of 1994 and 2000 together with the migration results are shown in Fig. (6). The prominent seismic reflector SE1 is clearly visible as well as the Erbendorf Body at 12-14 km depth. Again, in Fig. (7) the hypocenters of the events are shown together with the tensor of permeability estimated for the lower part of the borehole. The hypothesis that the tensor is quasi-parallel to the pre-existing fracture systems is confirmed by this result. Therefore, we conclude that the orientations of pre-existing fault structures and fractures affect the hydraulic diffusivity and spatial distributions of the microseismicity clouds. The horizontal as well as the vertical slices included in the migration image also show that the upper part of the rock is characterized by a lower reflectivity than the lower part. It is clearly seen that the upper cloud occurred within a depth domain which shows less reflectivity (and therefore less pre-existing natural fracture systems). The lower cloud occurred in a domain which is characterized by higher reflectivity (and therefore occurred in a more fractured part of the rock). This observation is in agreement with the previous estimates of hydraulic diffusivity: it is smaller in the upper part of the considered rock volume and it is higher in its lower part.

CONCLUSIONS

By analysing two data sets from the German continental deep drilling site (KTB) it was possible to estimate values of diffusivities for two different depth intervals at the same horizontal location for the first time. Moreover, we compared our results with a 3D pre-stack Kirchhoff depth migration. This has shown that the influence of the orientations of pre-existing natural fracture systems on the triggering of microseismicity is obvious. Event clouds in the upper part of the rock under consideration show more compact shapes which can be correlated with a medium showing less reflectivity. Also, the magnitude of hydraulic diffusivity is by a factor of 100 smaller than that at the lower depth level. Here, the hypocenters of the events are aligned along preferred orientations of natural fracture systems. The medium at this depth is characterized by a much higher diffusivity, correlating with larger reflectivity.

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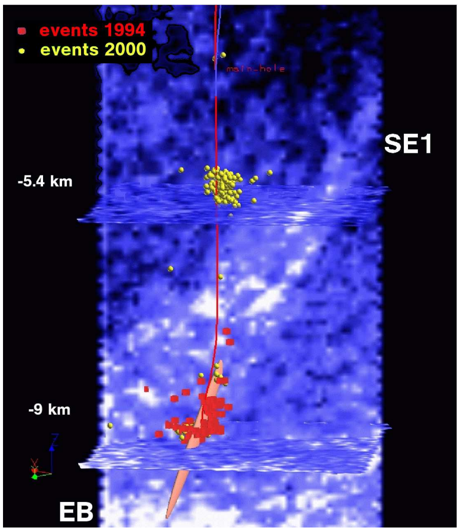

Figure 7: 3D migration (view from NW) together with the microseismic hypocenters (1994=red, 2000=yellow) and the tensor of permeability estimated from the 1994 data set. The volume of rock where the more spherical upper cloud occurred is characterized by lower reflectivity. The lower cloud of events seems to be preferentially orientated along the directions of the high-reflective (SE1) zone. The reflectivity in this domain is found to be much higher.

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