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FAULTING MECHANISMS AND STRESS TENSOR AT THE EUROPEAN HDR SITE OF SOULTZ-SOUS-FORÊTS

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ABSTRACT

The state of stress and its implications for the shearing mechanisms on fault plane during hydraulic injection are crucial issues for the general functioning of HDR systems. It is especially true for hydraulic stimulation experiments, aimed at enhancing the permeability and connectivity of natural fracture network: they tend to induce the shearing of joints, which is controlled by the local stress tensor.

In this study we present some results about the shearing mechanisms of microseismic events occurred during the 2000 and 2003 stimulation tests at Soultz-sous-Forêts and their significance in terms of stress. About 7200 microearthquakes have been located in 2000 and 2250 in 2003, from a surface seismological network. In both cases, several hundreds of double-couple focal mechanisms have been automatically determined with the FPFIT program (Reasenberg and Oppenheimer, 1985), using first-motion polarities. Results indicate a majority of normal-faulting movements with a more or less pronounced strike-slip component. Quasi-pure strike-slip events also occur, especially in the deeper part of the reservoir.

Although we find a double-couple solution for all events, we tried to observe and quantify the proportion of non-double-couple component in the seismic moment tensor for several microseisms from the 2003 data. The study shows that there is a higher proportion of tensional opening for the events in the vicinity of the injection well than in the far reservoir.

We used the method of Rivera and Cisternas (1990) to perform the inversion of the deviatoric part of the stress tensor from P-wave polarities. We applied this method to different sets of the 2000 data, taken from the shallower and deeper parts of the reservoir. Results shows a stable, horizontal, NE-SW-oriented trend of the minimum stress, but a rotation of the maximum stress from a subvertical direction (top of the reservoir) to a subhorizontal one (bottom of the reservoir), which implies a change from a normal-faulting regime to a strike-slip regime with depth, in agreement with our fault-plane solutions. Finally we applied the stress tensor to the nodal planes of several events and we have been able to determine their fault plane and to obtain a 3D image of the fracture network, based on real data.

INTRODUCTION

In 1987, the European Hot Dry Rock project was founded at the site of Soultz-sous-Forêts (Alsace, France) by France, Germany and the European Commission (Kappelmeyer et al., 1991). Soultz-sous-Forêts is situated within the central upper Rhine Graben, about 50 km north of Strasbourg (Fig. 1). It is located within the former Pechelbronn oil field, in a zone of large temperature gradient anomaly, which was measured in the subsurface sedimentary layers (Schellschmidt and Schultz, 1991). These sediment deposits exhibit a thickness of about 1400 m and cover a large granitic rock massif, in which the geothermal reservoir is being developed: the purpose is to create an artificial, deep heat exchanger in the hot, fractured granite by stimulating the natural fracture network. Indeed the aim of stimulation experiments is to enhance the permeability and connectivity of the joint network and to connect it with the open-hole sections of boreholes. Hydraulic injections tend to induce shearing on fracture planes, which are favourably oriented for slip within the local stress field.

For almost 20 years, several phases of the project were completed, consisting mainly in the characterization of the granite massif down to 5 km depth and in the development of the technology needed to extract heat from rocks. Several wells have been drilled for this purpose. Five are observation boreholes, into which downhole seismic sensors are deployed and used to monitor the seismic activity associated with the hydraulic injections. 4 deep wells were also drilled during the course of development. GPK1, reaching 3590 m depth, has been stimulated in 1993 (Baria et al., 1995). In 1995, GPK2 has been drilled down to 3876 m and stimulated twice in 1995 and 1996 (e.g.Baria et al., 1999; Gérard et al., 2002).

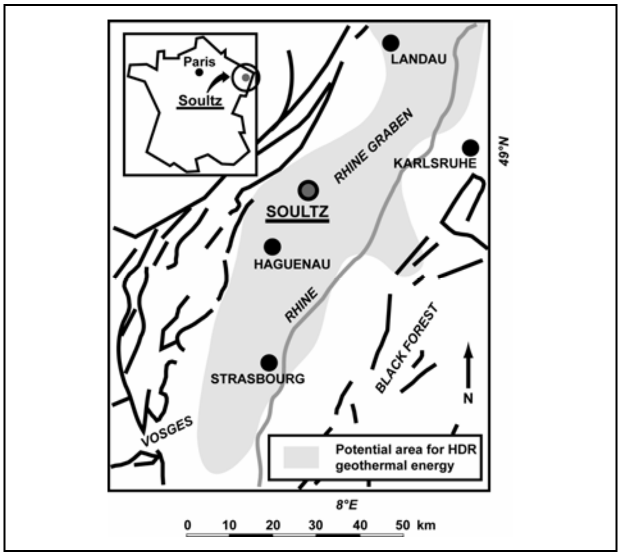

Figure 1: Location of the European HDR site at Soultz-sous-Forêts (from www.soultz.net).

In addition to several others hydraulic tests (injection and production) a successful 4-months circulation test has been performed between these 2 wells (Baumgärtner et al., 1998). In 1999 GPK2 was deepened to 5084 m, where a rock temperature of more than 200°C has been measured, and stimulated in 2000 (Weidler et al., 2002). In 2001 a new phase of the project began, during which a three-wells system is being developed as a scientific pilot plant: in addition to GPK2, GPK3 was drilled to 5091 m depth in 2002 and stimulated in 2003 (Baria et al., 2004). GPK4 was completed in 2004 down to 4981 m depth. Its stimulation began in late 2004 and will continue in early 2005.

In this study, we present some results on faulting mechanisms of induced microseismic events occurred during the 2000 and 2003 stimulation tests. The determination of several hundreds of focal mechanisms gives insights about the faulting regime in the geothermal reservoir. Furthermore, in order to better characterize the faulting mechanisms, we investigate the proportion of tensional opening in the seismic moment tensor for some 2003 events. Finally, we performe an inversion to calculate the deviatoric part of the stress tensor at Soultz. The results, combined with focal mechanisms, allows us to determine a 3D view of the fracture network.

THE 2000 AND 2003 STIMULATIONS

The 2000 and 2003 stimulation tests were performed using different injection strategies. In this paragraph we briefly describe the hydraulic parameters of both stimulations, the seismic monitoring systems and general results on microseismic activity.

The 2000 stimulation

Hydraulic parameters

The injection scheme was rather simple in 2000. The injection lasted about 6 days (June, 30th – July, 6th) and were performed in 3 injection steps: 30 $l.s^{-1}$ during 24 h, 40 $l.s^{-1}$ during 27 h and 50 $l.s^{-1}$ during 90 h have been injected through the open-hole section of GPK2 (4400 m–5000 m). The measured overpressure in the reservoir instantaneously reached a peak of 12 MPa and then declines for the first 2 steps. On the contrary, the rate of 50 l.s-1 induced an initial overpressure of 12 MPa, but the pressure continued to increase up to 13 MPa until the shut in (Weidler et al., 2002). After the shut in, an instantaneous pressure drop of about 5 MPa was observed, then the pressure decreased very slowly.

Seismic monitoring networks

In addition to the downhole seismic network, which consisted in three 4-components accelerometers and two hydrophones, several surface stations were installed by EOST, University of Strasbourg. The surface network was composed of eight vertical seismometers, six 3-components seismometers, one broad-band station and three permanent stations belonging to ReNaSS (French national seismic network). A plane view of the 2000 seismic monitoring system is given in Fig. 2.

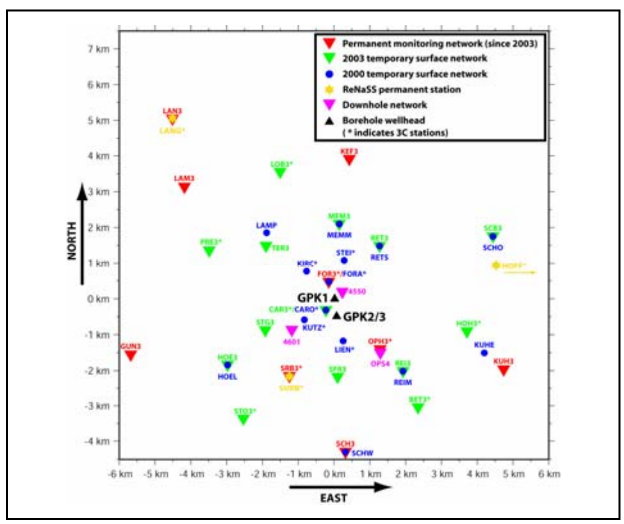

Figure 2: Downhole and surface seismological networks deployed for the 2000 and 2003 stimulation tests.

Microseismic activity

More than 10000 microseismic events have been recoded during the stimulation until the 11th of July on the surface network. They range in magnitude between –0.9 and 2.6. Among them, about 7200 have been precisely located with the method of Thurber, which is a simultaneous tomographic inversion of the velocity structure and location parameters (Thurber, 1983). They form a NNW-SSE oriented cloud of about 1.5 km long and 0.5 km wide. In depth the cloud ranges between 4 and 5.5 km (Cuenot et al.), (Fig. 3). The orientation of the microseismic cloud seems in agreement with the N-S to NNW-SSE trend of the majority of natural joints suggested by Genter and Traineau (1996).

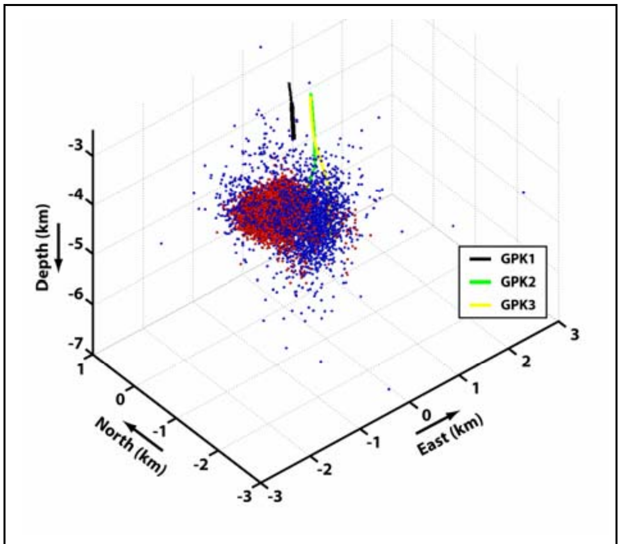

Figure 3: Plane view of the 2000 (red) and 2003 (blue) microseismic cloud.

The 2003 stimulation

Hydraulic parameters

The 2003 stimulation strategy of GPK3 was rather different from the 2000 stimulation of GPK2. Baria et al. (2004) described 4 phases during the 2003 stimulation. From May, 27th to June, 2nd injections began at 30 $l.s^{-1}$ and were later increased to 50 $l.s^{-1}$, with two short periods at 60 and 90 $l.s^{-1}$. From June, 2nd to June 4th the concept of dual, focused injection was introduced: 50 $l.s^{-1}$ were injected in GKP3 while 20 $l.s^{-1}$ were pumped into GPK2. From June, 4th to June, 6th GPK2 was shut-in and, after a short increase to 90 $l.s^{-1}$, injection in GPK3 was decreased in 3 steps. Finally, because of a remaining microseismic activity after GPK3 shut-in, GPK2 was vented at 10 $l.s^{-1}$ to reduce the pressure in the reservoir.

Seismic monitoring network

The 3 downhole 4-axis accelerometers were in the same configuration as 2000; 3-component geophones were also added. On surface, the main improvement consisted in the installation by EOST of a permanent monitoring network (three 3-C sensors and six vertical sensors). In addition, a temporary surface network (six 3-C stations and eight vertical stations) has been deployed for the time of the stimulation test.

Microseismic activity

About 5000 microseismic events were recorded on the surface network in the magnitude range –0.9 to 2.9. 2250 have been located using the TomoDD code (Zhang and Thurber, 2003). As in 2000, the cloud is oriented in the NNW-SSE direction. It is situated in a more southern position than the 2000 cloud. The cloud is about 2 km long and 1 km wide. It ranges between 3 and 7 km depth. On figure 3, the 2000 and 2003 seems to be imbricated. it would mean that at least a part of the seismic structures that had been stimulated in 2000, did not slip in 2003.

FOCAL MECHANISMS

We determine automatically several thousands of focal mechanisms using the program FPFIT (Reasenberg and Oppenheimer, 1985): nodal planes are calculated from the first-motion polarities by a maximum likelihood procedure and manually checked afterwards. More than 14 polarities are available in average for the 2000 events and more than 16 for the 2003 seismicity. Results indicates a majority of normal-faulting movements, pure or with a more or less pronounced strike-slip component. But, on the deepest part of the reservoir, a strike-slip regime seems to dominate, with some quasi-pure strike-slip events. Some representative focal mechanisms examples for the 2000 and 2003 stimulation tests are given in Fig. 4 and Fig. 5.

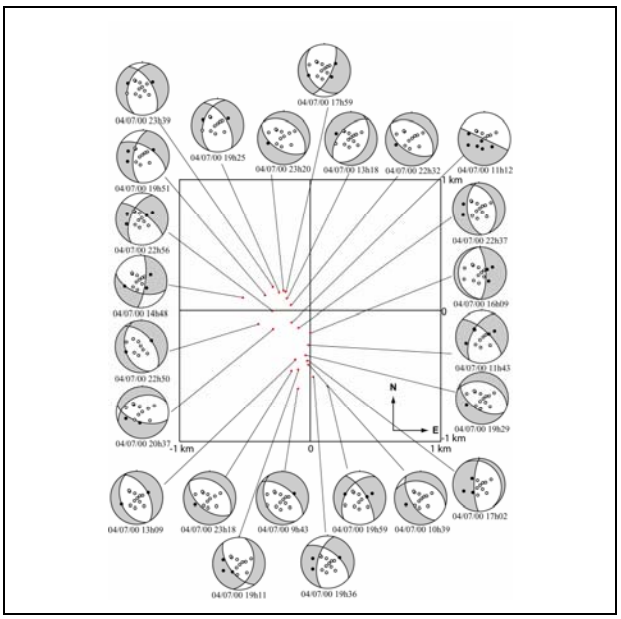

Figure 4: Representative focal mechanisms for the 2000 stimulation test.

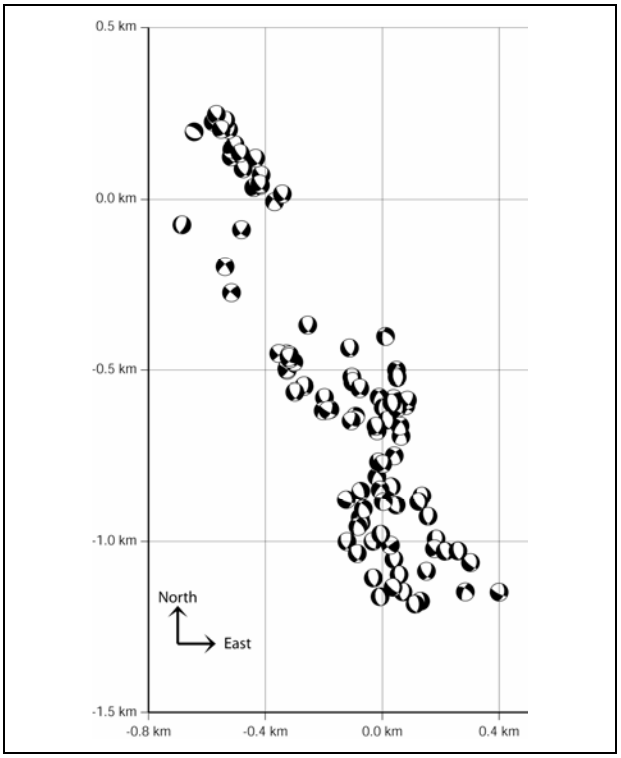

Figure 5: Representative focal mechanisms for the 2003 stimulation test.

NON DOUBLE COUPLE COMPONENT

From the full determination of the seismic moment tensor (1st order) we are able to describe the equivalent forces at the source, which can be correlated with the physical processes involved at the source. Moreover, the seismic moment tensor can be written as the sum of a double couple (DCC) component and a non double couple component (NDCC), which gives the proportion of tensional opening in the seismic rupture. This proportion is here expressed as a function of an index ε. ε ranges between –0.5 and 0.5. A positive ε indicates tensional opening in addition to shearing , while a negative ε describes compressive movements in addition to shearing. If $0 \le \varepsilon \le 0.25$, the DC component dominates. This the case in our study, as we have been able to find a DC solution for each seismic event. However, the variations of ε between 0 and 0.25 give the proportion of NDC component in the movement. On the Figure 6, several 2003 events are presented as coloured spheres. The colours correspond to the value of ε. As all events were similarly computed, the variations of ε between each others are significant. It is striking that events occurred at the direct vicinity of the injection well GPK3 show a high value of ε. However, events occurred far from the injection well do not show such a high value of ε. Some of these latter events even have a zero ε value. It indicates that events in the vicinity of GPK3 have a non negligible NDC component, and the fractures that support the rupture may undergo tensional opening in addition to shearing. This result may be a consequence of a large overpressure increase near the well due to the massive injections, which can cause the joints to slightly open. On the contrary, as far as we depart from the injection well, the fracture tensional opening component seems to be in less proportion. It would mean that the overpressure is less effective, maybe because it quickly drops with the increasing distance from injection well.

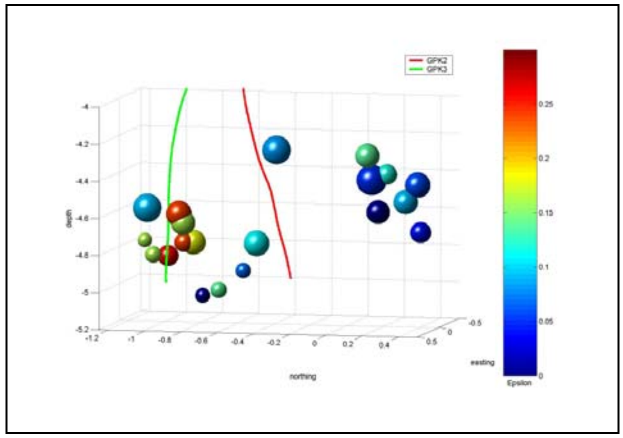

Figure 6: Non double couple component proportion for several 2003 events.

In conclusion, we determine a double couple solution for each microseismic event, which indicates that the dominant process of the faulting movements is shearing. This result seems quite common also at other HDR sites. But, by the analysis of the seismic moment tensor, we show that the rupture process involves a non double couple component. This indicates a proportion of tensional opening at the fracture planes. Moreover this NDC component is significantly higher for events in the vicinity of the injection well, probably because of greater pressure effects.

STRESS TENSOR INVERSION

Two observations suggested us to perform a stress tensor inversion. First our results on focal mechanisms show a higher proportion of strike slip events in the deepest part of the geothermal reservoir. Moreover Klee and Rummel (1993) determine a stress regime profile at Soultz-sous-Forêts using hydrofracturing stress measurements. Their results show a possible cross-over between the vertical stress S_V and the maximum horizontal stress S_H at around 3500-4000 m depth. This would imply a change in the faulting regime with depth, from a normal-faulting regime to a strike-slip regime. In order to check the reliability of the assumption, we decided to perform the stress tensor inversion.

Method

We used the method of Rivera and Cisternas (1990), which involves the direct inversion of the deviatoric part of the stress tensor and of focal mechanisms from first-motion polarity data. The stress tensor is defined by three Euler angles and a shape factor, which indicates the faulting regime. From an initial trial solution (tensor and focal mechanisms), theoretical polarities are calculated and compared to the observed data at each iteration. Then the solution is modified in order to maximize a likelihood function. The quality of the solution is expressed in terms of likelihood and score (the score describes the fit between observed and theoretical polarities).

Data

We performed two inversions with two different data sets of events from the 2000 stimulation experiment. A first set contains microseisms occurred in the upper part of the reservoir (depth ≤ 4.5 km), the second is composed of events occurred in the bottom part of the reservoir (depth ≥ 5 km). For each set, about 60 microseismic events have been randomly selected among those which exhibit the largest number of available polarity data. Indeed, each selected event shows a number of polarities between 14 and 18. In order to check the reliability of the inversion, we performed several calculations with different sets containing different arrangements of events. Similar results have been obtained from the different calculations.

Results

The results of the inversion are shown in Figure 7 and Figure 8. In both figures, the picture at the top corresponds to the 100 best tensor solutions and the bottom picture gives the best estimate of the stress tensor. Figure 7 shows the inversion for the upper part of the reservoir while results of the inversion for the bottom part are displayed on Figure 8. Stresses are expressed in terms of σ_1, σ_2 and σ_3, where $\sigma_1 > \sigma_2 > \sigma_3$.

A first observation is the stability of the orientation of the minimum horizontal stress S_h, which trends in both cases NE-SW to NNE-SSW. This is in agreement with the general orientation of S_h at regional scale in the upper Rhine Graben. On both figures the maximum horizontal stress S_H is oriented NW-SE to NNW-SSE. This results is also consistent with regional estimates of S_H. However, at local scale, other studies show a more N-S orientation of the maximum horizontal stress (e. g. Bérard and Cornet, 2003). The method of Rivera and Cisternas suppose that the stress tensor is homogenous over the studied region. In the case of Soultz-sous-Forêts, fluid injections may introduce strong local stress heterogeneities that we cannot see with our inversion method: our results may correspond to an “average” stress tensor, which could be more representative of the regional stress field. The relative scatter of the solutions may reflect these stress heterogeneities.

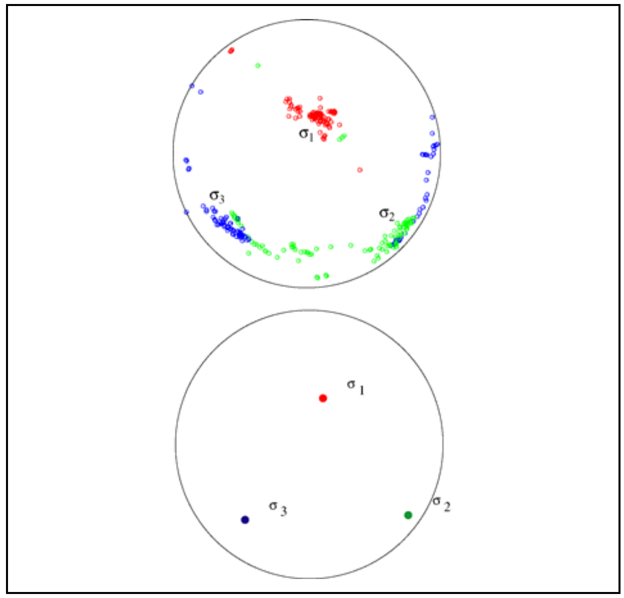

Figure 7: Results of the stress tensor inversion for the top of the reservoir. Top: 100 best tensor solutions; Bottom: best tensor solution.

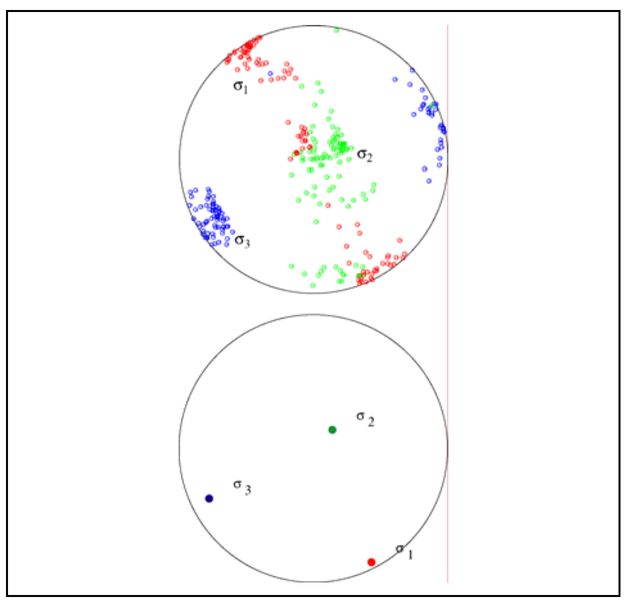

Figure 8: Results of the stress tensor inversion for the bottom of the reservoir. Top: 100 best tensor solutions; Bottom: best tensor solution.

But the most important result concerns the rotation of the maximum stress σ_1 from a subvertical orientation at the top of the reservoir (Fig. 7) to a horizontal direction (Fig. 8). We effectively observe this feature, which was predicted by other measurements. It means that the maximum horizontal stress S_H becomes the maximum stress at the bottom of the reservoir. Thus this imply a change in the failure mode. At the top of the reservoir, the dominant regime is normal-faulting whereas strike-slip is likely to occur in the deepest part of the reservoir. This result is in agreement with the results on focal mechanisms. Nevertheless, both figures 7 and 8 show a relative dispersion of the solutions. In particular on figure 8, some solutions still indicate a subvertical trend for σ_1 and a subhorizontal direction for σ_2. This suggests that the faulting regime may have not completely changed at the bottom of the reservoir, that is, the stimulated volume is located within the region of stress rotation. And moreover, this confirms the fact that the magnitudes of S_V and S_H are very close, as suggested by Klee and Rummel (1993), facilitating the stress rotation.

3D imaging of the fracture network

We applied the stress tensor on the nodal planes that we determine for the 2000 stimulation in order to define the plane having sheared. Figure 9 shows the result in a 3D view.

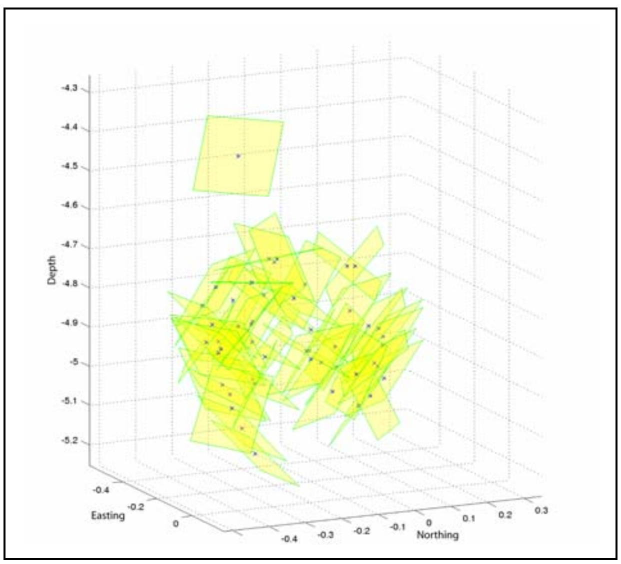

Figure 9: 3D representation of the fracture network.

The majority of fault planes are oriented NNW-SSE to NW-SE with a dip either to the West or to the East. We can also observe that most of the planes dipping to the West are subvertical, while those dipping to the East seems more subhorizontal. In addition, several fault planes exhibits an "en echelon" structure. Nevertheless, the fracture system appears to be rather heterogeneous.

CONCLUSIONS

Our analysis of the faulting mechanisms suggests that the main involved process is shearing on the fault planes, which has already been highlighted at several other HDR site. Here at Soultz-sous-Forêts the faulting mechanisms are highly related to the extensional regime, which dominates in the Rhine Graben.

Thus from the determination of focal mechanisms, it appears that the failure mode is mainly normal-faulting, with a more or less marked strike-slip component. But in the deepest part of the reservoir, our observations suggest a strike-slip regime. The inversion of the deviatoric part of the stress tensor confirms this feature: the maximum stress rotates from a subvertical trend to a subhorizontal stress with depth, implying a change from a normal-faulting regime at the top of the reservoir to a strike-slip regime at the bottom of the reservoir. In reality the change is quite gradual and it is possible that the geothermal reservoir crosses the zone of stress rotation. Nevertheless, the stress conditions, as well as the pre-existing seismogenic structures seems to be suitable to ensure good stimulation results in terms of permeability and connectivity enhancement.

Furthermore, we have been able to determine a double couple solution for each event both in 2000 and 2003, indicating that shearing is the dominant process. But by calculating the seismic moment tensor of several 2003 events, we show that, at least a part of them have a non-negligible non-double-couple component. It is striking that they tend to occur in the vicinity of the injection well, whereas events located farther do not exhibit such high NDCC values, or do not exhibit NDCC at all. It means that events near the well show a part of tensional opening in addition to their main shearing process. This behaviour is highly correlated with the overpressure induced by the fluid injections. The pressure is highly effective close to the injection well and is able to slighty open the fracture. This leads to implications for the permeability creation in the vicinity of the injection well and for the connection between the well and the fracture network. However, the proportion of tensional opening is close to zero for events occurred far from the injection well: this indicates that the pressure effects on joints opening are limited to the vicinity of the injection well.

Finally, by applying the stress tensor to the nodal planes of events, we have been able to determine a 3D representation of the fracture system based on real data. As a next step, it would be interesting to obtain a similar figure with fault lengths scaled to the magnitude of microseismic events.

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