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Stress measurements in salt mines using a special hydraulic fracturing borehole tool

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ABSTRACT: Hydraulic fracturing tests are often utilized in order to measure stresses in rock. In most cases, the fracture forms perpendicular to the orientation of the minimum principal stress whose magnitude can be determined by the so-called shut-in pressure. In order to find the orientation of the minimum principal stress the fracture orientation has to be measured. This can be done by Acoustic Emission (AE) measurements. Usually, for this purpose AE transducers are positioned in separate boreholes around the central borehole where the hydraulic fracturing takes place. Recently, we have developed a new borehole tool which is able to do the same job utilizing only one borehole. The said tool includes the hydraulic pressurization unit with the AE sensors. Due to the small distance between the injection interval and the AE sensors, this tool is much more sensitive than the conventional AE method. In addition, the sensitivity is the same for all fractures independent of borehole depth. During the last six years, we have performed about 100 hydraulic fracturing tests on rock salt and anhydrite in different salt mines. The paper presents some results of these tests which demonstrate the capabilities of the new borehole tool.

1 INTRODUCTION

The hydraulic fracturing method is able to measure the stress in rock directly. During a hydraulic fracturing experiment the hydraulic pressure in a sealed volume of a borehole is increased up to fracture initiation in the rock. At the end of the forties of the last century, the hydraulic fracturing technique was applied first to raise the oil or gas output by increasing the permeability of rock. Later on, in the fifties, a lot of attempts were made to find out the correlation of in-situ stress state and results of hydraulic fracturing tests. Significant in this field was the work of Hubbert & Willis (1957). They were the first to demonstrate the influence of local tectonic stresses on the orientation of hydraulically induced fractures. They assumed that the fracture propagates in the direction of least resistance and that the pumping pressure to merely keep an induced fracture open is equal to the minimum principal stress. Kehle's (1964) determinations of tectonic stress through analysis of hydraulic well fracturing agree closely with those calculated using Hubbert's and Willis' model. Kehle concluded that the minimum principal stress corresponds to the so-called instantaneous shut-in pressure, i.e. the pressure reached some time after stopping pumping at the end of the test. Fairhurst (1964) was the first who suggested to use hydraulic fracturing for stress measurements in rock.

In all applications dimension, shape and orientation of the fractures are of upmost importance for determination of the in-situ stress state. The usually applied methods to determine the orientation of the fracture plane like overcoring, fissure forming with packer or visual inspection using a borehole camera are limited in borehole diameter and very expensive, in particular for hydraulic fracturing tests in greater borehole depths. All these methods need clearly discernible fissures at the borehole wall and assume that the direction of fracture propagation is not influenced by changes of the stress state close to the borehole. With other words, a change of the fracture direction due to stress redistribution in further distance from the borehole can not be observed.

In order to determine the orientation of the principal stresses, the fracture orientation must be known. A lot of papers show that acoustic emission (AE) is suitable to measure crack orientation and extension utilizing three-dimensional source location. Lockner and Byerlee (1977) located AE events during hydraulic fracturing experiments in small Weber sandstone specimens. Eisenblätter (1988) located microcracks during hydraulic fracturing tests in a salt mine. Manthei et al. (1989) applied AE measurements during a hydraulic fracturing test on a large specimen of rock salt. Ohtsu 1991 used the moment tensor analysis to study crack types and orientations of AE sources detected during in-situ hydraulic fracturing tests in siliceous sandstone. Manthei et al. (1998a) demonstrated that macroscopic crack orientations depend on the tectonic stress field in the rock. They showed that the orientation of the fracture planes as measured by acoustic emission agrees remarkably well with the orientation of the calculated principal stresses.

In order to measure the crack orientation and extension, AE transducers are usually positioned in separate boreholes around a central borehole (Manthei et al. 1998b) where the fracturing tests take place. Recently, we have developed a new borehole tool which is able to do the same job utilizing only one borehole. This borehole tool includes the hydraulic pressurization unit with the AE sensors. Due to the same distance between injection interval and sensor arrays the sensitivity of AE registration is always the same independent of the borehole depth. It is possible to trace back the realistic fracture propagation in distances up to 15 to 20 times of the borehole diameter. Other expensive inspection methods are not needed.

During the last six years, we have performed about 100 fracturing tests on rock salt and anhydrite in horizontal as well as in vertical boreholes in different salt mines. In the following, after a short description of the experimental set-up some examples will illustrate the capabilities of the new borehole tool.

2 EXPERIMENTAL SET-UP

The new borehole tool which was developed by IfG Leipzig and GMuG Ober-Mörlen (Manthei et al. 1989) is shown schematically in Figure 1. It consists of two parts – the hydraulic pressurization unit in the middle and two AE sensor arrays at both ends. It is applicable to borehole diameters between 98 mm and 104 mm. The overall length of the borehole tool is about 2 m. Each sensor array includes four AE transducers in a cross section perpendicular to the borehole axis. The distance between the AE arrays is approximately 1.5 m. The transducers with integrated preamplifiers are placed in a common housing which is screwed to the pressurization unit. The transducers are pressed pneumatically against the borehole wall. The preamplified signals are supplied to an 8-channel transient recorder card which is controlled by a portable personal computer. The transient recorder card (sampling rate 1.25 MHz, resolution 12 bit) is read each time a signal passes the trigger threshold. The borehole pressure and the pressure which is applied to the packer are measured using pressure cells. The signals of the pressure cells are digitized usually each second and stored on the hard disk of a notebook.

The evaluation of signals stored in digital form was made first in the laboratory. At present, a quasi online location is possible onsite. For locating the events the onsets of the compressional and/or shear waves are picked automatically. A special localization algorithm has been developed in order to estimate the distance, inclination (to the borehole axis) and the azimuth of the AE source. The test measurements showed that the accuracy of distance and azimuth estimation was about 0.15 m and ±10°, respectively.

After a tightness test a high pressurization rate is applied for fracturing the rock. In the shut-in phase the pressure is observed up to several hours. After each hydraulic fracturing test a refracturing test is normally performed in order to confirm the observed shut-in pressure. During a fracturing test several hundreds of milliliter oil are injected.

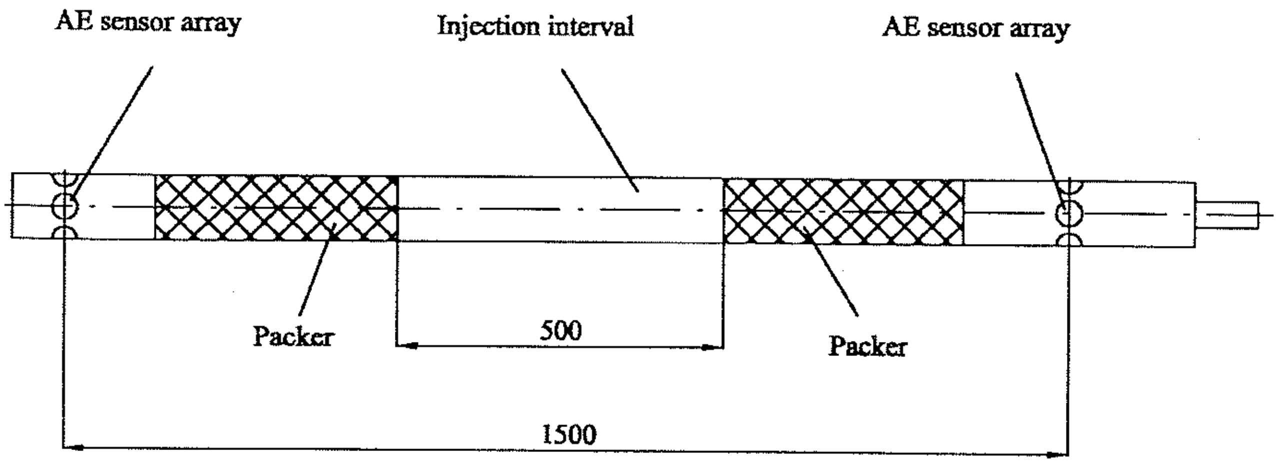

Figure 1. Hydraulic fracturing borehole tool (schematically).

3 RESULTS

3.1 *Hydraulic fracturing test series at the 500-m level in the salt mine Bernburg*

A hydraulic fracturing test series at the 500-m level in the salt mine Bernburg was performed in an area where the rock stresses are influenced by the propagation of an excavation front in direction to the test site. Figure 2 shows the location of the AE events which were detected during a hydraulic fracturing test (including the fracturing and the refracturing test) in 4 m depth in a horizontal borehole in projection to three coordinate planes (x–y-plane: top view; x–z-plane and y–z-plane: two lateral views). The location of the transducer arrays and the injection interval is indicated by means of circles and rectangles, respectively. The y-axis is parallel to the injection well.

All together, more than 5,100 AE events could be located during the test. The located events mark a clearly discernible fracture plane. The fracture initiated in the middle of the injection interval and propagated in radial direction transverse to the injection well. In order to get the orientation of the fracture plane the volume of a parallelepiped was minimized through rotation in perpendicular axes. The edge lengths of the parallelepiped are the mean deviations of the events from the centre of gravity in each coordinate axis. Two rotations (first with azimuth angle around the z-axis and second with inclination angle around the x'-axis) are necessary to minimize the volume. After rotation of the coordinate system a nearly perfect plain fracture appears in the x'–y'-plane in Figure 3. Most events are located at the crack tip (x'–z'-plane). This is due to the fact that during fast crack propagation at the beginning of each fracture phase AE events are emitted so frequently that they overlap each other and, therefore, cannot be located. Figure 4 shows separately the events of the fracturing (left-hand side) and refracturing tests (right-hand side) in 4 m borehole depth in a rotated coordinate system where the fracture plane lies within the x'–z'-coordinate plane. During the refracturing test the crack slightly enlarged from 2.1 m to 2.5 m (measured in the largest diameter). The AE activity of the refracturing test starts after reaching the crack extension of the previous performed fracturing test.

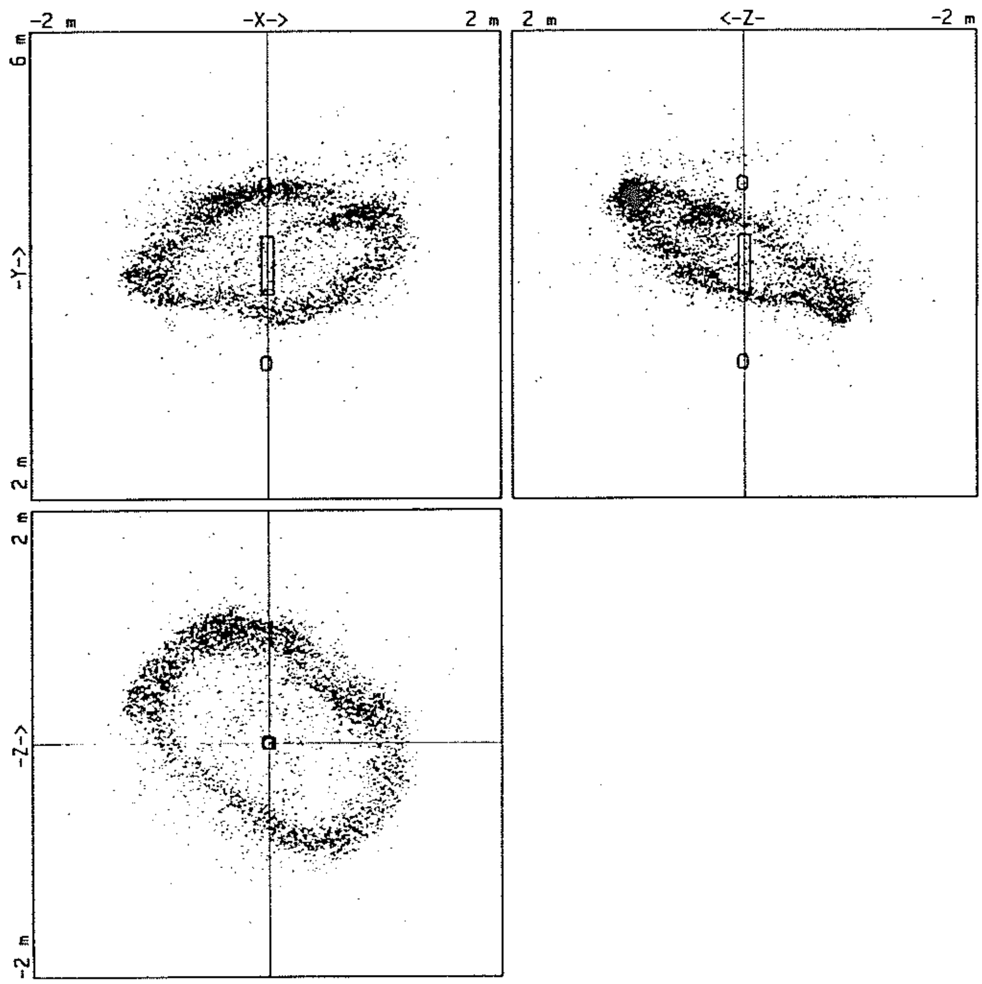

Figure 2. Located AE events of a the hydraulic fracturing test in 4 m borehole depth in projections to the three coordinate planes.

Figure 5 gives an overview on all hydraulic fracturing tests performed in this borehole at depths of 2 m, 4 m, 7 m, and 10.4 m. Approximately 15,000 located events are shown in a top view (at the left-hand side) and in a lateral view (at the right-hand side). Most of the events (11,216) could be localized during the fracturing test in 2 m and 4 m borehole depths. On the contrary, in larger borehole depths much less events (3696) were located in spite of the fact that the same oil volume was injected. This observation may be explained by larger deviatoric stresses close to the contour of a gallery. The extension of the fractures is nearly independent of borehole depth.

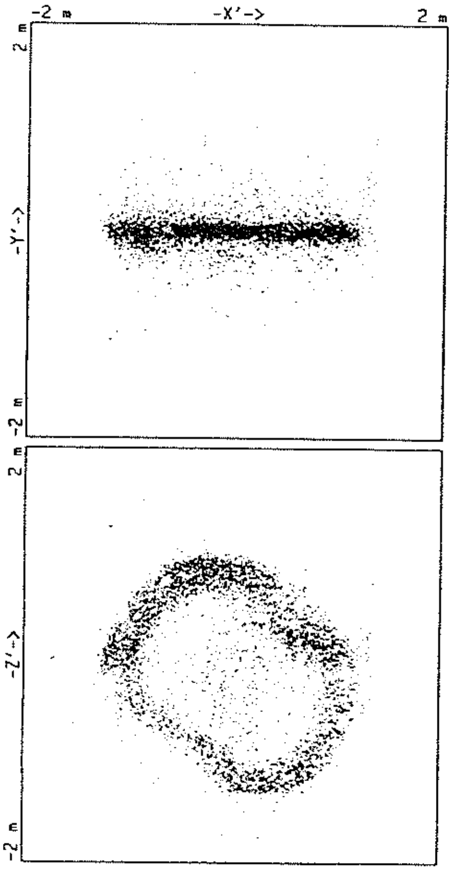

Figure 3. Located AE events of a hydraulic fracturing test in 4 m borehole depth in projections to the rotated coordinate planes.

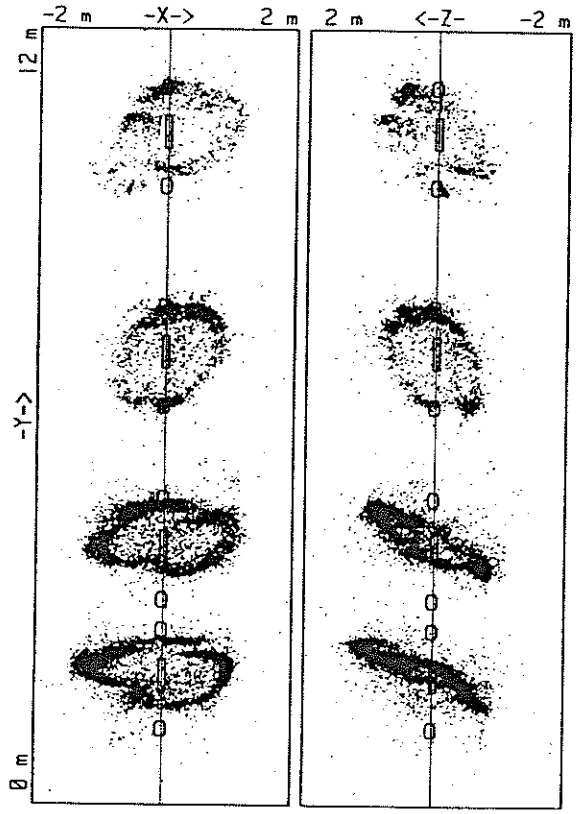

Figure 5. Located AE events of a hydraulic fracturing series at the 500-m level of the salt mine Bernburg in projections to two coordinate planes.

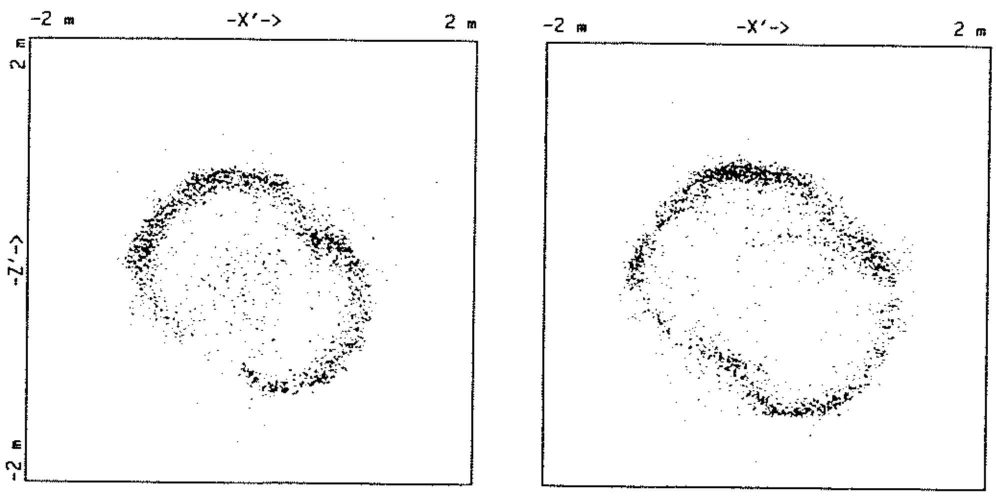

Figure 4. Located AE events during a fracturing test (left-hand side) and a refracturing test in 4 m borehole depth (right-hand side) in projection to the rotated coordinate system.

Figure 6 displays the orientation of the normal vector of the fracture planes (filled dots) in a so-called Schmidt-net diagramme. In this diagramme the cutting points of the normal vectors which correspond to the direction of the minimum principal stress are plotted in an equal-area projection to the lower hemisphere for each fracturing test. The injection well runs west-east (marked by a thick line). The orientations of the fracture planes change with borehole depth. In distances up to 4 m from the contour of the gallery, the fracture planes are inclined nearly vertical and orientated in west-east direction. The azimuth angle (measured clockwise from north) ranges from 83° (at 2 m) to 72° (at 4 m). In greater borehole depths the inclination of the fracture planes decreases up to a value of approximately 45° and the fracture planes turn north.

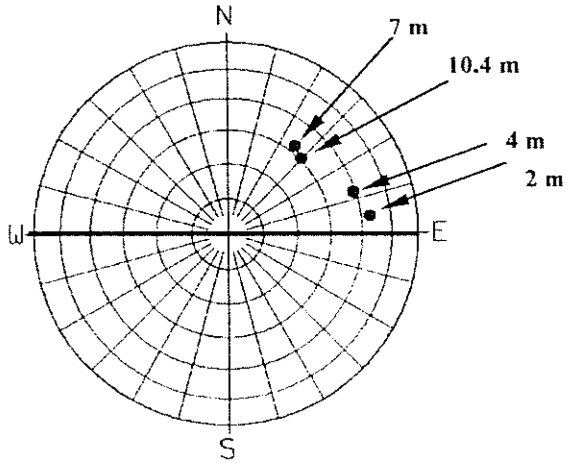

Figure 6. Orientation of the normal vector of fracture planes as seen in Figure 5 in the Schmidt-net diagramme.

3.2 *Hydraulic fracturing test series at the 800-m level in the salt mine Asse*

The fracturing series in the salt mine Asse was carried out in a pillar of 10 m width between two drifts. The horizontal injection well of 35 m length was located in the centre of the pillar and was drilled parallel to the drifts. In this injection well four hydraulic fracturing tests took place in 3.5 m, 7 m, 10 m, and 13 m borehole depths. Figure 7 shows at the left-hand side the located AE events (in total 6125 events) in projection to two coordinate planes. In the top view (x–y-plane) it can be seen that all fracture planes have nearly the same orientation independent of borehole depth. The Schmidt-net diagramme at the right-hand side indicates the same.

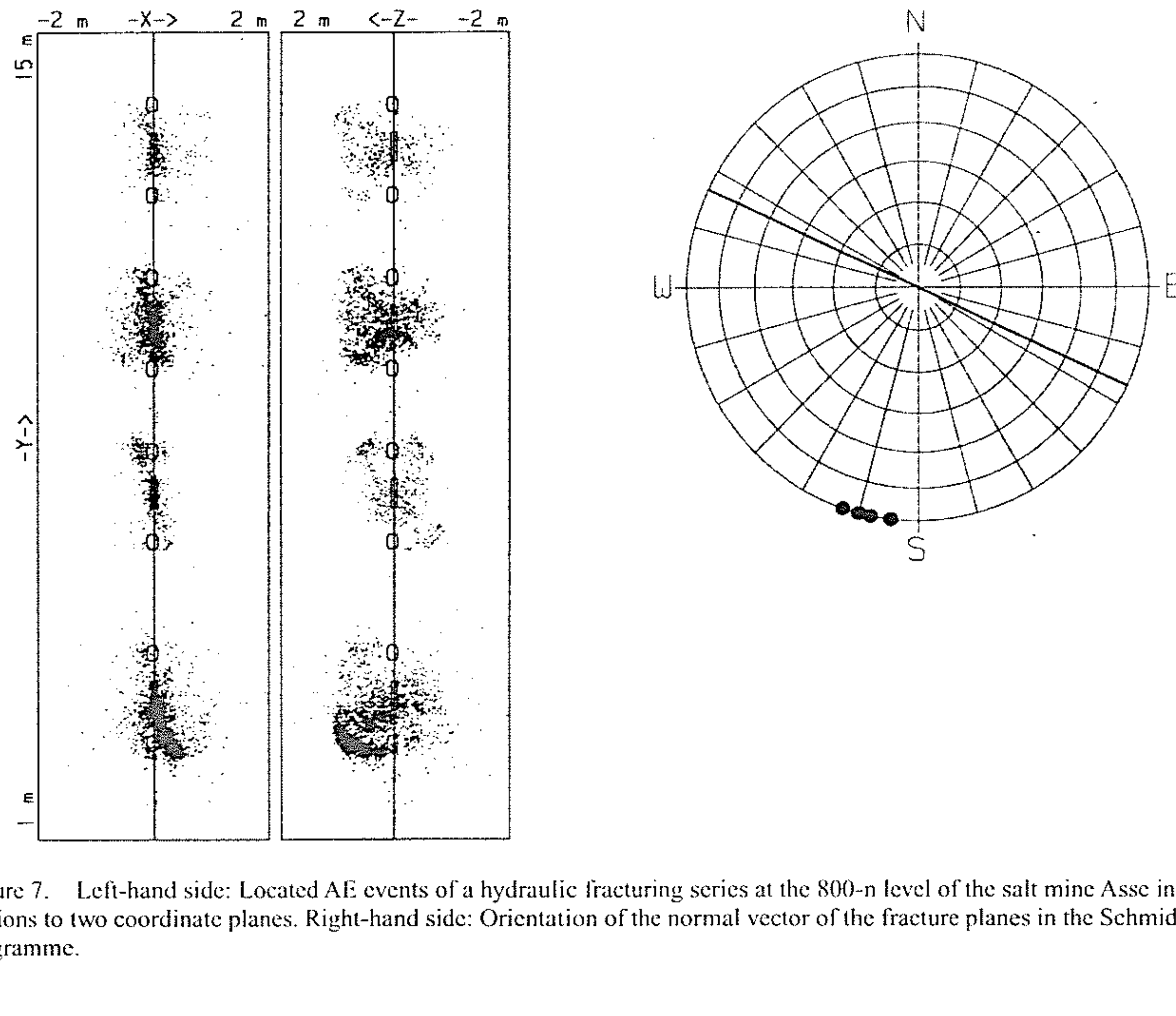

Figure 7. Left-hand side: Located AE events of a hydraulic fracturing series at the 800-n level of the salt mine Asse in projections to two coordinate planes. Right-hand side: Orientation of the normal vector of the fracture planes in the Schmidt-net diagramme.

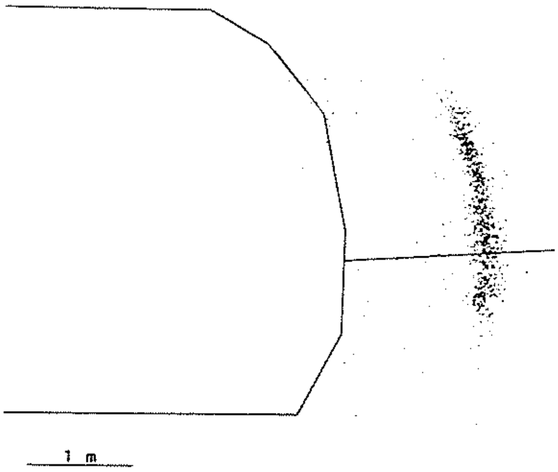

Figure 8. Location of AE events in projection parallel to the gallery axis together with the profile of the gallery and the location of the injection well.

All fracture planes are vertical and extend between the transducer arrays parallel to the borehole axis.

Another example of a hydraulic fracturing test with remarkable results is given in Figure 8. The test was carried out in approximately 2 m borehole depth in a horizontal injection well at the same test site in the salt mine Asse. This figure shows a projection parallel to the wall of the gallery together with the measured profile of the gallery and the location of the injection well. During the fracturing and two refracturing tests about 1560 events could be localized. The fracture plane runs parallel to the contour of the wall imaging perfectly its profile. This of course indicates that the stress state in this zone is strongly influenced by the free surface at the wall of the gallery.

4 CONCLUSIONS AND FURTHER APPLICATIONS OF THE BOREHOLE TOOL

The presented examples demonstrate that the new hydraulic fracturing borehole tool is capable of measuring the orientation of the minimum principal stress by three-dimensional AE source location utilizing only one borehole. The short distance between the injection point and the AE sensors leads to a high sensitivity of AE event registration. Therefore, the macroscopic fracture plane will be imaged by a great number of AE locations. Due to the fast progress of registration hardware and computer technique the number of located events could be raised in the last years by orders of magnitude. During the first fracturing tests with the said borehole tool, only a view hundred events could be localized. Now it is possible to locate up to ten thousand events during a single test.

Generally, the borehole tool is applicable in all rocks which show spontaneous and fast crack formation. Difficulties will occur in layered or multiply jointed rocks. Such rock types have a high attenuation and strong absorption of the elastic waves.

The borehole tool was developed and applied in underground waste disposal research projects where knowledge about the stress state in rocks was needed to characterize strength, tightness, and deformation behaviour of the host rock which has to isolate hazardous radioactive or chemical wastes from the biosphere for a long time. On the other hand, hydraulic fracturing measurements deliver valuable data like absolute magnitude and orientation of the minimum principal stress for the validation of structural models which are used to calculate the geomechanical evolution of the long-term stability of mines.

The borehole tool is also useful where stress measurements are needed to evaluate safety aspects in operating mines as well as to support the licensing procedure for sites of underground waste disposals.

Further promising applications relate to tunnel excavation in rock and to the construction of geotechnical barriers like dams.

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