INFLUENCE OF MINING ACTIVITY ON THE INTEGRITY OF SALT FORMATIONS AS CANDIDATE HOST ROCKS FOR NUCLEAR REPOSITORIES

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ABSTRACT

The opening, operation and post-closure of a nuclear waste repository in a saliferous system require an in-depth understanding of the stress redistribution within this system. While the stress is released in rock salt by creep, the stiffer anhydrite layers tend to store higher loads that create fracture conditions. Thus, natural joints or newly developed fractures in the anhydrite can become pathways for brines affecting the long-term safety of the repository. To investigate the effect of large-scale stress redistribution on the anhydrite in response to mining, advantage is taken of the underground environment offered by the Bernburg mine in Germany. The room-and-pillar mining conditions induce a more intense loading than expected for a normal repository.

A microseismic array composed of 16 three-component accelerometers is employed to monitor the fracture occurrence within a region of 160 x 160 x 100 m over a period of four years as the mining approaches. The analysis includes an examination of the seismic event locations, frequency, event clustering, and source mechanism. As expected, the seismic activity increased as the mining works came closer. More than 1700 seismic events that occurred during non-working days have been recorded and located. No significant fractures are observed at the interface between the rock salt and the anhydrite, but several roughly parallel band-like structures within the 35 m thick anhydrite layer exhibit high seismic activity. The source mechanism is mostly thrust-like, with few pure-shear events.

From an overlying drift, a 59 m long borehole is drilled into the center of the most active seismic cluster. An inspection with a borehole camera shows two brine-bearing joints exposed at approximately 10 and 15 m depth below the rock salt/anhydrite interface, respectively. These observations match closely the fractures derived from event locations. Furthermore, the hydraulic integrity of the anhydrite is investigated through permeability tests. Brine injection results in the borehole show significantly increased permeability in the joint region ($2 \cdot 10^{-15}$ m^2), which does not appear to affect the integrity of the anhydrite above the joint (permeability below 10^{-18} m^2).

INTRODUCTION

The salt formations have long been proposed as potential host rocks for nuclear waste. Rock salt and anhydrite layers are part of the normal stratigraphic sequence of the saliferous system, which is subject to geomechanical load changes during the opening, operation, and post-closure phases of a radioactive waste repository. In contrast to the rock salt, which shows a pronounced creep behaviour resulting in the reduction of the increased stresses, the stress tends to concentrate in the stiffer anhydrite. As a result, natural joints or newly developed fractures may be present in the anhydrite. They can become potential pathways for brines, thus affecting the long-term safety of the repository.

Due to the critical role played by the anhydrite in the stress transfer within salt formations, its properties and behaviour have been investigated in detail throughout several projects carried out at the Bernburg mine, Germany [1, 2, 3]. Earlier work concentrated on the analysis of the mechanical and hydraulic parameters of the anhydrite in laboratory, and on the determination of the properties of the excavation damaged zone and exposed joints in the anhydrite in-situ. The results of these investigations suggested that the anhydrite is very tight, with permeabilities below 10^{-21} m^2 both in the undisturbed rock as well as in the presence of closed or filled joints. These measurements, however, were performed at rather stable stress conditions, far from large excavations.

The current study investigates the effect on the anhydrite integrity of large-scale stress redistribution in response to mining. Microseismic monitoring is employed for the identification of the instantaneous stress release in the anhydrite as a result of fracture occurrence. At selected locations, hydraulic measurements by liquid injection into boreholes are performed, and their results are independently checked by visual camera inspections.

TEST SITE AND INSTRUMENTATION

The Bernburg mine is located approximately 35 km south from Magdeburg, in the state of Sachsen-Anhalt, Germany, and is operated by the European Salt Company (ESCO). Here, the Leine salt is mined out using the room-and-pillar method. The test site is located north-west of an exploitation panel which is situated between 350 m and 400 m below sea level (427 m and 477 m below ground level, respectively). The rooms are typically 220 m long, 20 m wide, and 35 m in height, separated by 28 m wide pillars (Figure 1). Mining is performed in two steps: at first, a relatively small drift is made to remove the upper 4 m layer, after which the salt is produced by drilling and blasting. The operation proceeds from south to north. Room 2113 (the second from the south in Figure 1) was finished in 1999, room 2112 (the third from the south) in March 2001, and room 2111 (the northernmost) was mined during 2002.

The main anhydrite layer underlying the mined Leine rock salt has an average thickness of 35 metres. Unlike rock salt, the anhydrite does not creep. Instead, it exhibits high stiffness, which under the mechanical loading conditions of the rock leads to the formation of joints. These joints will always be present within the anhydrite, either closed or filled with secondary minerals like carnallite or halite. In order to detect fracture formation and opening, a microseismic monitoring system was installed underground.

The microseismic array consists of 16 three-component accelerometers with a flat response (to within ±3 dB) between 10 Hz and 5 kHz, and a sensitivity of 3 V/g. It has been designed to cover a region of approximately 160 x 160 x 100 m located north-west of the exploitation panel, where fractures occur in the underlying anhydrite as a consequence of mining (Figure 1). At the test site, the interface between the Leine salt and anhydrite is at a depth of approximately 415 m below sea level. Four of the sensors are located right in the anhydrite layer, whereas the rest of them are located in the overlying rock salt. Signals are transmitted through copper cables from sensors to a central acquisition, trigger-based ESG Hyperion Microseismic System (HMS) where they are digitized at 20 kHz with 16-bit resolution. The system allows for automatic event identification, location, source parameter evaluation, visualization, reporting and archiving.

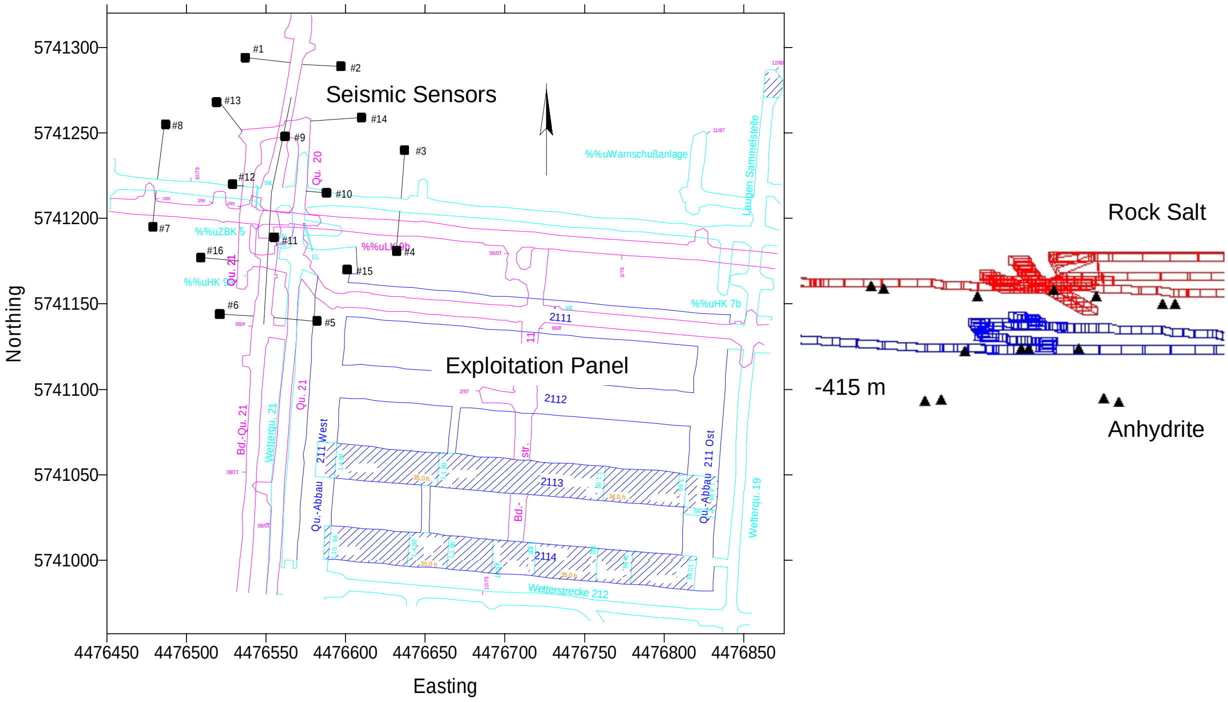

Fig. 1. North-east (left) and east-depth (right) projections of the microseismic array and the nearby mining area at the Bernburg mine

The monitoring started in 2000, and continued over a period of four years, during which the mining face approached the study region from the south. Changes in the seismic event frequency hint to fracturing processes, whereas event locations and source mechanisms yield information about the position, size, and failure characteristics of these fractures. The compressional (P) and shear (S) wave velocities required for event locations have been evaluated by active seismic measurements, using a sledgehammer as the source. The derived values are 4,781±145 m/s and 2,734±49 m/s, respectively. The majority of the location errors are below 5 m in the horizontal coordinates and below 8 m in depth.

SEISMIC RESPONSE TO MINING

Automatic First Arrival Picking

After an early testing and recording phase in 2000, which had to be interrupted due to interference with mining operations, the main recording phase started in July 2001 and lasted until May 2004. The seismic system recorded on average about 10,000 triggers per month, with almost 30% of them located in real-time. The visual inspection of records shows that a very high noise level associated with the general mining activity is not only responsible for the heavy triggering, but also for many automatic first arrival mispicks. Since much of this triggering is unrelated to the actual fracturing, in the view of the above difficulties, the decision was made to restrict the analysis to those events occurring during non-working days, mainly weekends, when no underground shift work was undertaken.

Event location uses first wave arrivals in a Geiger technique [4]. Since manual processing is very time consuming, automatic picking appears attractive. The standard P-wave algorithm includes threshold and short time vs. long time (STA/LTA) average levels. In this study, the P-wave picking additionally includes an analysis of all the recording maxima: (i) if more than 5 acceptable picks are detected the seismic signal is treated as a multi-source event and the sensor dropped out; (ii) a check for potential spikes in the signal is introduced; and (iii) a test is performed to verify whether identified picks are preceded by significant jumps in signal energy, in which case the data is rejected [5]. Network confirmation checks all pairs of sensor picks for arrival time differences less than the time necessary for the P-wave to travel between the respective sensors. The group of sensors that do not contravene the above criterion is selected and all inconsistent picks are reevaluated against it, thus restricting the search for P-wave arrivals on problem traces.

The default S-wave detection technique employed by the HMS is based on a functional [6] defined as the product of (i) the polarization coefficient, (ii) the normalized depletion angle, and (iii) the energy ratio of the rotated transversal component to the sum of radial and transversal components, with each of these parameters reaching the maximum value of 1 at the arrival of the S-wave. The revised picking also includes the total energy ratio in time windows preceding and following the S-wave pick. For every pair of sensors a consistency check is carried out for both P- and S-wave arrivals. Inconsistent arrival picks are subsequently reevaluated against the entire group of consistent arrivals.

The comparison of revised automatic and manual picking for about 1,500 events reveals time differences of ±0.5 ms for both P- and S-waves, well within the average residuals expected for this array. Not only do the resulting spatial coordinates match closely, but also the location error distributions are similar, peaking – in a vectorial sense – between 3 and 5 m for the automatic location, and just under 4 m for the manual location. The automatic identification misses 20% of the manually processed events, but less than 2% of the automatically located events are not real seismic events. This means that revised automatic picking will more likely miss an event than provide unreliable event location.

Event Location and Frequency

The distribution of event locations and that of event occurrence frequency are shown in Figure 2 for a recording period of nearly four years. More than 1700 microseismic events were located, the vast majority in the anhydrite, but some of them in the overlying rock salt mined area south of the seismic array, around an excavation damage zone. The event moment magnitudes are below zero, mostly between -3 and -1. The events in the anhydrite are mostly arranged in roughly parallel, band-like structures (Figure 2A). They are not concentrated along the transition zone between the rock salt and the anhydrite, but lie well within the anhydrite layer.

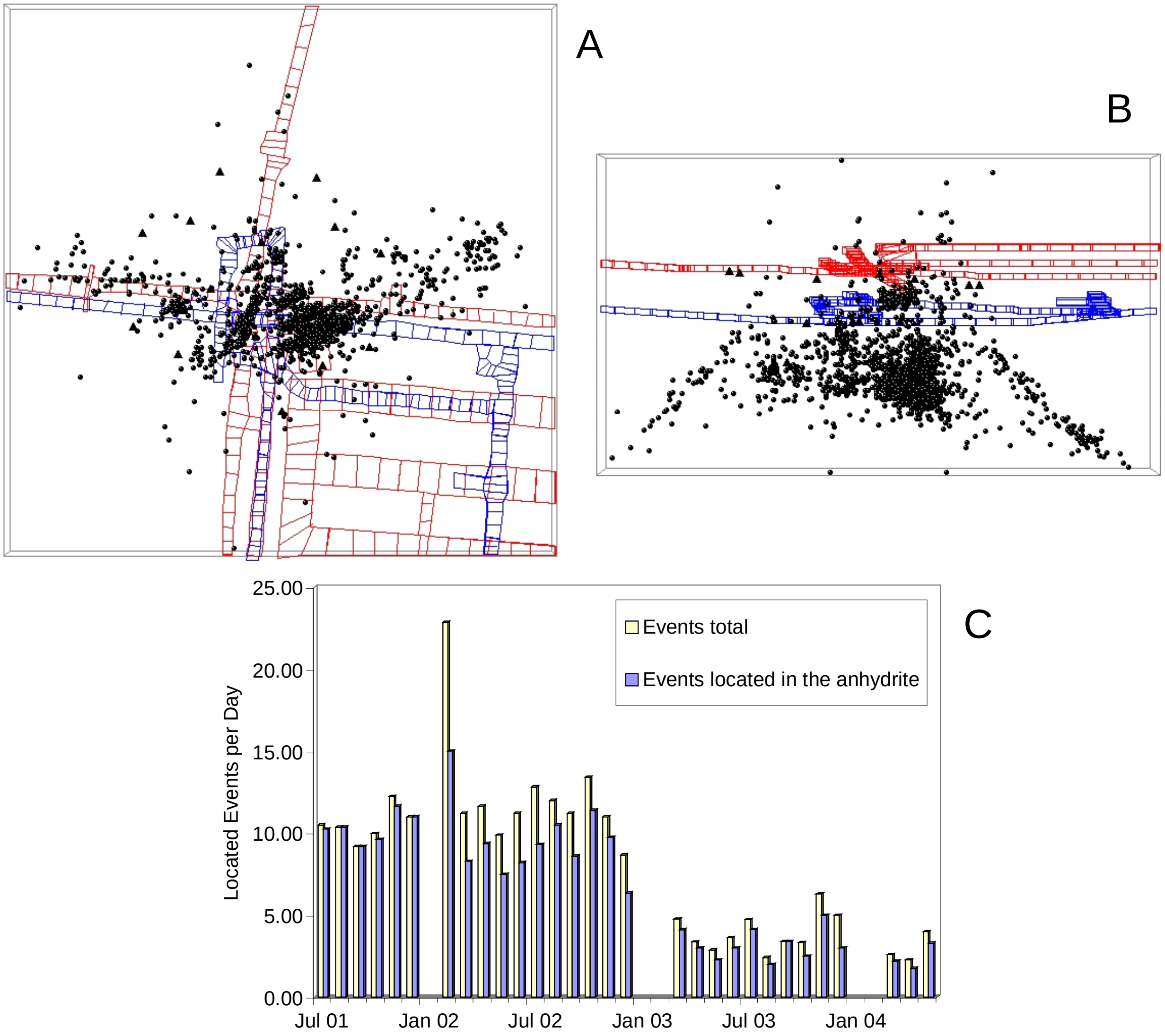

Fig. 2. North-east (A) and east-depth (B) projections of event locations and event frequency (C) between July 2001 and May 2004

The frequency of event occurrence (Figure 2C) shows high values until the end of 2002 when the nearby mining ended, after which it reduces significantly. A sharp increase is noticeable, especially of events in the rock salt, at the beginning of 2002 when the exploitation of the closest room to the array started. Seasonal variations are also visible, with somewhat higher frequencies during autumn and winter when the mining activity was increased in view of the road de-icing needs. The lack of located events in January and February 2003 and 2004 is a consequence of the high production rate during these months that included work shifts during weekends.

Event Cluster Analysis

For a detailed analysis of the characteristics of microseismicity located in the anhydrite, accurate manual processing was employed for the events occurred during the days with no work shifts between July 2001 and September 2002 (1795 events). Figure 3 shows a pronounced event clustering, with the clusters represented as blue ellipsoids. Objective cluster identification was done using the Maximum Expectation (EM) algorithm [7]. The most active cluster contains nearly 60% of all the events and is marked with a red ring.

Except for the cluster in the rock salt south of the seismic array which is most likely related to the generation of an excavation damage zone around the mined out rooms, all clusters are located well within the anhydrite rather than near the transition zone. The cross correlation between most of the largest cluster pairs is highest at zero time lag, which indicates that microfracturing occurs in them independently of each other, and that it is generated by the same external source.

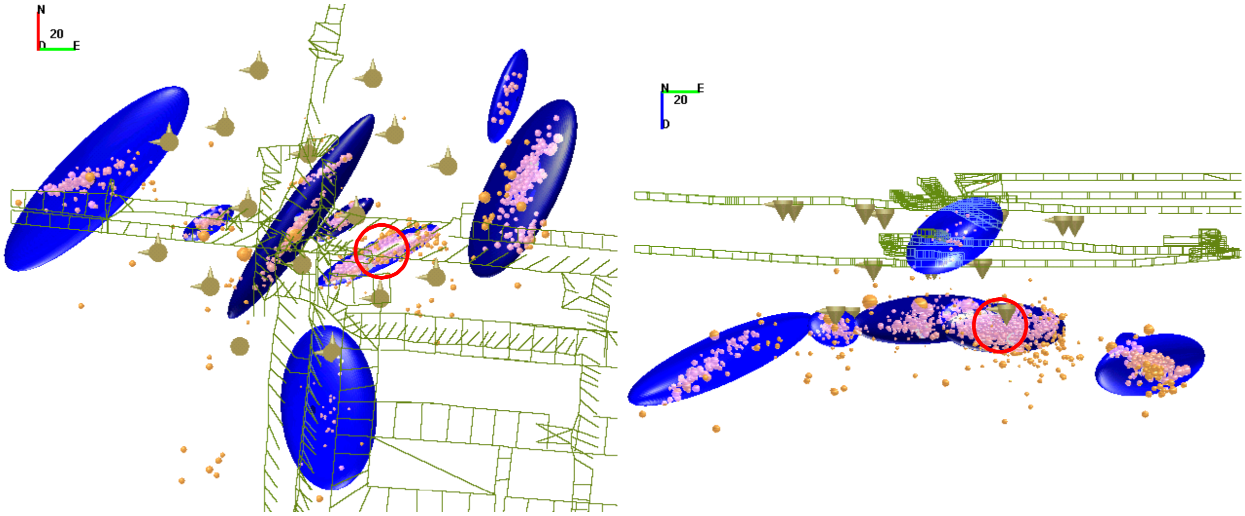

Fig. 3. Event clustering between July 2001 and September 2002 in north-east (left) and east-depth (right) projections. Clusters are shown as blue ellipsoids, with the most active one denoted by a red ring

Source Mechanism

The event mechanism was investigated for the events that occurred between July 2001 and September 2002 (Figure 3) using a fully automatic seismic moment tensor inversion technique [8, 9]. The presence of low signal-to-noise first arrivals in the recorded waveforms represents a source of uncertainty in polarity picking, which can lead to alterations of the moment tensor solution. Therefore, objective (automatic) data analysis is required to increase the accuracy of first arrival polarity picking.

The waveforms were first rotated into the ray coordinate system, using the known source location. For P-waves, only picks with residuals less than 2 ms (location error <10 m) are retained. The picks are then adjusted based on an extension of STA/LTA approach in which the highest dispersion ratio is searched using three different time windows calculated to include one to four cycles at the signal’s predominant frequency. For S-waves, the final detection criteria also included the coefficient of polarization, the depletion angle, the cross-correlation of signal components at zero time lag, and squared trace length along particle movement. The normalized squared amplitudes of these six parameters are multiplied and weighted by the S-wave time residual, the resulting maximum indicating the S-wave arrival. Polarity is estimated for the first statistically significant deviation prior to wave arrival.

The moment tensor solutions indicate that the predominant source mechanism is thrust-like. While there are very few pure shear events, both positive and negative volumetric failure components are present as well. The results support the conclusion that there are no strong shear stress accumulations. This is indicative of the formation of new fractures in intact anhydrite, along already present zones of weakness within the rock.

ANHYDRITE INSPECTION

In order to gather information about the state and the hydraulic properties of the anhydrite in the study region, a borehole is drilled into the center of the most active cluster for inspection and for performing hydraulic tests. Due to mine requirements, the borehole is drilled steeply inclined from the upper level of 370 m depth. It has a diameter of 56 mm and a length of 59 m. Its end point corresponds to the center of the red ring in Figure 3.

During the drilling it was found that the lower part of the borehole bears brine. Borehole inspection with camera showed no signs of alteration at the transition between rock salt and anhydrite. Instead, two carnallite-filled joints several centimeters thick were detected at depths of about 49.5 and 54.5 m, or about 10 and 15 m below the salt/anhydrite boundary, respectively. The joints are located exactly in the seismically active zone. While the anhydrite above the joints appears intact, brine is found dripping from the joints deep into the borehole during the inspection, and a brine pool has accumulated at the bottom of the borehole. Figure 4 presents photos of the upper joint and the intact anhydrite above it.

PERMEABILITY TESTING

In order to investigate the hydraulic properties of the anhydrite in the joint region and above, permeability tests with a four-packer probe were designed. Originally, gas injection tests had been planned, but problems with the lowering of the probe into the borehole and the fact that the formation was bearing brine led to the decision to fill the borehole with water and afterwards perform brine injection tests. Due to the great depth within the borehole at which the tests had to be carried out, it was assumed that the probe could only be coupled to the rock once; the possibility of moving or retrieving the probe afterwards seemed unlikely.

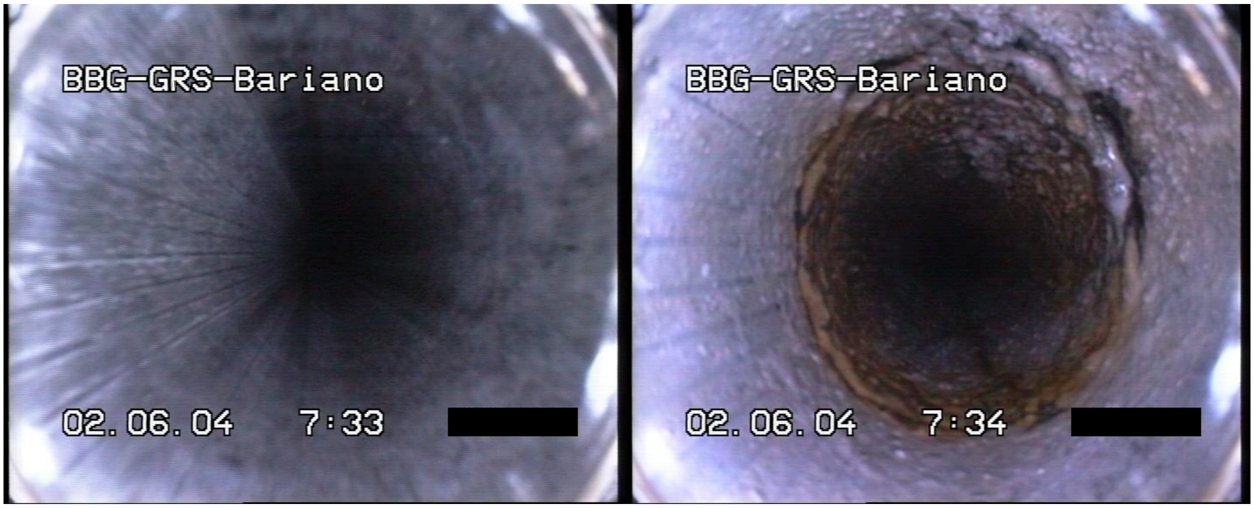

Fig. 4. Borehole camera inspection shows intact anhydrite at 47.45 m depth (left) and brine-bearing carnallite-filled joint at 49.55 m depth (right)

The probe is a four-packer system with 0.5 m long oil-filled packers. Between the four sealing elements there are three test intervals. The central interval is 0.8 m long, whereas the other two are 0.3 m long each. Since the probe can only be positioned once within the borehole, it was placed at a depth where both the upper joint and the anhydrite above it could be tested using the upper and lower test sections of the probe, respectively. The centers of these sections are located at the depths indicated in Figure 4.

The above probe was installed three weeks after filling the borehole with water, in June 2004. For the brine injection tests, a system previously developed [10] for the investigation of the excavation damage zone in rock salt [11, 12] was employed. At injection rates between 0.2 and 0.6 l/h, each of the test intervals was filled to a maximum overpressure of 3.2 MPa. The pressure evolution during the injection and subsequent shut-in phase was recorded. From these measurements, the permeability of the formation around the respective test interval was derived using the commercially available "Weltest 200" code for oilfield testing [13].

As expected, the two tests resulted in significantly different permeability values. The test in the upper interval, located in the apparently undisturbed anhydrite, exhibited a permeability to brine below 10^{-18} m^2. Since the recording time for this test was too short for the slow pressure decay, the above value is only an upper estimate. It is very likely that the actual permeability is significantly lower. It is worth noting that earlier tests performed at the Bernburg mine reported anhydrite permeabilities below 10^{-21} m^2 [1]. In the joint region within the lower test interval, the pressure decay was fast enough to allow two successive injection tests. The evaluation resulted in a high permeability value of $2 \cdot 10^{-15}$ m^2.

CONCLUSIONS

Microseismic monitoring has proven to be a reliable and accurate tool for detecting weak zones in the stiff anhydrite that are activated as a consequence of stress load redistributions in the course of mining. These redistributions resulted in the activation of existing joints and the formation of new fractures in the anhydrite, but not in the alteration of the transition zone between the rock salt and anhydrite.

With regard to the construction of a radioactive waste repository in rock salt, the room-and-pillar mining conditions at the Bernburg mine introduce a much more intense loading than expected for a high-level waste repository with relatively small openings. The underground study site at Bernburg had been deliberately chosen in order to obtain a maximum effect. The results obtained in this analysis support the conclusion that highly permeable zones are restricted to the inner anhydrite without affecting the salt/anhydrite boundary. Consequently, it appears that with proper care it should be possible to construct a salt repository without creating shortcuts to hydraulically active joints in the anhydrite. However, more permeability measurements would be desirable in order to convincingly validate the above statement.

It is worth mentioning that independent microseismic monitoring, visual borehole inspection, and permeability measurements led to consistent and plausible results. This strongly suggests that these techniques are useful and should continue to be developed for employment in future investigations.

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