MULTIPLET ANALYSIS FOR ESTIMATION OF STRUCTURES INSIDE AN AE CLOUD ASSOCIATED WITH A COMPRESSION TEST OF A SALT ROCK SPECIMEN

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Abstract

A multiplet analysis of acoustic emissions (AE) from a salt rock specimen was performed. A multiplet is a group of events with similar waveform considered to be generated on the same crack plane. We applied a multiplet analysis to determine the precise relative source locations of AE events and delineate the structures inside the rock specimen. The results were compared with the source locations determined by the joint hypocenter determination method. The crack planes were estimated from the source locations of multiplets, and the orientations of the planes were evaluated. No trend in the orientations of the crack planes defined by their source locations was found, and the multiplets did not occur on a single crack plane but on adjacent microcracks within a region. The feasibility of a multiplet analysis for finding microstructures and evaluating crack extension was demonstrated.

Keywords: Signal processing, microseismology, cross-spectrum analysis

Introduction

The determination of acoustic emission (AE) source locations is a key procedure for crack distribution evaluation and source mechanism analysis. Several precise mapping technologies have been developed in engineering seismology [1-4]. The application of precise mapping methods to phenomena such as earthquakes on natural faults, subduction zones, and geothermal or oil and gas reservoirs has revealed that such methods are feasible for the evaluation of fault/crack orientation and dynamics, such as the fault slip rate, as well as for determining the locations of the faults/cracks. The collapsing method is an advanced mapping technique for delineating structures. We previously applied this method to AE events from a salt rock specimen to identify the structure inside the specimen [5]. The collapsing method emphasizes structures by optimizing source locations, and it is a feasible means of quickly delineating structures from AE clouds of large numbers of events. However, with this method it is difficult to interpret directly the physical meaning of the delineated structures because the collapsing method is a relocation method, which moves the original source locations by taking into account the size and shape of the error distribution for each source location and then redetermines the source locations through mathematical optimization. On the other hand, a multiplet analysis is a precise mapping method for similar AE events and then determining their relative source locations by a cross-spectrum analysis. This method has been applied to AE events in geothermal fields to estimate the fractures activated by fluid injection to enhance the reservoir [6, 7]. Recently, multiplets were used to evaluate repeating earthquakes in a subduction zone in northeast Japan, and a multiplet analysis was found to be a feasible method for evaluating the slip rate and the relationships between slip behavior and earthquakes in the subduction zone [8]. However, a multiplet analy-
sis has not been applied to AE events from a rock specimen because the frequency component of AE events from the cracking of a rock specimen is several hundred kHz, which makes it difficult to obtain reliable full-waveform data, to which a cross-spectrum analysis can be applied, owing to the limitations of the digital data acquisition system. If a multiplet analysis could be applied to AE events associated with cracking in a rock specimen, then this technique would be feasible for measuring crack extension and investigating the dynamic behavior of cracks such as has been done in the case of natural earthquakes and AE events in geothermal fields. In this paper, we apply a multiplet analysis to AE events from a salt rock specimen to show the feasibility of a multiplet analysis for the evaluation of structures inside the specimen.

![Example of waveform](image)

**Fig. 1 Example of waveforms composing a multiplet.**

**Multiplet Analysis**

Figure 1 shows waveforms of a multiplet detected during one axial compression test of a salt rock specimen. A group of similar microseismic events is called a multiplet [1]. A multiplet is most likely the expression of stress release on the same crack plane, with the same source mechanism. High-resolution mapping of multiplets by a cross-spectrum analysis makes detailed identification of small-scale fractures possible. A multiplet analysis is a method for determining relative source locations of similar AE events. AE events with similar waveforms are detected using a coherency function and visual observations. A cross-spectrum analysis is applied to similar AE events to detect differences in the relative arrival times of the waves. In general, source location errors are caused by picking errors in the detection of $P$- and $S$-wave onsets, because the precise detection of wave onsets is difficult. The introduction of a cross-spectrum analysis makes it possible to detect wave arrival times of slave events relative to the master event. In a multiplet analysis, the source locations are considered to be adjacent to one another; therefore, the wave propagation paths of similar events are almost the same, and the effect on the velocity structure along the ray paths can be cancelled. Thus, source locations determined by considering the origin of similar events can provide information on the spatial distribution and orientation of seismically activated cracks.
Experimental Procedures

The experiment was conducted on a cylindrical salt rock specimen (diameter, 150 mm; length, 300 mm) from the Asse salt mine in Germany, in the laboratory of the Department for Waste Disposal Technology and Geomechanics at the Technical University of Clausthal, Germany [5]. A triaxial hydraulic loading system, which contains a hydraulic cell where a cylindrical rock sample covered by a Viton sleeve is subjected to high hydraulic pressure, up to 75 MPa, and additional axial force up to 2.5 MN, was used for the test [9]. During the test, the axial displacement and axial force, the radial pressure, and the volume change (dilatancy) of the specimen were measured and displayed on the screen of a computer. The digitized data were recorded by means of a personal computer (PC) running Linux and stored every 5 s on the hard disk. The pore volume of the specimen, which corresponds to the change in the oil volume in the triaxial cell, was measured using a double-acting hydraulic cylinder. The accuracy of the dilatancy measurement was about 0.0025% of the total volume within the load cell. At the beginning of the test, the specimen was compacted overnight (16 h) under isotropic stress conditions at a pressure of 20 MPa to close open fractures at the surface of the specimen, which had been created during the forming of the sample. After the compaction phase, the test was performed by applying a constant strain rate of 0.05%/min and a constant radial pressure of 5 MPa. The strain rate corresponds to an axial displacement of 0.15 mm/min.

Fig. 2 Locations of sensors.
AE sensors were countersunk into the surface of the specimen in small milled holes (Fig. 2). A stiff strain gauge glue was used to affix the sensors within the holes. Each sensor was a piezoelectric disk made of lead metaniobate ceramic with an aperture of 7 mm and a thickness of 5 mm. Lead metaniobate ceramic has a low mechanical quality factor, a low dielectric constant, and no planar coupling factor. This material is used primarily when a clean impulse response is required. A brass casing protects the piezoelectric disk against damage from deformation of the specimen during compression. The AE measuring system includes three four-channel transient recorder cards in the PC. The transient recorder cards (sampling rate, 10 MHz; resolution, 14 bit; storage capacity, 512 kByte/channel) were read each time when at least two channels were hit. The digitized signals were stored on the hard disk of the PC.

Additionally, ultrasonic transmission measurements in the axial direction and at two high levels in the radial direction were performed using separate senders. A wide-band signal (like a step function) with a rise time of 1 µs was used. For the transmission measurements, which were repeated every 5 min, the axial compression and the AE measurements had to be interrupted. The overall duration of the test was about 4.3 h.

**AE Source Location by Joint Hypocenter Determination**

First, we determined the source location by using the travel-time inversion method, where $P$-wave arrival times were used to determine the source locations and the origin time. The velocity structure was assumed to be homogeneous ($V_p = 4650$ m/s). The RMS (Root Mean Square) of the residuals was 1.596 µs. Next, the joint hypocenter determination (JHD) method was applied to determine the source locations. The JHD method determines AE source locations jointing the whole events and picking values [10]. The source locations can be estimated by removing systematic errors through iterative compensation of the station correction. Figure 3(a) shows the source locations determined by the JHD method. The location accuracy was slightly improved and the RMS of residuals decreased from 1.596 µs to 1.549 µs (Table 1) when only the source locations of AE events identified as multiplets were plotted.

**Application of A Multiplet Analysis**

The best way to find similar waveforms is to identify them by eye. However, it is impossible to deal in this way with large numbers of events. To solve this problem, we previously introduced a coherence function, which calculates the correlation between two time series in the frequency domain [1]. A total of 10,000 events were searched for similar waveforms using the Ch. 1 signals, and the mean coherency values in the frequency range of 50–150 kHz were calculated. The time window used for the calculation was 400 µs, and the $P$- and $S$-wave codas were also included. AE events with a coherency of more than 0.68 were identified as a group of similar events. In all, 2856 events (approximately 29%) were classified into multiplet groups. Twenty-nine % is not a high value when compared with AE in, for example, a geothermal field. The waveform coherency when $P$- and $S$-waves are included is lower than that of AE events in a geothermal or other large field. In the case of AE in a small specimen, some of the events occur within the area regarded as the near field, because the distance from source to sensor is small compared with the wavelength. Therefore, the $P$- and $S$-waves cannot be distinguished, and the waveforms change dramatically depending on the apparent incident angle from source to sensor, which is the reason that the proportion of similar events is low.
Table 1 RMS of the residuals for different mapping methods.

<table>
<thead>
<tr>
<th>Method</th>
<th>RMS of the residuals (µs)</th>
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<tbody>
<tr>
<td>Single Event Location</td>
<td>1.596</td>
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<tr>
<td>Joint Hypocenter Determination</td>
<td>1.549</td>
</tr>
<tr>
<td>Multiplet Analysis</td>
<td>0.317</td>
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</tbody>
</table>

Fig. 3 Source locations by (a) JHD and (b) cross-spectrum analysis (multiplet analysis). The different symbols denote different groups (some of the groups have the same symbol due to the limitation of the number of symbols).
We selected those groups consisting of more than four similar events, and applied a cross-spectrum analysis to determine the relative travel time. A total of 199 groups were analyzed, and the relative source locations of 449 events were determined, where events were removed from the analysis if the RMS of the residuals exceeded 1 µs.

Figure 3(b) shows the source locations determined by the cross-spectrum analysis, and Fig. 4 shows source location projections for 20-mm-thick slices. AE clusters corresponding to each multiplet group are shown. The center of gravity of the multiplets is the same before and after the relocation of the AE clusters. A multiplet analysis can determine source locations only relative to a master event; and the absolute locations cannot be determined. Therefore, the relocated source locations for each group are shifted to the position, for which the center of gravity of source locations becomes the same before and after the relocation.

Figures 5(a) and 5(b) show the source locations of a multiplet before and after relocation. The source distribution occupies a smaller area after the relocation because the error in the source locations was decreased by the cross-spectrum analysis. The RMS of the residuals for all of the estimated events was 0.317 µs in the multiplet analysis; therefore, the source location accuracy was improved.
Discussion

The smaller RMS of the residuals suggests that the source location accuracy was improved by the multiplet analysis. On the other hand, because a multiplet can be considered to be the expression of stress release and destruction at the same crack with the same source mechanism, we might infer that the planes formed by each cluster represent the crack planes induced in the rock specimen. Therefore, we calculated the crack planes defined by the best-fitted plane for each source location. Figure 6 shows the poles of the calculated planes, where each pole represents a multiplet of at least five similar events. Although we expected the orientation of the planes to be vertical because the rock specimen was compressed in the vertical direction, thus inducing vertical cracks by tensile stress, no tendency was found in the orientations of the estimated planes. Figure 7 shows the contribution ratios calculated using the covariance matrix defined by the coordinate systems of the source locations and the eigenvalues of the matrix. This analysis is a part of the principal component analysis, and the contribution ratio is an indicator of the source distribution in space. For instance, if the first and second contribution ratio indicates 1.0, then the
source locations in the group lie on a plane. The population mode of the first contribution ratio was high, around 0.7, but the first and second contribution ratios ranged from 0.3 to 1.0 (Fig. 7). These contribution ratios indicate that the source locations were distributed within an elliptical region and not on a flat plane. This result implies that similar AE events did not occur in a simple crack plane; thus, AE behavior differed from that of AE in a subsurface field such as a geothermal field [6].

A moment tensor analysis suggested that crack formation was accompanied by a significant isotropic part and an increase in the specimen volume, and that the source mechanism was also a combination of tensile and shear modes. These analyses and observations suggest that the AE events did not occur along a crack plane caused by shear dislocation, such as with a fault in the Earth's crust, which is supported by the observation that a computed tomography image of the specimen embossed the visible open cracks associated with the compression test. On the other hand, the salt rock was composed of grains a few millimeters in diameter and exhibited a cellular structure. In such a case, the AE events would occur at the boundaries between grains, when grains become separated from each other or as a result of friction caused by the compression of the specimen, and the source locations would be dispersed around the grains.

![Fig. 7](image)

**Fig. 7** Contribution ratios calculated using the coordinates of the source locations.

Therefore, we infer that the AE events with similar waveforms were induced by microcracks or by friction at the grain boundaries with the same source mechanism, and that the multiplet analysis of the rock specimen delineated the region where the AE events had the same source mechanism, which was not a planar structure like a fault in the Earth's crust. Clear planar structures could not be delineated because the AE mechanism in a rock specimen is different from that in the Earth's crust. AE events in the Earth's crust are generated along a fault by shear slip, and the source locations are distributed along the plane represented by the fault.

**Conclusions**

We used a multiplet analysis to determine relative source locations by a cross-spectrum analysis. The source locations were estimated by both the JHD method and the multiplet analysis. The RMS of the residuals revealed that the location accuracy in the multiplet analysis was better than that in JHD, and clusters could be identified after the relocation. The planes defined by the source locations of the multiplets were calculated to estimate the orientation of the crack planes in the specimen. No tendency was found in the orientations of the estimated planes, indicating that the source locations determined by the multiplet analysis depicted volume structures rather than planar structures. The explanation is that the AE events with similar waveforms were induced by microcracks or friction among the grains with the same source mechanism, and did
not occur along crack planes such as faults in the Earth's crust. Although crack plane-like structures were not clearly delineated, we confirmed that a multiplet analysis is a feasible method for estimating more precise source locations and for delineating structures within a rock specimen.

Acknowledgements

The authors thank Dr. U. Düsterloh and Mr. Niens from the Technical University of Clausthal for conducting the experiment. We are grateful to Dr. T. Spies and Dr. J. Hesser (Federal Institute for Geosciences and Natural Resources, Hannover) for providing us with the AE measuring system. This work was carried out as a part of MTC International Collaborative Projects.

References