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MINE, Mining Environments: continuous monitoring and simultaneous inversion

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Abstract

Continuous monitoring of fracturing processes in mine environments and the consequent characterization of the damage induced during mining exploitation is of primary interest both for mining engineering and civil protection. The development of improved monitoring and imaging methods is of great importance for salt mines as potential reservoirs for CO_2 sequestration. Imaging tools able to handle continuous data streams and providing fast reliable information about stress perturbations and fracturing state will offer important new information to support local authorities in decision-making processes. The monitoring framework will manage continuous datasets, including acoustic, seismic, deformation and thermal data, give access to different inversion and modelling techniques. Continuous data acquisition and storage and automated routines for data analysis will be implemented to image the time evolution of 3D structures at a very local scale. Acoustic and seismic data, whose routinely use in mining survey is typically limited to estimate location and magnitude, will be more widely analysed thanks to full waveform analysis, learning from seismological applications at larger scales. Automated processing will include triggering, source location, moment tensor and extended source parameters inversion. This knowledge can be subsequently used to derive local stress perturbations. A set of different tools, based on statistical analysis of spatiotemporal crack distribution, will be applied to identify rupture clusters and fracturing processes. Local earthquake tomography, which couples source location and seismic velocity inversions, will be applied and interpreted to image the velocity structure. The inclusion of data from cavity deformation, thermal and chemical monitoring will complement acoustic and seismic information, providing a multidisciplinary dataset. The coupling of different data and joint interpretation/inversion methods within a common surveying framework will finally provide high-resolution 3D and 4D tomographic images of the mining area and a continuous monitoring of fracturing processes.

1. Introduction

Human activity and mining exploitation may produce significant damages to the surrounding rocks and locally induce seismic activity, with rupturing process scales ranging from mm-long microcracks up to hundreds of meters rupture lengths of induced earthquakes. It is important to monitor the dynamics of rupturing processes and the perturbation to the background stress field in order to detect weakened regions and evaluate risks of further dangerous ruptures or changes in hydraulic permeability. The development of new monitoring tools that are economically and ecologically rentable, able to handle continuous and multi-stream data processing, and derive underground models by a combined interpretation/inversion of different observations, would offer a chance to substantially improve the imaging of the subsurface 3D structure and permeability and its time evolution.

Common geophysical mining monitoring techniques include acoustic, seismic and deformation data. Acoustic data acquisition is done by piezoelectric sensors, which detect high-frequency radiation associated to microcracks. Geophones and broadband seismometers sometimes complement acoustic sensors to detect larger events. The standard approach of seismic-acoustic surveys consists of the analysis of discontinuous recordings, based on event triggering (e.g. JAGUAR project, deep gold mines in South Africa). Typically, only arrival time information is saved and only in rare cases, for larger events, short time windows are stored. Due to discontinuous and incomplete waveforms, data interpretation is often limited to source location and magnitude estimation. Limitation towards continuous recording related to computational requirements are nowadays overcome, as storage devices can now handle multi-trace continuous records for periods of some weeks. Continuous acoustic and seismic data would allow the implementation of automated full waveform analysis tools. Full acoustic waveform inversion can be used to derive source location, magnitude and moment tensor (e.g. Manthei et al. 2001).

Waveform modelling of seismic data is routinely used in seismological approaches at local to teleseismic distances. Real-time moment tensor solutions procedures are well established. Fast automated routines to derive extended source parameters have been implemented by German projects Kinherd and RAPID (Cesca et al. 2010, Heimann 2011). Applications in mine environments included source estimation of mining induced seismicity (Dahm et al. 1998, 1999, Fletcher & McGarr 2005). Local earthquake tomography (LET) is a powerful tool to invert the local 3D velocity structure and simultaneously improve hypocentral locations. Limits of LET applicability may arise by poor distribution of travel paths and significant diffractions at galleries. LET applications to mining monitoring are rare until now, but successful applications at local scale have been carried out. Mine environments, with small study regions and convenient receiver configurations, are a favourable case study to successfully implement these techniques. If source location, modelling and LET allow monitoring the time evolution of fracturing processes, stress inversion is helpful to evaluate further rupturing risks. Stress field data, based on average regional scale estimations, have been included within mine models. However, local stress perturbations, which are likely to be significant in highly heterogeneous ruptured regions, are typically not considered. Seismic source modelling provides valuable information to estimate local stress perturbations. Existing tools for stress inversion, developed within the field of local-scale seismology, can be adapted for mining applications (Maxwell & Young 1992, Marsan et al. 1999, Urbancic & Trifu 2000).

Information concerning induced seismicity can be also learned by statistical analysis of detected events, following acoustic and seismic triggers. A wide set of statistical techniques have been implemented, providing a standard and useful approach to evaluate acoustic emission in mines. Spatial and temporal event clustering and anomalous behaviour of induced seismicity indicators, such as the b-value (Hainzl & Ogata 2005, Becker et al. 2008), can be derived by statistical analysis.

Finally, additionally available datasets including deformation, thermal and chemical monitoring should be coupled within a common monitoring system. Free surface and internal deformation, recorded by GPS sensors and strainmeters allow the monitoring of surface, cavities and tunnel deformations. These data may help to constrain seismic data and acoustic emission interpretation. Thermal survey is often carried out at mines to preserve structural conditions. Small temperature variations may be related

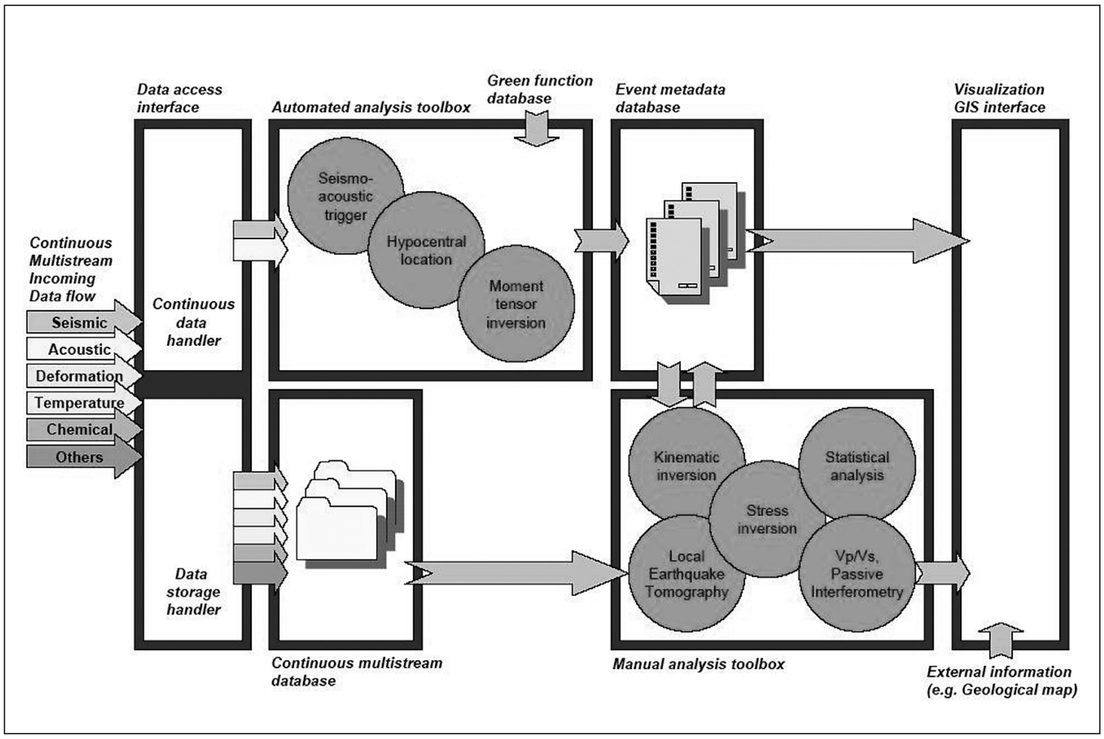

Figure 1: Planned structure of the MINE toolbox

to mining activity and stress perturbations. Chemical and radioactive survey may add information to detect degassing activity and may complement the information concerning the dynamic of fracturing processes.

2. Objectives

We plan to develop a new framework for the access, processing and analysis of continuous multi-stream data in mining environments, with the final purpose of monitoring and evaluating the fracturing process and the stress field evolution at a very local scale.

Developed package modules will provide opportunity for future extensions and inclusion of other data streams. Algorithms portability, parallelization and respect of standard data exchange protocols will be accounted, in order to ensure easy implementation and usage of the package. The package structure (Fig. 1) planned for an extended duration of the project of 6 years will include the following components: data access interface (acquisition of continuous multi-stream data), Green's functions database, event metadata database, continuous multi-stream database, manual and automated analysis toolboxes, visualization interface.

3. Project structure and collaborations

The project is structured in 4 Work Packages (WPs); 4 research positions (1 leading scientist, 3 PhDs) are encharged for the scientific and technical aspects of each WP. Researchers also act as link with our scientific partners. Main tasks, research lines and preliminary results of each WP are summarized at the end of this report. PhD supervision is carried out in collaboration with different partners (Fig. 2).

The collaboration with partner institutions and the private company GMuG will ensure data availability to test developed tools. We have identified different mines as possible test locations. Salt mines data access will be granted by collaboration with the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) and

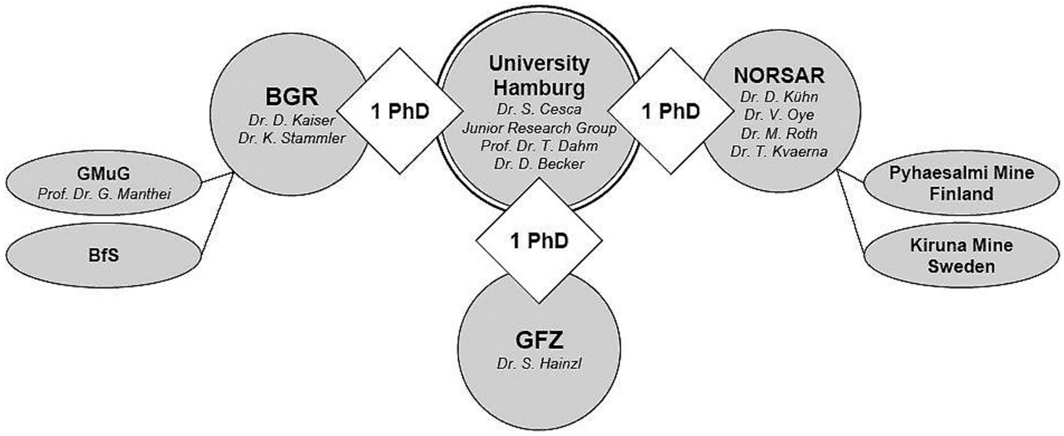

Figure 2: Structure of the Junior Research Group and planned collaborations

the Bundesamt für Strahlenschutz (BfS). Iron ore mines will be monitored in collaboration with NORSAR. Reduced continuous datasets will be collected at different test sites to simulate real time applications with continuous data streams. The collaboration with GMuG in data recovery and software development will ensure private company participation and promote further implementation of the developed package within industry.

4. WP1 Automated event detection and location in mining environments using continuous multi-stream waveform data

4.1 Introduction

Locally induced seismic activity involves a range of rupturing process, with spatial extensions varying from mm-length microcracks to hundreds of meters rupture lengths of induced earthquakes. Under such circumstances, it is important to continuously monitor the time evolution of rupturing processes. A detection of all range of events, an early location and an event characterization will allow for the detection and imaging of weakened regions, which is needed to evaluate risks of dangerous ruptures at both the underground mining area and the upper surface. The development of new monitoring tools, able to handle continuous records and multi-stream data processing would offer a chance to substantially improve the tomographic imaging of the subsurface 3D structure and its time evolution.

A significant improvement of detection and location techniques, as well as the combination of different approaches, can provide an early image of the local seismicity and its evolution. The combination of the location information with tools for a fast characterization of seismic event, as recently derived within the BMBF/DFG Exupery project, may then provide a first tomographic image of the mining structure, indicating areas were major weakening occur and different fracturing processes taking place. In order to use location and event characterization (including magnitude estimation) results with a tomographic aim, the first main goal is to derive specific tools focused on the generation of a complete seismic catalogue. The generation of such a complete catalogue within mining environments has to account for different problems. First, it requires tools for the detection and location of a range of different fracturing process and events magnitudes, possibly combining the information retrieved using different sensors. A second problem concerns the detection and identification of different events occurring within a short time gap, which can be significant in mining environments, owing to the possible presence of crack migrations. Finally, the identification and early characterization of different kind of events (e.g. creeping, crack processes within fractured fluid-filled host rocks), which may not be identified by standard triggers depending on their slower rupturing processes and/or the absence of sharp onsets, may increasingly complete new catalogues. The adoption of a continuous recording approach would give the opportunity to develop different detection and location techniques, based on full waveform, which are better suited to solve some of the highlighted problems. Novel full waveform location techniques have the potential for automated triggering and location applications, and has never been applied neither within mine monitoring nor to a 3D problem.

4.2 Detection and location of microearthquakes in a gas field using a single borehole array

The techniques previously described can be applied in other contexts, such as microseismic monitoring of reservoirs. To show the applicability of such methodologies, we developed specific applications to analyse a microseismic dataset from a gas field in Northern Europe. In the beginning of the project, we focus on the problem of detection and location of induced microseismic events at gas fields. Detection and location of microseismicity are important challenges in reservoir monitoring and characterization. High resolution location allows to estimate the distribution and the orientation of the faults and pore pressure changes inside the reservoir. Standard location methods use only arrival times of the main phases (P and S) of a seismic wavefield and can be succesfully used when these phases are clearly observable. If a dataset is mainly composed by small seismic events with low S/N ratio, these methods may have a poor resolution, and the problem of correct picking of P and S phases is non trivial. Our goal is to develop an automatic, picking independent, earthquake location method that make use of all the information contained in a complete seismic waveform (full-waveform approach).

For our intents we used one month of continuous data recorded using a single vertical array of 90 m, with six three-component geophones deployed at the end of deep borehole at about 2 km of depth. A software module for the detection of seismic events was first implemented, adopting a recursive STA/LTA algorithm (e.g. Withers et al. 1998) of the total energy trace to pick the first P-phase arrival. The cumulative envelope function (Baranov 2007) is used to set the ending time of the event. In this way we avoid to pick later phases and obtain a rough estimation of the duration magnitude of the seismic event. Since the sensors are not aligned and their absolute orientations are not known, sensor are aligned using an innovative technique based on a complex linear least square method.

The geometry of this network requires the development of an "ad hoc" location technique. We use polarization analysis to overcome the ambiguity of the azimuth and full-waveform inversion to improve the resolution of the location. To test the reliability of the methods, the alignment and location techniques are applied to synthetic and real data, and results compared to those obtained with other techniques.

4.3 Preliminary results

The STA/LTA is first applied to the total energy trace and then the relative characteristic function is computed. A STA/LTA recursive algorithm was chosen, because the exponential decaying impulse response was suitable for detecting purposes and requires less data storage. When an event is detected, the trigger algorithm should be temporarily interrupted to avoid more picks than the first arrival. To overcome this problem, we used the cumulative envelope function that allows to estimate the ending time of the event when this function become non positive.

The determination of the absolute and relative geophone orientations is a common problem that affect acquisition procedure of borehole data. Standard techniques used to solve this problem are generally based on polarization analysis or signals cross-correlation. Here, we

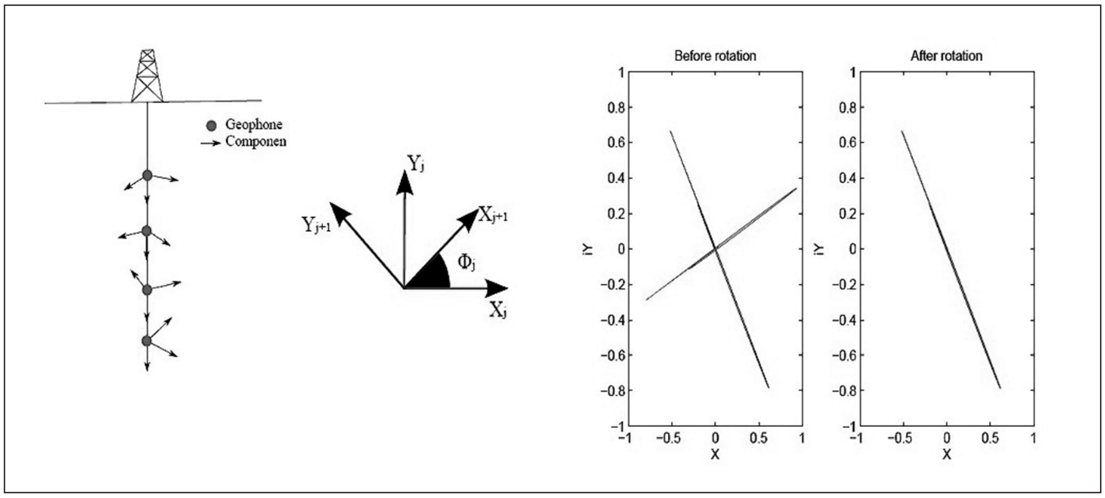

Figure 3: Receivers geometry (left), sketch of the inversion problem (center) and rotation results (left, complex trace hodograms show the polarization of the signal at two different sensors, before and after the rotation is performed).

present an alternative method using a complex algebra approach. In the Complex field, a two dimensional vector can be written as a complex number whose real and imaginary parts are respectively components of the vector itself. Rotations can be performed by simple multiplication of the complex number itself with a complex exponentials whose phase is the rotation angle. Defining the "complex trace" as a complex valued vector whose real part is the X-component seismic trace and the imaginary part is the Y-component seismic trace we can apply these concepts in order to align multicomponent seismic traces.

Synthetic tests have been performed first, using the E3D software to generate a synthetic dataset with a borehole-type acquisition geometry. Satisfactory results have been obtained, by applying the developed method to align sensors with respect to a reference one (Figure 3). The polarization analysis of the stacked trace can then be used to derive the backazimuth and reduce the location problem to the bidimensional case (distance-depth). Currently, the last step of the location, using full-waveform to locate the event in the 2D case is being developed.

5. WP2 Source characterization of microseismicity in mining environments

5.1 Introduction

Earthquake source characterization is important to detect fracturing and shear processes, understand local seismotectonics, correctly evaluate stress field perturbations and early predict fracturing risks associated to seismicity. The development of fast automatic routines for the retrieval of point source parameters of medium to large earthquakes was convincingly established within the last decades, for tectonic earthquakes at teleseismic and regional distances. Further extension to small scale problems have been investigated in a wide range of environments, including seismic activity at volcanoes, mining induced seismicity, and induced seismicity in salt rock.

The standard approach to describe the seismic source is by a point source, using a moment tensor representation. Moment tensor inversion techniques include a variety of approaches. In addition to point source parameters, recent studies (Cesca et al. 2010, Heimann 2011) have successfully investigated the possibility of fast and automated kinematic inversions. Source inversion problem in mines are complicated by the heterogeneous velocity structure and the small size of acoustic emission and microcrack sources. While geophones and seismometers can record low frequency waveforms, which may be well reproduced with standard 1D earth models, high-frequency records are affected by structural heterogeneities (see Kühn et al., 2009). Modelling and inversion of these waveforms require prior computation of GFs and synthetic seismograms for specific 3D models. In particular, when focusing the application towards mine environments monitoring, void spaces (cavities and galleries) should be considered. The recent implementation of a 3D finite difference code and an eikonal solver H. N. Garti at our partner institute NORSAR provide specific tools which can be used for the quick generation of GFs. The code quickness enables its implementation for the generation and further modification of the GF database, which is important at mines, since mining activities may significantly affect the 3D structure of the area with time.

5.2 Coal mining induced seismicity at the Ruhr region

Coal mining in the Ruhr region, Western Germany, has been monitored continuously over the last 25 years by the Ruhr University Bochum. About 1000 seismic events with local magnitudes ML between 0.7 and 3.3 have been located every year. In 2006 a dense temporary network (HAMNET) was deployed to monitor the active longwall mining close to the town of Hamm. The HAMNET network includes 9 short period and 6 broad-band stations. From July 2006 to July 2007 more than 7000 events with magnitudes ranging from ML -1.7 to 2.0 were located with this dense network configuration. Out of this dataset, more than 900 events have magnitudes equal or larger than 0.0. Source depths are constrained in a narrow band, centered at about 1km depth.
Epicentral locations and depths mostly correspond to the region of active longwall mining. However, different clusters at further distances have also been observed. The spatial and time distribution of induced seismicity show a high correlation with the mining activity. We perform a moment tensor inversion for the largest recorded events, using a full waveform inversion technique and double couple constrain. We first generated Green functions databases for different 1D layered models.
The Kiwi inversion tools, which were developed and successfully applied in recent years to perform moment tensor inversion at regional and teleseismic distances, have been adapted here to carry out the inversion at a local scale (the maximal source-receiver distance is 3km). It is done tests to determine the suitable model and bandpass range. The inversion is carried out at different steps. First, a frequency domain moment tensor inversion is performed, fitting amplitude spectra of the full waveforms at frequencies between 0.1 and 4Hz. Then, a time domain inversion is used to solve the polarity ambiguity and to determine the best centroid location. As a result, we obtain information about the centroid location, source depth, scalar moment and best double couple (DC) focal mechanism.

5.3 Preliminary Results

Before applying the inversion to a larger dataset, we tested different velocity models and range of frequencies using a subset of events (2 months, 58 events). In this way, we investigate the performance and stability of the inversion approach.

(a) A layered model shows a consistent better performance than a homogeneous velocity model. In the following we use only the layered model.
(b) Inversion stability and quality of fit are best for frequency in the range 0.5 to 4 Hz. We choose to adopt 2 frequency ranges (0.5-2Hz and 1-4Hz) to investigate focal mechanisms of event in the magnitude range Ml 0,5-2,0. This choice limits the inversion to broadband station data only.

We then processed 12 selected events. Only solutions showing an amplitude spectra L2 misfit below 0.5 have been considered. Results

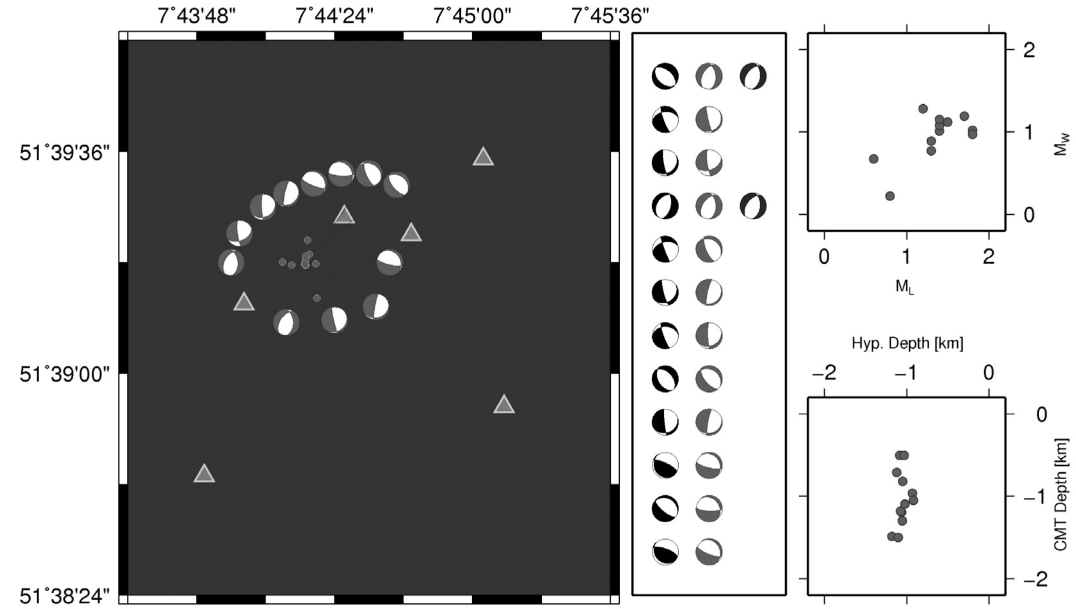

Figure 4: Comparison of 12 event results. Reference solution (left), full waveform inversion at 0.5 – 2.0 Hz (middle) and 1 – 4 Hz (right)

are summarized in Figure 4, and indicate low misfits and general agreement with reference solutions.

6. WP3 Statistical analysis of seismic catalogs in mining environments

6.1 Introduction

The imaging of stress perturbation and weakening zones and its time evolution, thus a 4D stress tomography, is extremely important for a safe monitoring of mining environments and an efficient hazard assessment at different time scales. Detection of daily/hourly stress perturbation, for example, may be used within short time scale decision-making processes, in order to secure the safety for workers. Long-term stress variations on the other hand may indicate the beginning of mining activity in a structurally instable part of the mining and may used for further planning. Finally, precursory stress localizations might be indicative of subsequent bursts or rock-falls.

The imaging of rock damaging at the first step will carried out on the base of statistical analysis of seismicity spatialtemporal evolution, clustering and event characterization. Local seismicity can be studied using statistic approaches by analysing standard indicators, such as the b-value or the volumetric release of seismic moment. Statistical and clustering analysis for different event subsets can support new information. Stress modelling and aftershock evaluation can be study based on the results that would be provided by statistical studies. Apart from the analysis of seismicity patterns, stress inversion can be also carried out based on focal mechanisms determination. The provision of focal mechanism information by WP2, would make possible the adoption of a similar approach and the combination of the two stress inversion methods (based on seismicity and focal mechanisms) resulting finally in a joined stress inversion and 4D tomography.

Goals of Work Package 3 are to establish and carry out a multi-step analysis, using seismic, acoustic and deformation data, which will finally bring to a 4D stress tomography tool. In the first step we have focused on seismicity studies in mining environments using real and synthetic catalogs.

6.2 Mc and b-value estimations

The size distribution of earthquakes in a seismogenic volume can often be adequately described over a large range of magnitudes by a power law relationship. The commonly used form of the power law relates the cumulative number N of earthquakes with magnitude equal or above M, and constants 'a' and 'b'. The parameter 'a' describes the productivity of a volume, while 'b' describes the slope of the frequency-magnitude distribution (FMD). The first step in this WP is extracting information on the b-value in mining environments. The minimum magnitude of complete recording, Mc, is an important parameter for most studies related to seismicity. Mc is defined as the lowest magnitude at which most of the events in a space-time volume are detected. It is well known that Mc changes with time in most catalogs, usually decreasing, because the number of seismographs increases and the methods of analysis improve. If a seismicity dataset strictly follows the Gutenberg-Richter law, Mc can also be defined as the magnitude at which the cumulative Frequency-Magnitude Distribution departs from the linear trends. In order to derive the b-value in the region of study, we first estimate Mc with different methods. Different techniques have been tested so far to derive Mc and b-value of seismicity catalogs. These include the maximum curvature technique (MAXC), the Goodness-of test (GFT), the Mc and b-value stability method (MBS) and the Entire-magnitude range technique (EMR). All these methods have advantages and disadvantages, and the adoption of a specific method may be recommended, depending on which type of catalogue is used. In general, different techniques may give different estimates of the completeness magnitude.

6.3 Preliminary results

At now, the mentioned different methods have been applied to derive Mc and b-value from different catalogs. First, the developed algorithms have been tested on synthetic catalogues (with and without noise). Tests were successful, and catalog parameters could be satisfactorily retrieved for both catalogs. At a further stage, the methods have been applied to a real catalog from a mining region. For this purpose, we use a data catalogue from Pyhäsalmi ore mine in Central Finland. This is the oldest operating metal mine in Finland and the deepest in Europe extending to a depth of 1441 m. Data are recollected and provided by NORSAR, that performs a microseismic monitoring, using 18 sensors, including 6 three-component stations, leading to source-receiver distances of 60 to 400 m. The network has been operational in a continuous mode since January 2003. Until March 2004, about 18,000 events were detected. About two thirds of those events were identified as mining blasts, the remaining events are microseismic activity. The range of magnitudes is -1.8 to 2. Because of some gaps in the catalog, we focus on a one-year subset from 01.08.2003 until 31.07.2004. Additionally, we have tested our analysis with two synthetic catalogs which resamble location and magnitude range of the real catalog.

7. WP4 Local earthquake attenuation tomography in mining environments

7.1 Introduction

The development of tomographic methods cover a wide part of seismology and in the last decades a large effort was done to develop and apply tomographic methods at very different spatial scales, ranging from local applications, able to image limited regions to teleseismic application to resolve the whole Earth structure and long time scale processes. The resolution of structural details is important to better determinate physical phenomena occurring at depth, and to evaluate transient processes. Tomography applications at mines may be then used to monitor fracturing processes and fluid migration, which is important for the hazard assessment, within the goals of the MINE project. Local earthquake tomography (LET) can be combined with active seismic tomography for the planned application, using waveforms generated both by microseismic events and mining blasts. Different LET approaches have been developed to either resolve the velocity or attenuation structure. Both attenuation and velocity anomalies may reveal fractured regions and fluid presence. Attenuation tomography is of special interest here because it can image fractured regions, which we intend to monitor. The attenuation of seismic waves when travelling through fractures and fluid-saturated rocks is generally higher than in dry rocks in most of the frequency bandwidth, and changes in the spectral and amplitude characteristics of the seismic signal have been associated with the presence of fluids and fractures. Laboratory measurements of wave attenuation have been performed at several frequency levels, generally showing how factors such as porosity, permeability, and clay content are responsible for wave attenuation (Del Valle-García & Ramírez-Cruz 2002). The basic data for studying the attenuation structure are the Fourier amplitude spectra of seismogram phases, the phase amplitudes on filtered waveforms using different range of frequencies, and the pulse width of seismogram phases (Iyer & Hirahara, 2001, and references therein). The availability of information concerning the seismicity (WP1), the focal mechanisms and the adopted 3D velocity structure (WP2), may be used to further develop full waveform tomography techniques. If tomography has been one of the main research field within seismology, mining applications have been mostly confined to controlled-source tomography, with most applications only involving the processing of arrival times of direct waves.

The potential of tomographic application in mining exploration has been investigated to identify different ore structures. The planned application has indeed a different aim, being focused on the identification of weakened and fractured regions, which could provide advance warning of mining hazards, or the early detection of regions of stress concentration, which may be indicative of rock burst risks. In this sense, a successful application was carried out by Cotten & Geldmacher (1990) at the Illinois basin, where a reduction of seismic velocity was identified and associated to a limited region of structural weakening above a worked coal seam, whereas a region of stress concentration (higher seismic velocity) was detected above the caved zone.

7.2 Preliminary results, adaptation of attenuation tomography techniques to mining areas

We are in the process of adopting and we plan to further develop local earthquake attenuation tomography methods, including the information provided by full waveform acoustic and seismic data. The application of these methods to the different datasets will provide tomographic images of the mining attenuation structure, which can be then interpreted in terms of the dynamic of fracturing processes. As a starting point, we are adapting and implementing a methodology based on the spectral ratio approach, as described by Monna and Dahm (2009), who successfully modelled the regional crustal structure beneath the Thyrrenian sea (Monna and Dahm 2009).

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