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Using engineering seismology and geophysical methods to minimize sources of danger in engineering and mining

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ABSTRACT

The application of geophysical methods in civil engineering and mining becomes more and more important. The combination of geophysical data with classical geotechnical measurements can greatly improve the quality and reliability of investigations e.g. regarding the stability of mines. A number of case examples are presented to demonstrate the potentials of geophysical methods such as georadar, sonar and seismic monitoring with respect to stability issues of mine workings, the risk assessment of safety at work and the exploration of the geological barrier above and below the mining horizon.

Key words: georadar, sonar, engineering seismology, seismic monitoring, geophysical exploration, risk assessment

INTRODUCTION

In case of mining, geophysics can be applied both for exploration purposes and for monitoring of the geomechanical conditions. In recent years monitoring and the assesment of mining fields with respect to stability issues were gaining more and more on significance in Germany. In this regard the combination of geophysical data with classical geotechnical measurements can greatly improve the quality and reliability of investigations e.g. regarding the stability of mines, dams or buildings because of the high data density provided by geophysical methods. In that way geophysical applications can be an important and in some cases essential source to early detect potentially dangerous conditions.
From the intensified exploitation of mines as well as from the aftertreatment phase or secondary use of the chambers after the mining result several sources of danger especially in potash and rock salt mining:

- Destabilization of mining fields or parts of mining fields and resulting inadmissible dynamic stress and strain at the surface
- Inadequate thickness of the protective layer or geological barrier for the protection against gases and fluids during mining and the use of the mines afterwards
- Weakening and disintegration of the contour of the mine workings with a possible reduction of safety at work

A number of case examples will be presented to demonstrate the application of geophysical monitoring and exploration techniques such as engineering seismology, sonar and ground penetrating radar for the assessment of the condition of mining fields and the assessment of the integrity and stability of the geological barrier of a mining field.

Case examples

Stabilization of a carnallitite mining field

The mining field considered in this case example was in operation between 1982 and 1991. Already in the last years of active mining, the field started to show signs of a rapidly increasing destabilization in form of an increasing seismic activity with event magnitudes larger than 1.5 in combination with high deformation velocities. In 1991 the geomechanical condition of the field had reached a dangerous level of weakening and in parts almost disintegration of the pillars.

Figure 1: Destruction of pillars in the abandoned carnallitite mining field.

Figure 2. press-ups of the drive way due to high formation pressure.

The level of destruction of the pillars is illustrated in figure 1 and figure 2.

Without stabilization, a rock burst producing an earth quake of Magnitude 4-5 was expected. Since the mining field is situated directly beneath a town centre at a depth of approximately 600 m, the rock burst would have caused severe damage to the infrastructure and buildings.

To avoid the collapse of the entire field, it had to be quickly stabilized. Since time was pressing, this could only be achieved by refilling the chambers with rock salt from neighbouring mining fields. Moreover, an entire mining field can not be refilled all at once, so a priority list had to be created of which pillar groups had to be treated first. The backfilling and stabilization of the field was carried out between 1991 and 1996.

The mining field was under a close monitoring regime already during production, which included both geotechnical observations like underground and surface deformation measurements, in situ stress measurements and the seismological monitoring of the mining field. These combined data series enabled the identification of especially weakened zones, which then were put on top of the priority list. While the in situ stress measurements provided direct information of the state of still accessible pillar ensembles, the seismic monitoring provided essential information of deformation processes in areas which were no longer accessible as well as of deformation processes within the formation above and below the mining horizon.

By refilling the rock chambers with rock salt, the weakened pillars were embedded and thus hindered in their lateral expansion. In that way the deformation processes in the mining field were slowed down, resulting in a significant reduction of the energy release from seismic events. The development of the seismicity of the mining field is presented in figure 3. There, the epicentres of the seismic events are plotted for each year with respect to the layout of the mining field. The event magnitude is characterised by the size of the dots. Most of the events were located within the mining horizon and thus representing deformation processes and fracturing of the pillars. Until 1992 a large part of the smaller events were distributed more or less randomly within the field, while in particular the stronger events were concentrated to certain areas. These areas were related to the parts of the field with high stress from the ongoing deformation processes. On the other side, areas with no or less observed seismicity correlated in most cases with pillar ensembles, which were already so much damaged, that these pillar groups did no longer take part in the load bearing of field.

The procedure of identifying the most critical pillar groups from the results of seismic monitoring and in situ stress measurements, first stabilising these pillar groups and afterward refilling the rest of the field, was in that way successful that a significant reduction of seismic events could be observed almost immediately after the stabilization measures had started in 1991. The following years were characterised by a steady but strongly reduced seismicity until a new increase in the seismic activity could be observed in 1995. The stabilization measures ended in 1996 with 95 % of the cavities of the mining field refilled. The seismic activity in the field was decreasing again from 1996 on until in 2000 a low level was reached which has been kept constant since then. The intermediate increase in seismicity in the years 1995 / 1996 was interpreted in that way that the in filled rock salt was compacted and started to take part in the load bearing.

Stabilization of a mixed salt mining field

This mining field is part of the same mine as the previous example and was in production between 1978 and 1991. In contrast to the previous field where carnallitite has been mined, the field considered here is a mixed salt field and was in part mined in up to three levels. After the closure of the mine in 1991 the field was left open but still in stable conditions. This situation changed in 1996 when the field suddenly started to show a high seismic activity by a series of relatively strong events with magnitudes reaching M_L=2.0. Until then, seismic events had been observed only sporadically in this field. Moreover, the recorded events were preferably located in the overlying layers of the mining horizon. Additionally, the epicentres of the events did line up along or in parallel to known fault and ridge systems within the field (see Figure 4). A relationship between the events and the local tectonics was also indicated by the calculated focal parameters (e.g. stress drop, dislocation, size of fault plane, etc.) of the events. It was feared due to these indications that the fracturing of the overburden could lead to the activation of existing fault systems which eventually could penetrate the geological barier and thus open up water paths into the mine. The mining field has not been accessable since the abandoning of the field in 1991, so the indications from the seismic monitoring were the only data available at that time. Since other parts of the mine were used as a waste disposal site, the risk of losing the integrity of the geological barrier had to be overcome. In this respect it was decided to regain access to the field and to stabilize it by backfilling of rock salt in analogy to the prior case example. The stabilization measures started in 1996 and lasted until 2004.

Beside the alignment and grouping of the seismic epicenters, the calculated focal parameters such as stress drop, dislocation, size of fault plane and released seismic energy can be directly used for further geomechanical assessments.

An other way of characterising the development of the field’s condition over time by means of observed seismicity is shown in figure 5. There, the cumulative released seismic energy or respectively the square root of the energy, which is directly proportional to the stress release, is plotted over time (Benioff, 1951). Moreover, the shape of the curve gives qualitative indications of how the stress is released. A high number of small events will result in a rather smooth curve while a small number of strong events would give a blocky shape. A change in the mean slope of the curve indicates a change in the characteristics of the deformation processes.

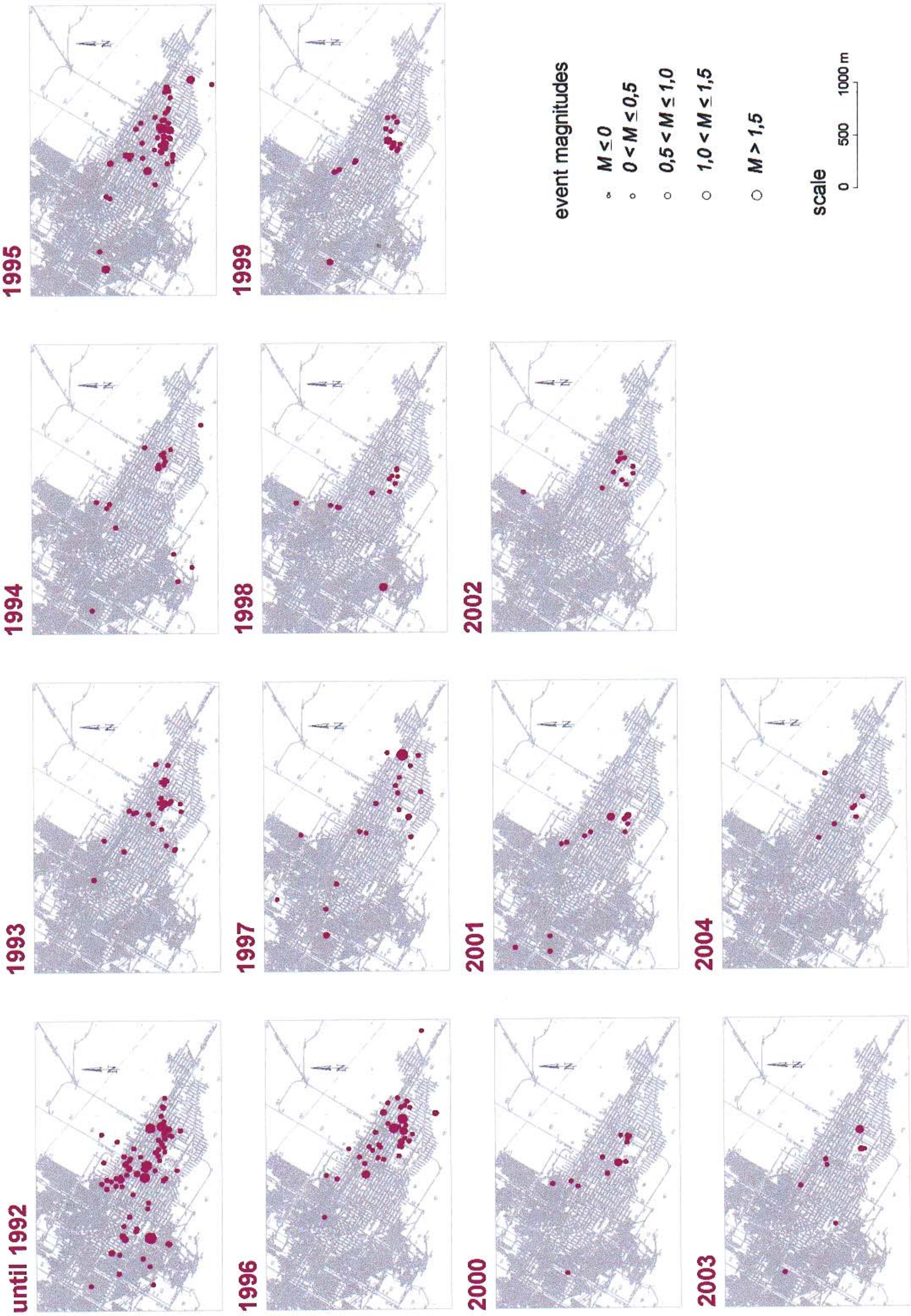

Figure 3. Development of seismic activity in the Carnallitite mining field.

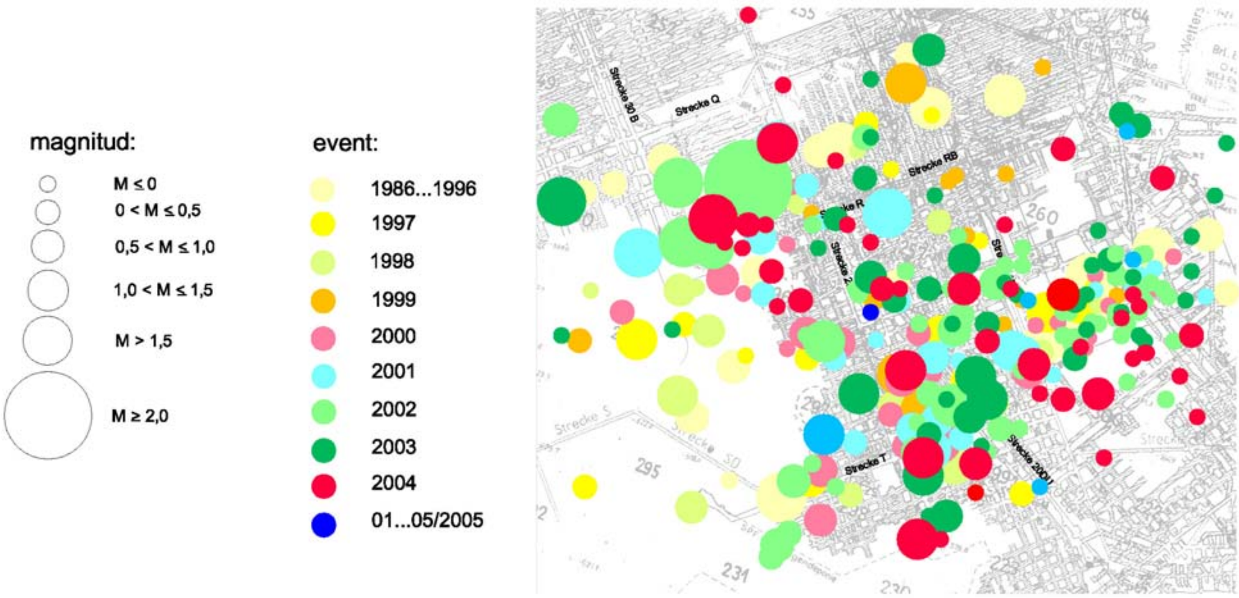

Figure 4. Distribution of epicentres within the mixed salt mining field.

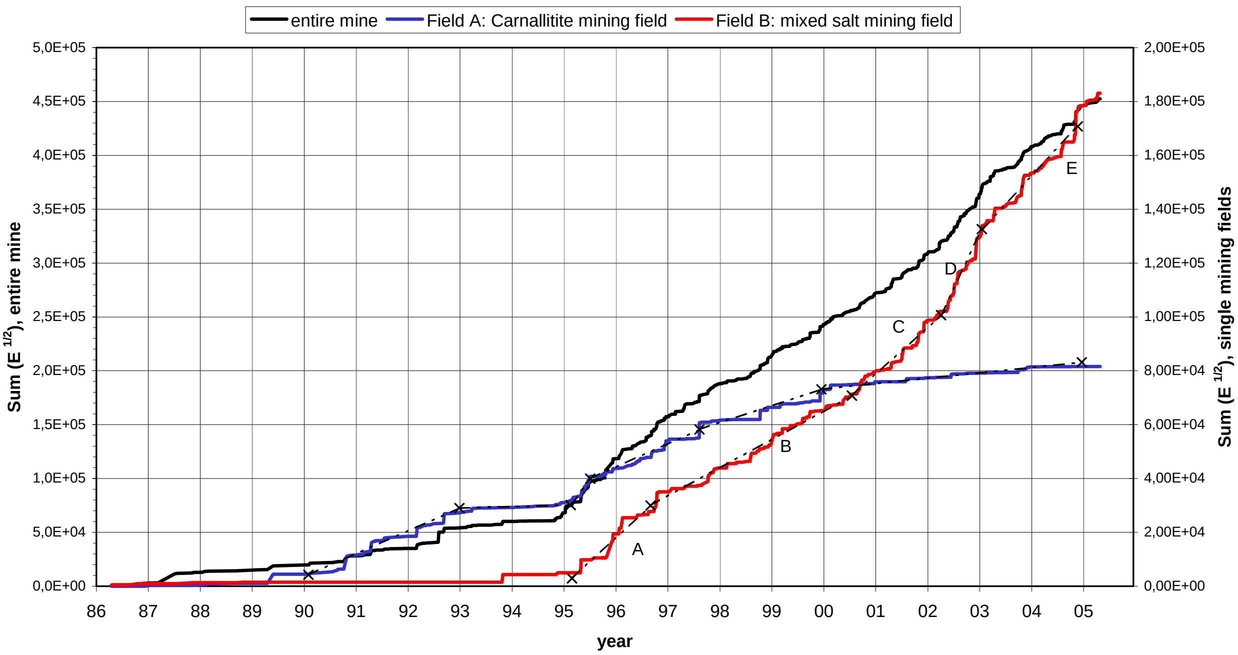

Figure 5. Cumulative stress release (Benioff-curve) trough seismic events in the mixed salt mining field, the carnallitite mining field and the entire mine, respectively

Figure 5 shows the Benioff-curves for the mining fields of both examples as well as of the entire mine. As can be seen in figure 5, several periods of activity can be distinguished from the curve of the mixed salt field. The sudden onset of seismic activity (Period A) is represented by a rather steep slope and a blocky shape due to the series of strong seismic events. This period was followed by a more or less constant energy release at a still high level, but lower than in period A. From 2000 on an increase in the energy release could be observed (Period C). A further acceleration of the deformation processes took place in the beginning of 2002 (Period D). Period E marks the first slight reduction of the stress release in the middle of 2003. The seismic activity is kept on a more or less constant high level since then, although the characteristic of the deformation processes seems to point more towards the accumulation of energy and the stress release by stronger seismic events at greater intervals.
Although the strategy as well as the application of the stabilization measures in both mining fields was similar, the effect does not seem the same. The main reasons for the different behaviour are the different types of salt (carnallitite vs. mixed salt), the local geology, in particular the presence of faults, as well as the duration of mining. Moreover, the mixed salt field was mined on multiple levels and only the lowest level could be refilled due to safety issues at work.
As the result, the seismically relevant deformation processes were ongoing in the layers above the mining horizon in contrast to the carnallitite field, where the main seismic activity was located within the mining horizon.
In this respect it is expected that it will take longer for the stabilization measures to take full effect. The first indication is given by the Benioff-curve for the mining field, which points out that the deformation processes do not accelerate any further.

Application of engineering seismology and georadar for increasing the safety at work

Special precautions for the safety at work had to be taken during the stabilization work within the mixed salt field. The mining field was abandoned for some years and the deformation of the pillars had reached a critical level. In those areas, which have been mined in multiple levels, the horizontal pillars between the mining levels have been particularly weakened that the upper levels could not been entered without risk. In some cases theses pillars had already been collapsed (Figure 6).

Figure 6. Collapsed horizontal pillar in the mixed salt mining field.

Due to the instability of the mining field, a procedure had to be found to quickly and reliably assess as well as to monitor the stability of the mine workings in order to limit the risk of the miners at their work place. A combination of methods such as in situ stress measurements by hydraulic fracturing of the pillars, seismo-acoustic monitoring of the critical parts of the field as well as the application of ground penetrating radar (georadar) for the inspection of the mine workings with respect to fractures and detachments especially in the roof were applied.
The hydraulic fracturing test offered direct information of the state and stability of single pillars. It is however only a point measurement and comparably expensive.
Although the mining field was already monitored by a seismological network as mentioned above, a seismo-acoustic subsystem was installed to monitor micro-seismic events, which are related to the fracturing of the pillars. The difference between the main system and the seismo-acoustic subsystem is the higher frequency range and shorter spacing of seismometer stations of the subsystem. It was thought to obtain indications from the recordings of potentially dangerous situations such as the increased fracturing of critical pillars. For example an increasing number of events within a short period of time at the same place would point towards increasingly instable conditions.
The distribution of recorded micro-events is shown in figure 7.

Figure 7. Distribution of recorded micro-seismic events in the mixed salt mining field.

The seismo-acoustic system was in operation for only one year but recorded 1632 events. As can be seen from figure 7, the majority of the events gather along line structures, which obviously are related to larger fractures or fault systems. These faults were not visible in the mine workings in most cases. However, this appearance correlates with the observations from the main seismic system as mentioned above.
Although a direct connection between the observed micro-seismic events and the mining activity could be documented as was expected, no hard criteria could be established for distinguishing between normal and potentially dangerous conditions. The system was shut down after a year of operation as the result.
The application of ground penetrating radar for inspections of the mine workings with respect to fractures and deeper

detachments especially in the roof proved to be a very reliable approach. Radar measurements can be carried out at relatively low costs and are not much time consuming. In this respect, the method is well suited for investigation of larger areas.
Example data of a roof inspection is presented in figure 8. A high frequency antenna (900 MHz) was used for the investigation, which provided a high resolution together with a penetration depth of several meters. Fissures of width as small as 1 mm could be detected.

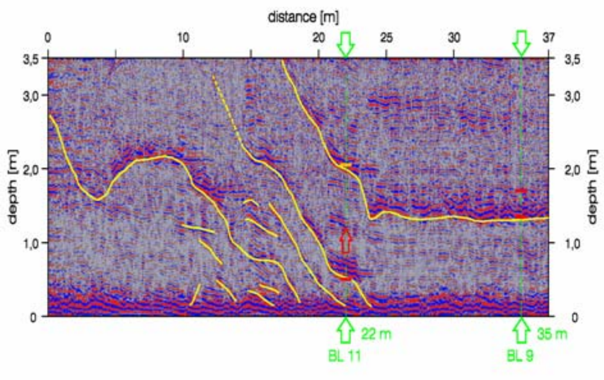

Figure 8. Example of a radar inspection of the roof of the mine workings.

The results of the radar investigation shown in figure 8 were tested by two boreholes. The positions of the boreholes on the radar profile are marked in the figure. The indications for fractures from the radar investigation fit exactly to the fissures found by the boreholes.
Changes over time can be monitored by repeated measurements. The results were used as a basis for decisions of whether the contour of the mine workings could be held stable by means of anchors or the controlled blasting of the detachments.

Application of georadar and sonar in mining for investigations of the geological barrier above and below the mining horizon

Active geophysical exploration methods can also provide valuable information for the geomechanical assessment of a mining field. Especially for salt mining both radar and sonar are well suited to easily cover large investigation areas. Both methods are based on the same principle: a pulse is generated and radiated into the formation. If the pulse passes a boundary between physically different materials, a part of the pulse is reflected. The reflections are recorded and if the velocity of the wave propagation is known, the distance between source / receiver and reflector can be calculated.
While electromagnetic waves are used for the georadar, elastic waves are used for the sonar. According to the wave type both methods react differently to certain material boundaries. The radar is reflected at boundaries with contrasts in the electrical properties of the material while the sonar records reflections from boundaries with changes in the elastic properties. Moreover, electromagnetic waves are strongly attenuated in media with high electric conductivity. As a result, the penetration depth of georadar is greatly limited in case of high contents of conductive materials such as clay, for example. On the other side, materials with low conductivity provide good conditions for the penetration of electromagnetic waves, which makes the georadar an ideal exploration tool e.g. in salt mining.

Both georadar and sonar can be applied from e.g. roadways within the mine for:

- Investigation of thickness of protective layers, both below and above the mining horizon
- Exploration of geological structures
- Investigation of the contours of the mine workings for safety reasons
- Estimation of thickness and integrity of horizontal pillars in case of multi-level mining.

The following case example describes the exploration of the layers above and below the mining horizon within a rock salt mining field. The task was to estimate the thickness of the layers, especially the sulphate layers above and below as well as to investigate the presence of faults within these layers. A combined application of georadar and sonar was suggested for this investigation.
The exploration started close to an existing borehole, which provided the necessary geological information in order to assign the observed reflectors to certain geological boundaries. These reflectors could then be mapped through out the mine.
Figure 9 shows the results from a radar profile measured with a 200 MHz antenna.

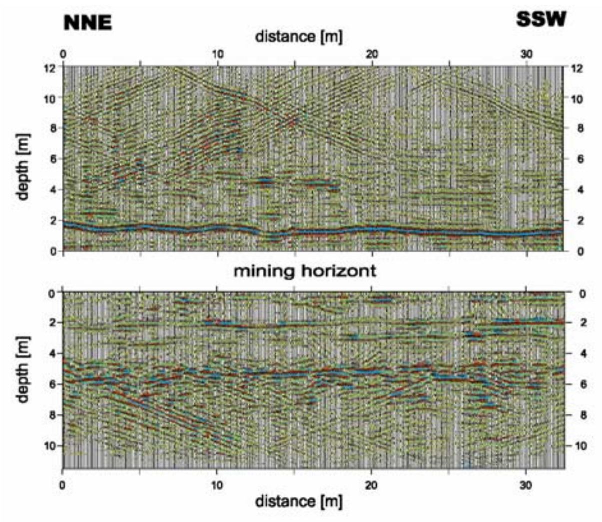

Figure 9. Exploration survey with georadar (200 MHz antenna) for exploration of the integrity of the geological barrier above and below the mining horizon.

The measurement into the hanging wall shows a strong reflector at a distance of less than two meters. This reflector marks the beginning of the upper sulphate layers, which means that less than two meter of salt remain above the roof of the mine workings. Only few weak reflectors could be detected above this horizon. The deepest reflector is found at 6 m above the roof.
The downward investigation revealed a series of reflectors between 2 m and 4.5 m distance, which were assigned to an anhydrite layer.

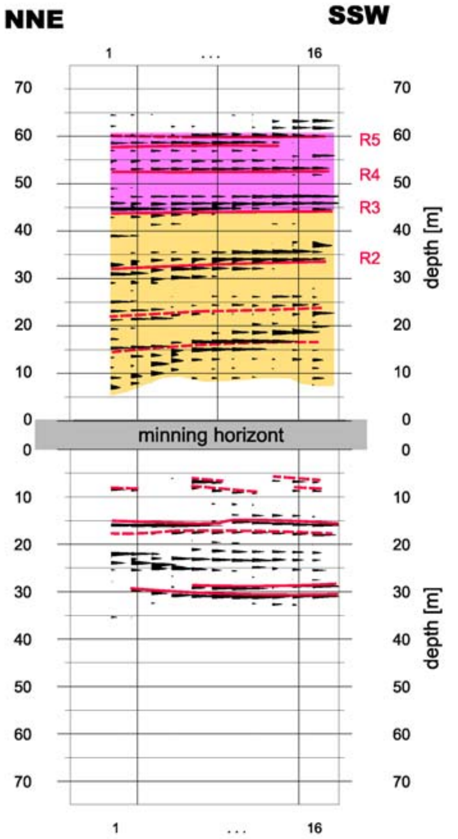

Figure 10. Exploration survey with sonar for inspection of the integrity of the geological barrier of a rock salt mining field.

The results from the sonar measurements at the same place are shown in figure 10. The near field (the first 5-10 m) above and below the mining horizon had to be blanked out because of overmodulation of the data. In contrast to the radar investigation, the penetration depth reached more than 60 m in the upward measurement and approximately 30 m in the downward investigation. In both directions, a number of reflectors can be identified but not all could be correlated with boundaries of stratigraphic horizons from the neighbouring borehole. These reflectors refer to internal material changes within the geological layers. The upper boundary of the upper sulphate layers was detected in correlation with the borehole at 45 m above the roof of the mine workings. The lower boundary of the lower sulphate layers was assigned the reflector at 30 m below the mining horizon. This information could not be verified by the borehole because the borehole was to shallow and did not penetrate this boundary.

As mentioned above, the penetration depth of the radar was limited to a few meters only, which was caused by high content of conductive material in the sulphate layers. On the other side, the sonar did not provide useful data in the near field for technical reasons. In this respect, the data from the radar and sonar measurements did ideally supplement each other. The combined interpretation of both methods is given in figure 11. The aim of mapping the thickness of the upper and lower sulphate layers could be achieved.

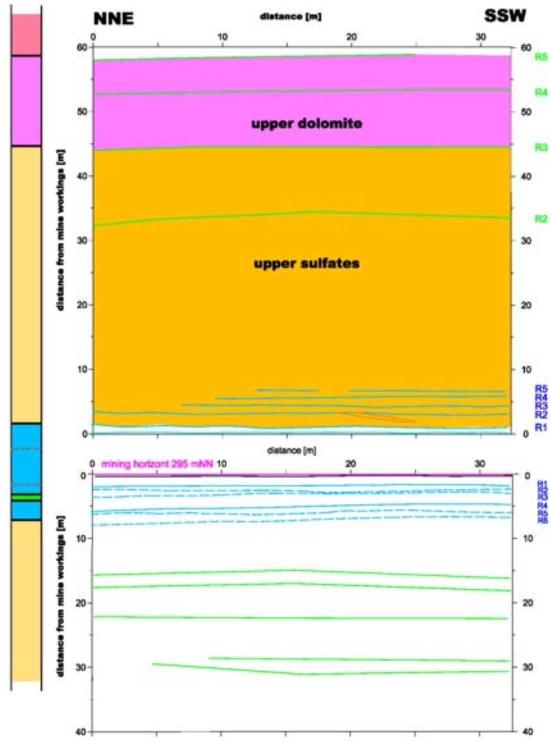

Figure 11. Combined geological interpretation of the sonar (green reflectors) and radar (blue reflectors) surveys. The geology information from the nearby borehole is shown on the left.

DISCUSSION AND CONCLUSIONS

A number of case examples were presented concerning the application of geophysical methods in mining.

It could be demonstrated that seismic monitoring contributes essential information for the geomechanical assessment of mining fields. The observed seismicity of a mining field can in some cases provide additional information for stearing of stabilization measures as well as the verification of the effects of the stabilization work. It may also help to increase the safety at work although no direct criteria could be worked out yet. This may be a task for further research.

It could also be shown that georadar is a suitable tool for inspection of mine workings with respect to stability issues especially in salt mining to increase the safety at work.

Combining geophysical methods which are sensible to different physical properties reduces the ambiguity of the data and thus greatly improves the reliability of the interpretation.

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