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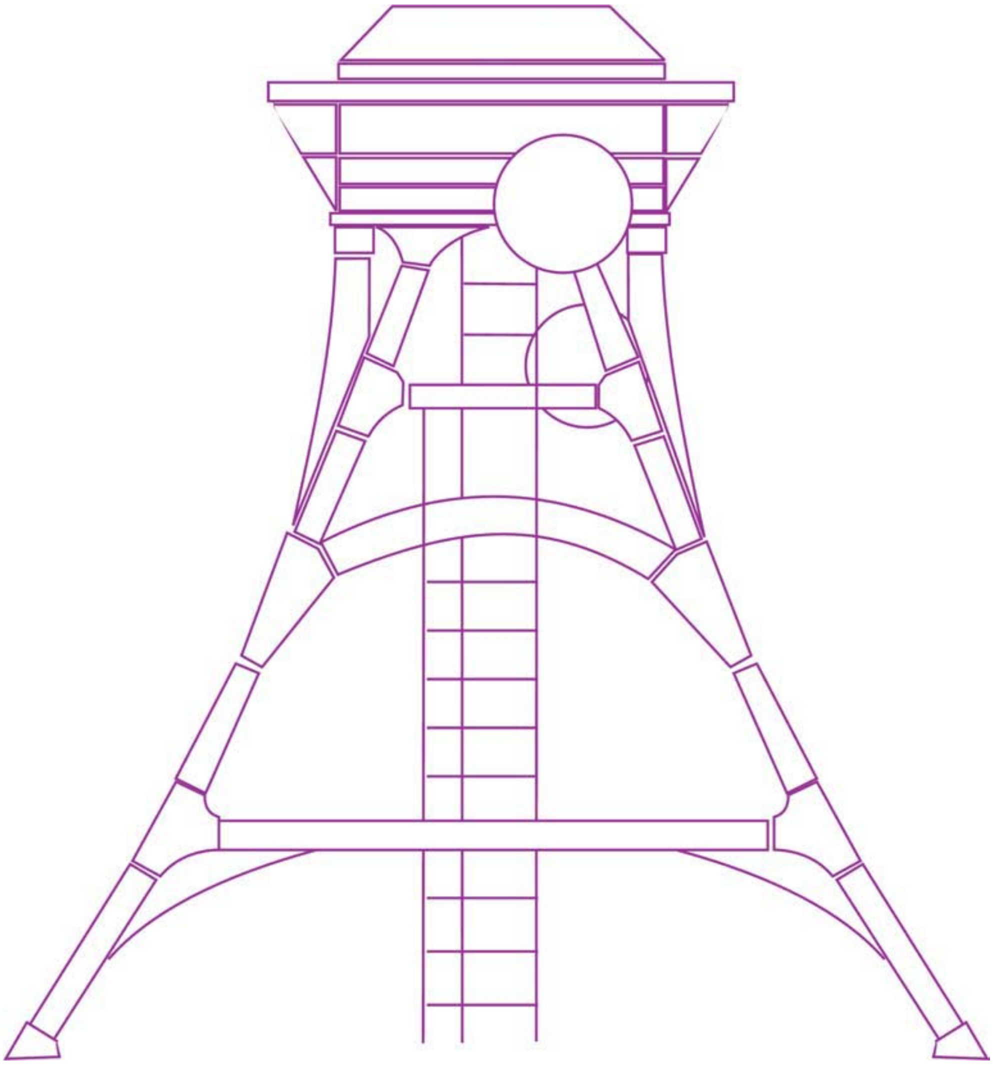


Seismic Monitoring

Seismic Monitoring

Kali – Umwelttechnik GmbH (K – UTEC)
Am Petersenschacht 7
99706 Sondershausen
Germany

Phone: ++49 – 3632 - 610 - 0
Fax: ++49 – 3632 - 610 - 105
e-Mail: kutec@kutec.de

Managing Director: Dr Heiner Marx
Dr Holger Thoma

Sector: Geophysics

Person in charge: Dr. M. Jordan

Phone: ++49 – 3632 - 610 - 190
Fax: ++49 – 3632 - 610 - 105
e-Mail: geophysik@kutec.de

Specialist for the field of **seismic monitoring** of Potash mines:

Cert. Geophys. Olaf Klippel
Cert. Geophys. Astrid Gessert

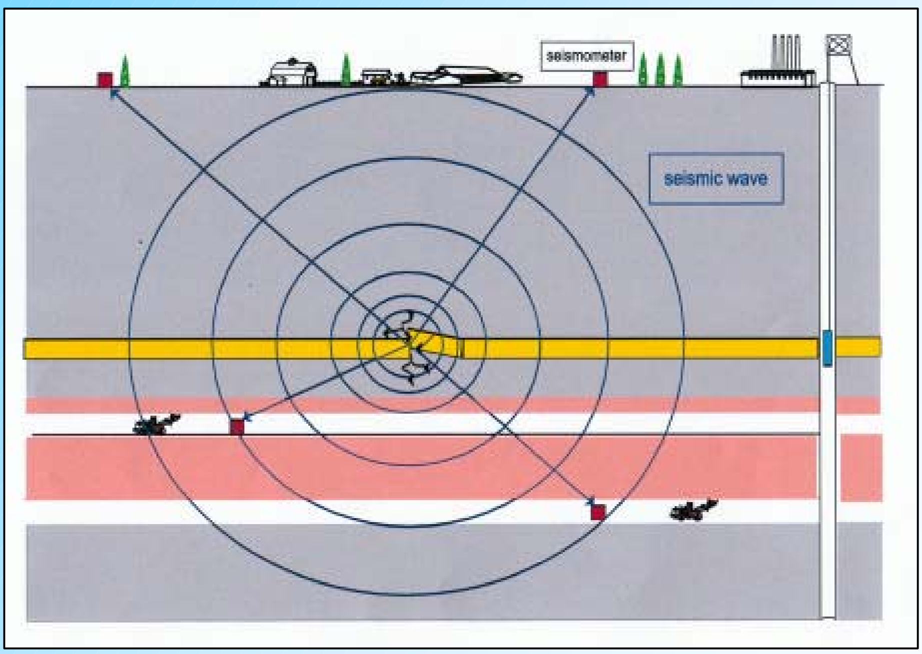
Seismic monitoring system

K-UTEC GmbH
Am Petersenschacht 7
99706 Sondershausen
Germany

Introduction

A seismic monitoring system consists of a number of seismometer stations distributed within the observation area and the data recording and processing centre.
The arrangement of the seismometers depends mainly on the observation task but also on the geology and local possibilities regarding accessibility and signal transmission. In general, the target area has to be spatially encircled by several seismometer stations, which also includes the positioning of the geophones in different depth levels. Possible locations for seismometer stations are for example the basement of a building, within a borehole or within an underground mine. The number or the density of the seismometer stations, respectively, determine the accuracy of the location of a seismic event.

To just locate a seismic event, 1D-geophones (only vertical component) are usually sufficient. Most important is a high sensitivity and a good coupling to the ground. The frequency characteristic of the used seismometers should be in the range of 2..200 Hz for a larger scale monitoring system and respectively higher (in the kHz-range) for micro systems or seismo-acoustic applications.
However, to further qualify the recorded seismic event regarding magnitude and source parameters (e.g. stress-drop, seismic moment, dislocation, size of the fault area, etc.) we strongly recommend to include at least one or two 3D-geophones in the seismometer network.



Principle of locating seismic events

Tel.: +49 36 32 - 61 01 00 Fax: +49 36 32 - 61 01 05 Email: geophysik@kutec.de http://www.kutec.de

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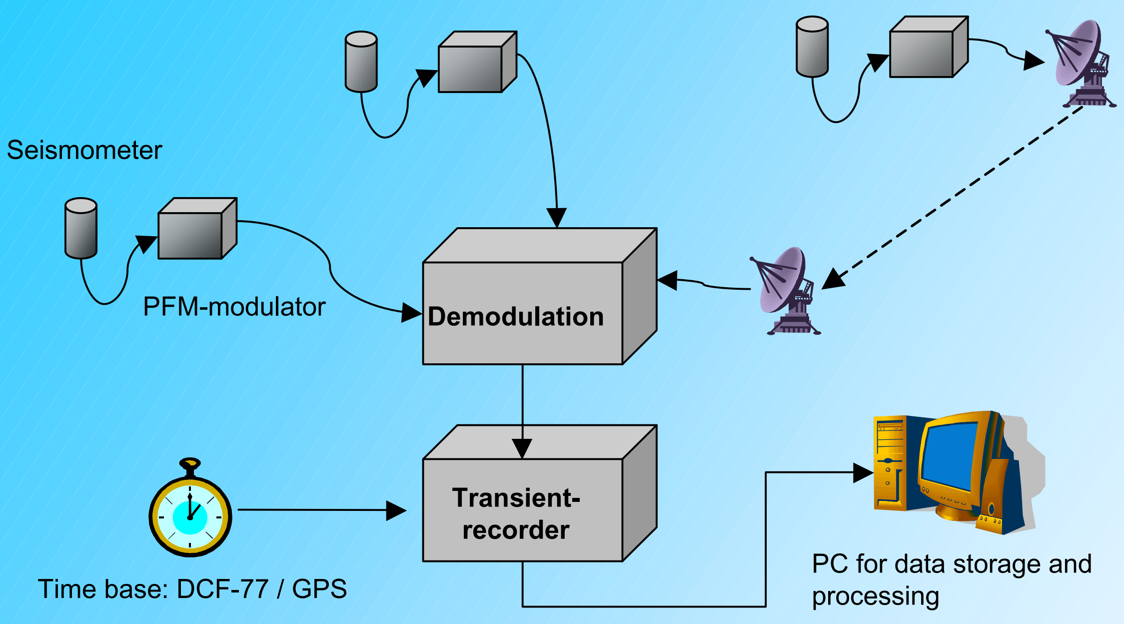
K-UTEC GmbH
Am Petersenschacht 7
99706 Sondershausen
Germany



Signal transmission:

A lot of possibilities exist to transmit the signal from the seismometer stations to the recording centre (e.g. signal cable, telephone cable, radio; analogue or digital). Especially for the application in mines and for very long distances on cable the signal transmission via pulse frequency modulation (PFM) has been proven to be the most reliable one. Modulators of this kind are also licensed for the use within gas-/explosion endangered mine workings (certificate I M2 EEx ia I).

data recording:

The signal from each seismometer is transmitted to the recording centre, where it is demodulated and processed for data storage and further interpretation. The heart of the data centre is the transient recorder, which makes the simultaneous and continuos monitoring of numerous input channels possible.
A very accurate absolute time base is needed to identify and catalogue observed seismic events. This is achieved by using a DCF-77 or a GPS time module to synchronise the timer in the transient recorder.
To limit the amount of data, the seismic monitoring system does not record the data continuously as for example seismological observatories but event orientated. This means that only the relevant seismic events with an appropriate time window before and after the event is stored on the disk.
The decision whether or not there is an event which has to be stored on the disk is made by the definition of trigger functions.

Tel.: +49 36 32 - 61 01 00   Fax: +49 36 32 - 61 01 05   Email: geophysik@kutec.de   http://www.kutec.de

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K-UTEC GmbH
Am Petersenschacht 7
99706 Sondershausen
Germany

Transient recorder:

The transient recorder is a measuring system enabling the simultaneous digitally recording of data from numerous input channels. The system used by K-UTEC has connections for up to 32 analogue or digital input channels and the integrated signal processor permits the definition of complex trigger functions and the online data processing.
The modularised design of this measuring system as well as the almost endless possibilities to configure it's controlling software makes it also possible to record other types of data (e.g. gas detectors, air conditions an many more) in addition to the primary seismic data. Moreover, the integrated signal processor together with the various digital and analogue output channels allow to communicate with or even control other peripheral systems.

Trigger functions:

The trigger functions are defined within the controlling software of the transient recorder. Possible trigger functions could be for example a simple threshold or the ratio of the short time and long time average. The different seismometers are often grouped together and the data recording is triggered when the conditions for one or more groups are met.
All input channels are monitored continuously and the data is stored in a memory loop. Once the trigger conditions are met, the data is copied from the memory loop to a file system on the disk. This procedure allows to also store an appropriate time window before and after the event. Especially the time window before the actual trigger time is necessary to ensure that the beginning of the seismic event as well as smaller leading events are recorded. The size of the pre-trigger time window can be freely chosen and is only limited by the number of used input channels and the size of the memory loop.

Data storage:

The data is stored on the hard disk of a normal PC, which can be connected to the transient recorder via a standard ethernet network. It is also possible to integrate a PCMCIA-type hard disk or flash card in the transient recorder, which then enables the stand alone operation of the system without the controlling PC.

Data processing and interpretation:

The identification and visualisation of the seismic events can be done directly on the PC where the data is stored. However, to ensure undisturbed data acquisition, we strongly recommend to do further data processing such as the estimation of the magnitude of the event and the calculation of the coordinates of the epicentre etc. on a different System.

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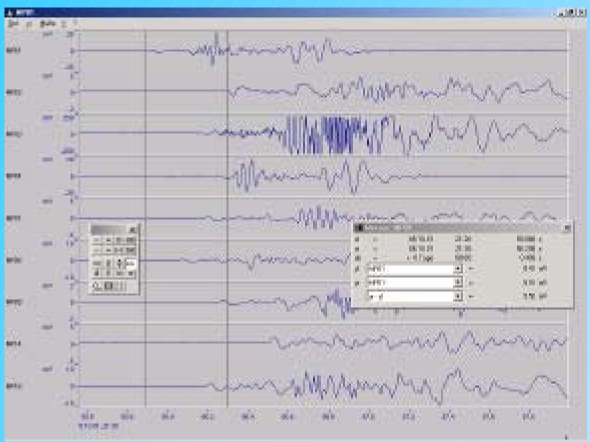
Numerous types of seismic shocks are recorded with the monitoring system and most of the events are not of a natural origin or do not come from within the observation area. This means that besides the main task to



Seismogram, Estimation of intercept times at the various seismometer stations

observe naturally occurring seismic events, all kinds of blasting in and around the target area as well as larger earthquakes from afar are recorded. Since it is impossible to automatically distinguish between these types of events, it is very important to correctly identify the event manually to avoid misinterpretation when assessing the general seismicity in the target area.

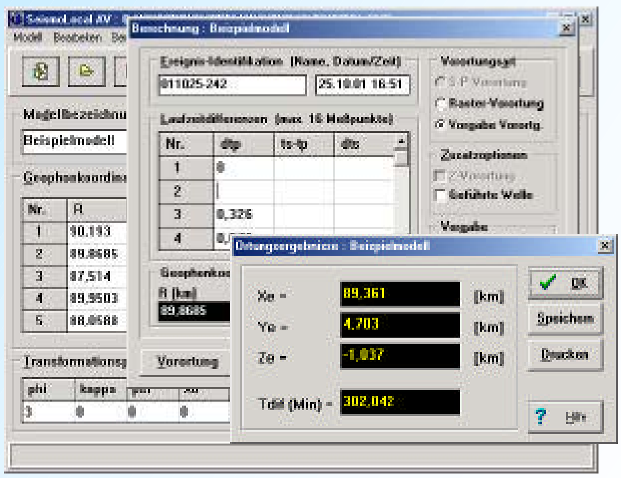
Locating the events:

K-UTEC has developed a special tool to calculate the origin of the seismic event. The tool is easy to use and runs on any Windows 9x/NT based system.
It uses the intercept times from the various seismometers and the information about the propagation conditions and especially the velocities of seismic waves from a given geological model to calculate the coordinates of the focal origin.
To be able to locate a seismic event, it has to be recorded by at least three, better by four or more seismometers.

Assessing the seismicity:

Seismic events, whether they are caused by local tectonics or induced by local mining, are only sporadically occurring events, thus the assessment of the general seismicity within an area can only be realised over a longer period of time.

K-UTEC has a long year experience with this subject and offers extensive support both in planning and installing seismic monitoring systems but we also offer extensive assistance for the operation of the monitoring system, the interpretation of the single events as well as the general assessment of the seismicity in the target area.



Tool SeismoLocal for locating local seismic events

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K-UTEC GmbH
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99706 Sondershausen
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Data recording and processing centre:

consisting of

- demodulation unit
- transient recorder
- PC for data storage and processing

transient recorder

Technical properties of the transient recorder (basic system):

- 32 analogue input channels single ended or 16 differential
- 3 special channels, AC-coupled for current fed accelerometers
- synchronous sampling of all input channels (2 time bases: intern + DCF-77 / GPS)
- 80 kHz max. sampling rate, 2 MB memory
- 15 bit resolution, input range: ±100 mV, ± 500 mV, ± 2 V, ± 10 V
- Thermistors and PT100-resistors directly connectable
- 32 digital I/O channel, incl. 4 channels for incremental encoders
- 8 analogue output channels, 12 bit
- integrated signal processor:
- connection for PC via Ethernet RJ-45 (NetBios)
- optional: PCMCIA-type HD / flashcard

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Signal transmission

technical properties PFM-modulator:

- power supply: 12 V, 24 V, 42 V or 230 V
- nearly all types of seismometers connectable
- up to 72 dB dynamic range

optional:
- intrinsic protection against explosive gases according to EN 50014 and EN 50020, EEx-ia-I (only 12 V power supply)

PFM-modulator and various types of seismometers

Demodulation unit with integrated transient recorder

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Continous seismic monitoring as one way to assess sources of danger in potash and rock salt mining

K-UTEC SONDERSHAUSEN

Kali- Umwelttechnik GmbH
Am Petersenschacht 7
99706 Sondershausen
Germany

Holger Thoma, Bernd Bode and Olaf Klippel*
Contact: Olaf.Klippel@kutec.de http://www.kutec.de

Part I

Abstract

The intensified exploitation of potash-deposits in central Germany in the last decades lead to an increasing seismicity in the region and large subsidences on the surface. The potentials of seismic monitoring systems in surveying and steering of stabilization measures for the mines will be discussed by selected case studies as the redevelopment of a Carnallite mining field and the assessment of a mixed salt field with multiple level mining.

Introduction

Ever since the beginning of the salt mining activities in central Germany at the end of the last century it repeatedly came to fracturing and deformation processes of the rock formations resulting in rock bursts, contour breaks and sink holes leading to considerable damage to the mines and the earth surface. From 1900 on 15 larger sink holes and rock bursts occurred in the German potash mining areas reaching magnitudes of up to 5.5 and intensities of 5 to 8.5 on the Medwedew-Sponheuer-Karnik (MSK) scale.
A large number of the now closed mines is situated very close to or even directly under dense populated

Table 1: Heavy rock bursts in German rock salt and potash mining

date	mine	type of salt	area [km2]	magnitude	
17.08.1879	Leopoldshall I/II, Staßfurt	Carnallitite	0.02		
23.12.1880	Leopoldshall I/II, Staßfurt	Carnallitite	0.12		
11.11.1901	Ludwig II, Staßfurt	Carnallitite	0.06		17 people dead
22.01.1916	Hallesche Salzwerke, Teutschenthal	Carnallitite	0.03	3.0	
24.05.1940	Krügershall, Teutschenthal	Carnallitite	0.6	5.0	42 people dead, damages on buildings
05.03.1943	Kleinschierstedt, Ostfeld	Sylvinite	0.3	4.0	
22.02.1953	Wintershall, Heringen	Carnallitite	0.7	5.2	damages on buildings, fault on earth surface
28.08.1955	Kleinschierstedt, Westfeld	Sylvinite	0.6		
07.08.1958	Merkers	Sylvinite / Carnallitite	3.0	5.2	
30.12.1959	Neustaßfurt VI/VII	Carnallitite	0.1		
29.06.1961	Merkers	Carnallitite	0.2	4.1	
04.04.1971	Aschersleben V, Nordfeld	Carnallitite	0.32	4.6	
23.06.1975	Unterbreizbach	Carnallitite	3.0	5.3	damages on buildings
02.07.1983	Bleicherode	Carnallitite	0.1	3.3	
13.03.1989	Merkers	Carnallitite	7.0	5.7	damages on buildings
11.09.1996	Teutschenthal	Carnallitite	2.5	4.8	damages on buildings

areas, thus special care has to be taken for the long-time stabilization and plugging of the mine workings to avoid larger damage on infrastructure and buildings. Figure 1 shows a sink hole from the Staßfurt VI/VII mine. The sink hole with a diameter of approximately 140 m was formed shortly after the mine was flooded in 1975 and has been growing ever since to the todays size of almost 300 m.

Figure 1:
Sinkhole Neustaßfurt VI/VII
Diameter: 300 m

The increased mining of Carnallitite and the extensive exploitation of the potash salt deposits lead to an increasing seismic activity, asking for the installation of large scale seismic monitoring networks. Figure 2 shows the location of the monitoring systems which are currently operated by K-UTEC.

Beginning in the early 80ies, a more complex methology was introduced for the assessment of the mining field conditions, including:

- geophysical methods such as
  - seismic monitoring
  - sonar and radar measurements
- geomechanical methods
  - hydraulic fracturing (in-situ stress measurement)
  - conventional deformation measurements
  - borehole video and photographic documentation
- remote sensing techniques:
  - arial and satellite images
  - laser scanning and others

From all the applied methods, the seismic monitoring is about the only way to obtain any instant information about ongoing deformation processes in those parts of the mine which are no longer accessible.

Figure 2:
Installed seismic monitoring systems in central Germany

The tasks for seismic monitoring systems can be defined in the following way:

Production phase:
Monitoring of the mining process and assessment of induced and naturally occurring seismicity

Aftertreatment phase:
Monitoring of underground disposal sites

Closing and plugging of the mine:
Overall seismic monitoring and assessment of the seismicity of sylvinite and mixed salt fields for supervision and steering of stowing and stabilization measures

The following parameters are provided by seismic monitoring systems:

1) from the intercept times of various wave types:
- spatial coordinates of the origin of the seismic event

2) from signal amplitude:
- particle displacement, velocity and acceleration
- magnitude of the event (localmagnitude, after lida)
- released seismic energy
- intensity
- fault plane solutions

3) from frequency characteristics:
- seismic moment
- dislocation at fault plane
- fault plane radius or area
- stress drop

Locating the seismic event

Each monitoring network consists of a number of vertical component seismometers (currently 8-17) distributed within the mine and on the earth surface above (Figure 3). Additionally, a number of independent mobile 3C-sensors are placed in public buildings or on the surface. These 3C-seismometers are primarily used for the damage assessment of infrastructure and buildings for larger events but provide also data for the calculation of the magnitude of the event and fault plane parameters (seismic moment, stress drop, etc.). Right now, they can not be used for the event localisation because of differences in the time base of the seismometer network and the independent stations.
The focal origin is calculated from the intercept times of P- and S-wave using a given velocitymodel. The model is extracted from borehole data as well as from seismic and sonar surveys.

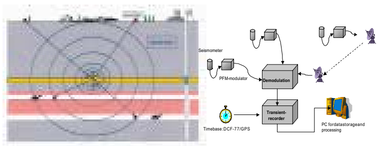


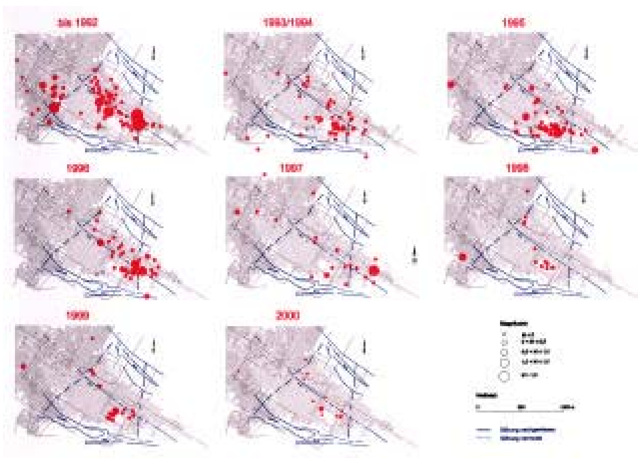
Figure 3: Scheme of a seismic monitoring network

Case examples

1. Stabilization of a carnallititemining field

Figure 4 shows the development of the seismicity over the last years of a carnallitite mining field. This field was mined between 1982 and 1991. The deformation characteristics of carnallitite-salt and the rather difficult geomechanical situation of the field resulted in a dangerous weakening and almost disintegration of the pillars. As a consequence, high deformation velocities and a rapidly increasing seismicity (Magnitudes larger than 1.5) could be observed. To avoid the collapse (rock burst) of the entire field, it had to be stabilized by refilling the chambers with rock salt. The backfilling and stabilization of the field was carried out between 1991 and 1996. The seismicity started to decline already during the refilling and plugging process. Moreover, the seismic monitoring together with the deformation measurements made it possible to identify especially weakened zones where special safety measures had to be considered.

Figure 4:
Development of the seismicity of a Carnallitite mining field during (1991-1996) and after stabilization measures



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99706 Sondershausen
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Part II

2. Stabilization of a mixed salt field

A similar situation was found in a mixed salt field, which has been mined out on several levels. Here, the stowing and stabilization measures are not yet completed and a rather high seismicity with magnitudes of up to 2.0 can be observed. The distribution of the seismic events in the mining field is shown in figure 5. As can be seen in Figure 5, only a minor part of the events is spread more or less randomly over the field. The vast majority of the seismic events is concentrated on lines which can be related to local tectonics. This indicates that the ongoing deformation processes focus on the reactivation of old, already existing fault systems, which inturn implements the risk of the opening of water-ways into the salt complex.

Figure 5:
Distribution of seismic events in a mixed salt field. The majority of the events are located at structures related to local tectonics

Figure 6 shows a cross section through the mining field and gives an overview of the depth distribution of the located seismic events. As can be appreciated from Figure 6, the majority of the seismic events with higher magnitudes have their origin above the mining horizon in the more competent layers such as the lower New Red sandstone (SU) or the main anhydrite (T3/A3). Events within or close to the mining horizons are related to the fracturing or even collapse of single pillars.

An other way of characterising the development of the seismicity over time is shown in figure 7. There, the cumulative released seismic energy or respectively the square root of the energy is plotted over time (Benioff, 1951). The slope of the curve is related to the amount of stress released by the seismic events. The shape of the curve gives information of how the stress is released: a large number of small events (smooth curve) or a small number of stronger events (blocky curve). A change in the mean slope of the curve indicates a change of the characteristic of the deformation processes. In case of this mixed salt mining field (figure 7, field 2b), an increasing activity can be observed, indicating that the ongoing stabilisation measures have not yet taken any effect. Moreover, the deformation and disintegration of the field seems to accelerate.

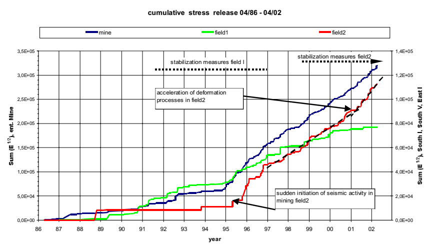

Figure 7:
Cumulative stress release (BENIOFF-curve) of mining field1 (carnallitite field), field2 (mixed salt field) and the entire mine

3. Controlled flooding of a mixed salt field

The mining field as shown in Figure 8 was abandoned and in parts already plugged after production. In order to prevent an uncontrolled flooding of the mining field due to brine inflows to the mine (partly saturated with NaCl), it was decided to geomechanically stabilize and plug the field by a controlled flooding with highly concentrated $MgCl_2$ brine.

In preparation of the flooding, experiments were made in isolated blocks to investigate how the NaCl-brine is reacting on the salt formation (consisting of sylvinite overlaying Carnallitite at a depth of 800 to 850 m) but also to test if the $MgCl_2$ brine can be produced within the mine without risking the collapse of the mining field.

A rather quick and also more intense reaction on the flooding could be observed in area D, which is characterised by a more complex tectonic situation. The period of high energy release was limited to a few month, where seismic events with magnitudes larger than M_L=1.0 were registered at very short intervals . The strongest event reached magnitudes of M_L=1.9

As can be seen in Figure 8, most of the events are located along a NW-SW striking structure indicating a close relation to the local tectonics. Moreover, the origins of the seismic event were partly located in depth regions far below the mining horizon, which also points towards a mobilisation of local tectonics.

The development of the seismicity of the field over time (BENIOFF-curve) is shown in figure 9. The period of high seismic activity in area D can be clearly identified.

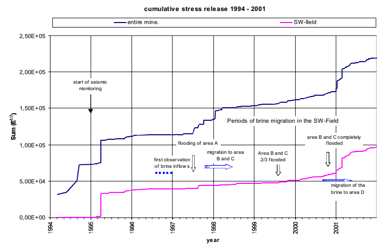

Figure 9:
Cumulative stress release (BENIOFF-curve) of the flooded mining field and the entire mine

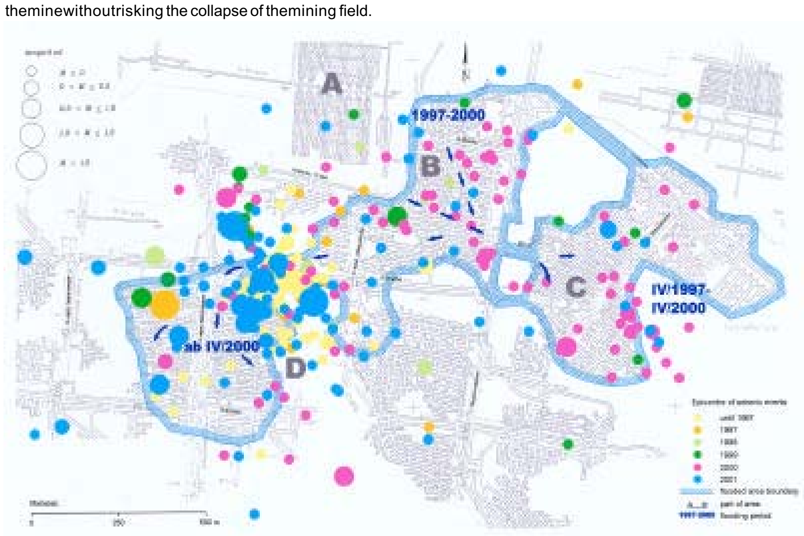

Figure 8:
Distribution of seismic events during the flooding of a mixed salt field

The development of the solution processes, the deformation dynamics as well as the development of the induced seismicity had to be monitored. The inflowing brine (partly saturated with NaCl) is led through the parts of the mining field which has already been plugged (Figure 8, area A) in order to mineralize with $MgCl_2$. In that way, the brine is almost saturated and has no relevant solution power left when it enters the more sensitive areas. Thus, the geomechanical effect of the flooding is mainly limited to the mobilisation of deformation processes due to reduced friction by the migrating brine and the related stress reallocation.

Development of the seismicity:

In areas B and C (Figure 8), a notably seismicity was developed not until 2 years after the beginning of the flooding, when two third of the blocks were filled. The seismicity was significantly reduced after one more year when these areas were completely flooded. The seismic events were generally characterised by rather small energies with maximum magnitudes of M_L=0.6. The origin of the events were located within the mining horizon and the layers directly above or below.

Figure 6:
Cross section through the mining field and depth distribution of the seismic events

Conclusions

Seismic monitoring systems play an essential part in the surveying of mining fields and rock formations in German potash and rock salt mining.

They are capable of detecting fracturing processes in the rock formations and provide appropriate parameters for the assessment and interpretation of the seismic activity.

By observing the development of the seismicity over time and the complex interpretation with rockmechanical and other surveying data, seismic monitoring systems allow for:

- early recognition and assessment of critical or possible hazardous conditions
- steer reconstruction or plugging measures and control its effects

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