Evolution monitoring of a solution-mining cavern in salt : identifying and analysing early-warning signals prior to collapse

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Experimental monitoring of a solution-mining Cavern in Salt: Identifying and Analyzing Early-Warning Signals Prior to Collapse

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Abstract

Risk management of underground cavities requires a good working knowledge of accidental phenomena like subsidence or large-scale collapse. This was the context when the opportunity was taken to instrument a large size in use saline cavern, so as to test various auscultation techniques available under controlled conditions. A micro seismic monitoring network coupled to a surface measurement system was installed to improve our knowledge of the mechanisms that initiate and govern the evolution of the cavern up to its collapse. After a stationary period combined with partial depressurization tests conducted in 2005 and 2007, the cavern appears to have entered into its final evolution phase, and this probably since early 2008. This results in continuous and highly sustained microseismic activity as well as the occurrence of a number of microseismic episodes localized around the cavern roof. The localization of the microseismic events, for some of these episodes, is closely correlated to the quasi-dynamic brine pressure variations and to the evolutions of the roof depth measured at observation boreholes. The microseismic activity turns out to be more precise when it comes to the evolution affecting the mine cavern than the movement measurements taken on the surface or sub-surface.

Key words: Solution Mining and Salt, Instrumentation and Monitoring, Sinkholes, Subsidence, Instrumentation and Monitoring, Geophysics

Introduction

Society's demand for improved risk management of hundreds of mining concessions and abandoned cavities (surface subsidence or collapse, changes in circulation of surface and underground water and their pollution, releases of gas from underground etc.) has grown, in France, since the end of the 1990s. The catastrophic events related to the iron mine at Auboué and Moutiers in Lorraine (France) illustrate the potential risk of abandoned mining structures (Couffin et al., 2003; Bennani et al., 2004).

Conducting a precise evaluation of risk areas and securing them either by reducing the hazards or by accurate monitoring, now represents a priority goal for the French government. In many cases, surveillance is required to quickly reduce the vulnerability of the areas involved. Such surveillance is then implemented thanks to early warning systems that make it possible to warn and intervene should any major evolution occur. Until now, for the most risk prone areas, microseismic techniques have taken the lead in providing surveillance over extended areas likely to be affected by subsidence or collapse. Nevertheless, the absence of any feedback on true-instrumented collapses does not allow us to answer fundamental questions related to the mechanisms and the kinetics of these phenomena on a large scale.

[1] Formely INERIS

It is in this context that the Cerville-Buissoncourt experimentation has been undertaken by the GISOS partners in collaboration with the Solvay mining company. This experiment consists in in-situ monitoring of a saline cavern in intensive use in the Lorraine salt basin, to the South of Nancy, France. It makes use of large geotechnical and geophysical instrumentation (Driad-Lebeau et al., 2008) ; the salt extracting method consists in issolving the entire salt layer from the bottom up then letting the overburden collapse before undertaking relandscaping.

In this article, we describe the on-site instrumentation deployed by INERIS between 2004 and 2008. This comprises a multi-parameter system including a microseismic monitoring network along with a system for measuring ground movements. The change in the microseismic activity and the time and space distribution of the events will be presented and compared with the upward movement of the cavern roof measured by diagraphy. We will focus on the 2008 data, the year when the cavern most probably entered into the collapse process. This data will then be discussed in the light of ground surface measurements.

Site Description

The Cerville-Buissoncourt site in the Nancy salt basin has been mined since 1997 using the channel and drilling method. The field is mined by dissolution, with aligned drillings hitting the base of the salt reserves at a depth of some 260 meters, where fresh water is injected (Figure 1). The circulation of the brine-filled water creates a communication channel and the extraction wells are placed downstream from it. Extraction then leads to the formation of a cavern in line with the water injection drilling holes which develops during operation. Once the entire deposit is mined, the cavern reaches the overburdens, which then collapse. The overburden collapses and on the surface appears a crater with a lateral extension that extends close to that of the cavern

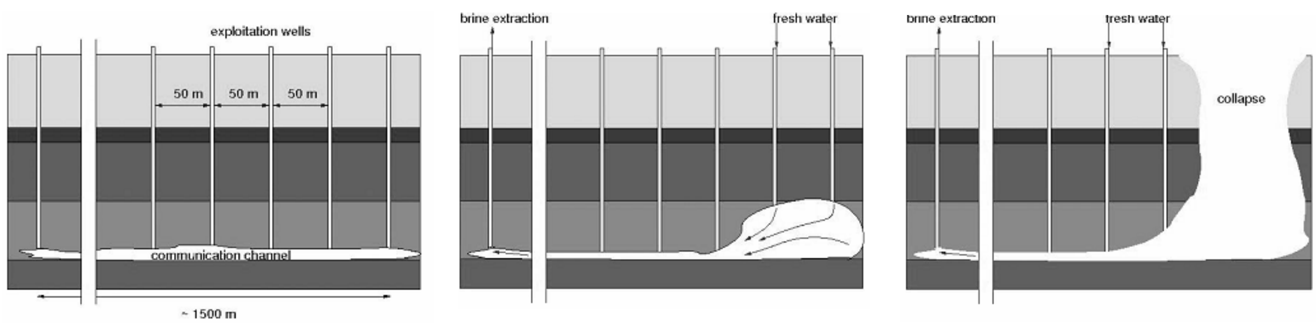

Figure 1: Layout diagram illustrating operations using channels and drillings: (on left) creating a communication channel at the base of the deposit, (on middle) the creation followed by the extension of the cavern, and (on right) the collapse of the overburden with the formation on the surface of a crater (Mercerat, 2007).

This site presents the advantage of being well-known thanks to the investigations undertaken by the mine and the GISOS partners. The cavern geometry, as created during the 2000-2003 period, was evaluated using the sonar measurements implemented by Solvay. A tomography profile and a vertical seismic profile were also made on-site (Suffert, 2006) prior to installing the instrumentation and while operations were placed on hold. In fact, the cavern's dimensions had become such that any continuing dissolution could have rapidly led to its collapse.

The site's geology is characterized by a succession of sub-horizontal layers (sloping < 2º, in the instrumented sector) from the ground's surface to the salt deposit. The cavern roof is located at a depth of 183.5 meters (Figure 2) and four main geological facies are highlighted: overburdens consisting of a succession of marls, marly limestone, sandstone and anhydrite marls with depths ranging from 0 to 119 meters, a massive, stiff, and scarcely-fractured layer of dolomite and anhydrite (i.e. Beaumont's Dolomite) at a depth of 119 to 127.5 meters and anhydrite marls that are more or less indurated at a depth of between 127.5 and 183.5 meters. Lastly, the salt layer is present down to a depth of ~ 270 meters.

The mechanical properties (low resistances) of the overburden located over the roof of the Beaumont Dolomite indicate that it does not apparently play any significant role in the stability of the site. On the other hand, the dolomite and anhydrite layer, which is characterized by a high degree of regularity within the salt basin, presents a high degree of resistance to failure (Nothnagel, 2003): it is accepted that the behavior of this bed conditions the stability of the overburden. More precisely, it is expected that the evolution phenomena will first involve blocks falling from the clay-sandstone and marl-type bed. During a second phase, the damage to, followed by the flexing failure of the dolomite layer, will trigger the sudden collapse of all of the overlaying terrain.

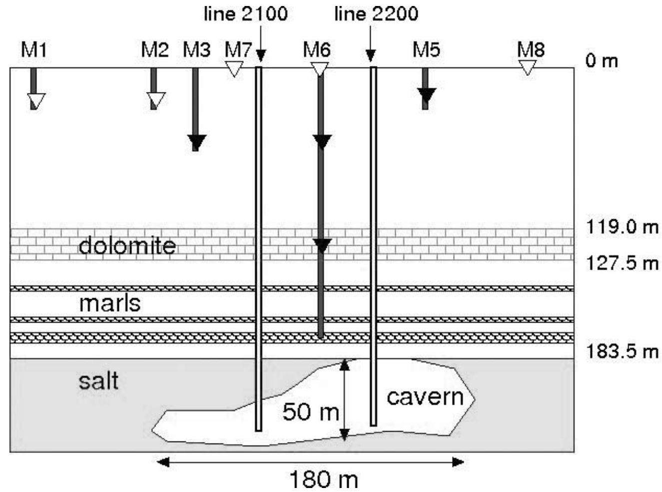

Figure 2: Simplified geological cross section taken in the E-W direction, including the position of the 3D and 1D microseismic probes represented respectively by black and clear symbols.

Description of the measurement system

Prior knowledge of the evolution mechanism as described above led to the installation of a microseismic monitoring network at the end of 2004 . This network comprises seven measurement sensors, including four 3D sensors, all equipped with miniature wideband geophones. These sensors are distributed and cemented into the drillings located around the cavern at depths of between 35 and 125 meters (Figure 2 and Figure 3).

So as to improve the coverage of the collapse area and improve the precision of the localization of microseismic events, two 1D sensors with characteristics that are identical to the others were added to the site in March 2008, at depths of some 2 meters.

An acquisition unit provides the detection, recording and automatic transfer, in quasi-real-time, of measurement data to INERIS Nancy. The automatic 3D localization of events is performed by the SYTMISauto software (Lizeur, 2008) from the P and S-waves time arrival and from incidence angles measured by the 3D sensors. A number of important parameters for the localization procedure, especially setting the velocity model, were determined from a series of setting blasts that took place on the surface in 2005. Although the mean localization error for blasts was determined to within 10 meters, the error on the position of the microseismic events is estimated at 60 meters.

This microseismic monitoring network is coupled with a device for measuring movement on the ground's surface (Figure 3) comprising a line of 17 reflectors (targets) located perpendicularly to the track axis in the expected collapse area and in the area that is considered stable. The reflector position is measured automatically at regular intervals (one measurement cycle every 20 minutes) using a tacheometer. The distance between the targets and the tacheometer is relatively high for this type of measurement. It varies from 150 to 270 meters. This mechanism, although sensitive to major meteorological variations, allows, after making corrections or conducting a moving average on a number of measurement cycles, to detect surface movements with a precision of +/- 3 mm for the points that are closest to the tacheometer. Data acquisition and analysis parameter setting is performed directly on-site and remotely, in real-time, from INERIS.

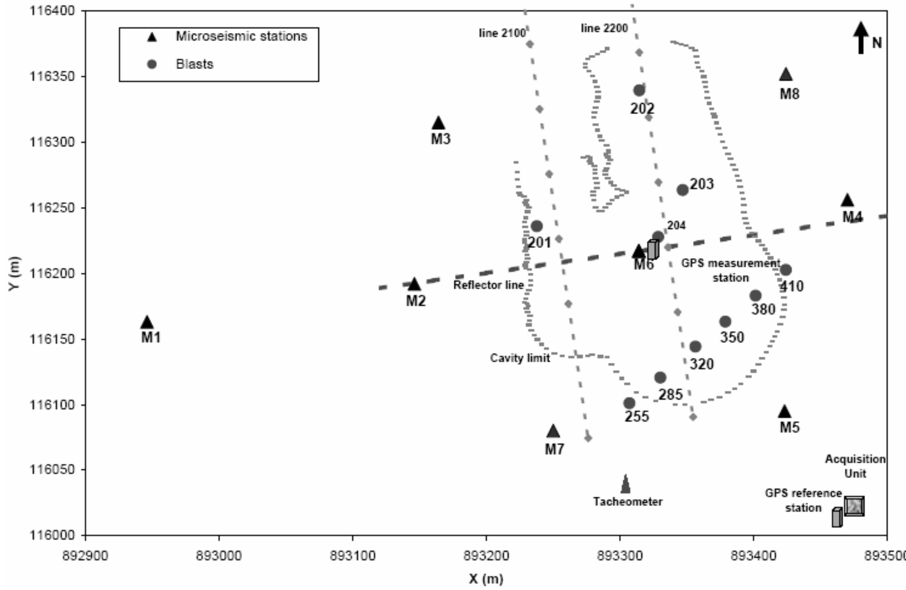

Figure 3: Map showing the layout of the microseismic monitoring network and the ground surface movement measurement device, including the positions of the setting blasts

The leveling mechanism, tested in the beginning of 2005, was completed in March 2008 with a GPS position measuring mechanism that works on the basis of a precise RTK (Real Time Kinematic) GPS differential measurement. Two beacons were installed (Figure 3): one as the reference is placed in an area that is considered stable, close to the acquisition unit; the other, the measurement unit, is positioned in the center of the expected collapse area. GPS position measurements are made every hour, with the measurement acquisition duration set to 20 minutes and each measurement file is automatically transferred to INERIS in Nancy in quasi-real-time. The high accuracy of the GPS measurement, estimated at +/-5 mm, is obtained thanks to the short distance between the two beacons.

Lastly, it would be useful to specify here that during normal operations, Solvay takes gamma-ray well logs at regular intervals so as to evaluate the vertical extension of the cavern alongside the operating drillings as well as of the brine pressure measurements. We note that other measurement mechanisms have also been installed on-site by the GISOS partners and that these are described in other forthcoming publications.

Initial State & Controlled Pressure Tests

Salt extraction operations were put on hold at the end of 2004 for reasons that are specific to the mine operator. This stoppage was used to allow site reconnaissance experiments to be conducted, along with the deployment of the various measurement mechanisms as well as a characterization of the cavern's "initial" state. This status is characterized, outside of any interference linked to dissolution, by microseismic background noise in the range of two events per day.

The resumption of dissolution operations in the instrumented cavern that was initially planned to take place during 2005 was repeatedly postponed for technical and production reasons. However, since 2007, dissolution operations have been conducted continuously from drillings located downstream from the instrumented cavern. However, two controlled pressure tests were conducted with the help of the mine operator so as to precisely evaluate the likelihood that the monitored geological system could transmit microseismic activity as a result of hydro-mechanical effects (see Mercerat 2007 and Mercerat et al., 2008 for further details).

These two tests performed in October 2005 and April 2007, in line with a virtually identical protocol with a limited fall in pressure of ~0.36 MPa, did not allow the detection of any significant measurement variations, thereby showing a relative hydro-mechanical stability of the system.

Microseismicity Induced by Cavern Evolution

Microseismic Episodes General Characteristics

Between May 2007 and April 2008, a number of microseismic episodes were observed on-site. These episodes are characterized by an acceleration in the number of microseismic records and/or of the energy measured on the 3D probes (Figure 4). The microseismic regime also presents a significant evolution during this period: it went from triggering a few times a day to almost 25 times a day on average from April 2008.

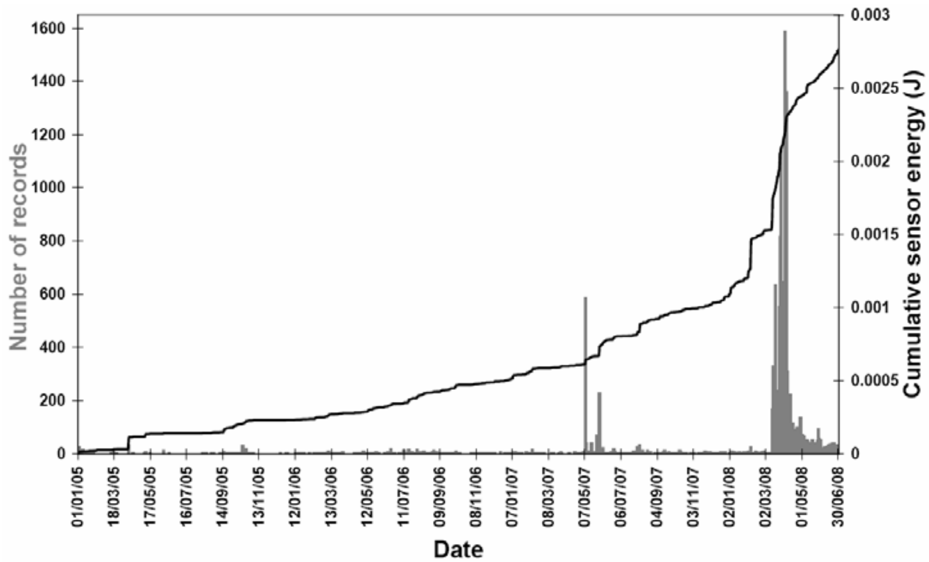

Figure 4: Histogram showing the number of microseismic records per day and the cumulative energy trend as measured by the 3D sensors from 01/01/2005 to 30/06/2008

The empirical criteria used to define the occurrence of an episode and to quantify it (strong acceleration compared with the background noise during considered period) were defined as follows:

- From 01/01/07 to 12/03/08: number of records in excess of 70 per day or cumulative 3D sensor energy in excess of 1.10^{-4}J per day.
- From 13/03/08 to 30/06/08: number of records in excess of 220 per day or cumulative 3D sensor energy in excess of 1.10^{-4} J per day.

From 01/01/2005 to 30/06/2008, six episodes were identified in this way (Table 1). The May 2007 episodes occurred while dissolution in the cavern had not yet resumed, whereas dissolution operations were ongoing downstream from track 2200, at some 200 meters away from the cavern.

Regardless of the episode considered, the records show two types of events:

- "Isolated" and clearly-identified events lasting less than 0.5 seconds with a frequency content that is between 40 and 700 Hz, presenting an P-wave that is more or less emergent and with or without the presence of S-waves.
- "Burst" events that result in the practically simultaneous occurrence of events of varying amplitudes that make any association between arrival times between the various network sensors difficult to make.

Table 1 clearly shows the change in trend starting in March 2008: the microseismic episodes last for a number of days and account for several thousands of events.

Start of episodes date	Duration	Cumulative energy on the 3D probes (J)	Number of events
08/05/2007	< 24 hrs	$5.16\ 10^{-5}$	622
31/05/2007	< 24 hrs	$1.11\ 10^{-4}$	226
06/02/2008	< 24 hrs	$4.12\ 10^{-4}$	28
12/03/2008	~192 hrs	$6.93\ 10^{-4}$	2,349
25/03/2008	~120 hrs	$4.13\ 10^{-4}$	3,538
31/03/2008	~ 168 hrs	$5.04\ 10^{-4}$	5,506

Table 1: Characteristics of the six main microseismic episodes recorded at the Cerville-Buissoncourt site between 01/01/2005 and 30/06/2008

Localization and Migration of Microseismic Events in 2008

Here we are looking at the major episodes in 2008 that led to a change in the microseismic trend referred to previous data. For the three episodes in March 2008, a sample of 15% of the total number of records that present a good signal to noise ratio were selected and then interactively examined so as to guarantee a sufficiently accurate localization result.

The spatial distribution of the events thus processed is presented in Figures 5 to 7. The apparent alignment of events is linked to the size of the grid used by the localization tool that is set at $10*10*10\ m^3$.

Figures 5 to 7 show a progressive migration of the induced microseismicity towards the north as well as a lateral extension in the cloud of occurrences. This cloud, which is concentrated towards the center of the cavern, presents a NW-SE orientation during the episode on 12 March. It clearly migrated towards the west during the episode on 25 March before heading towards and expanding in an E-W direction during the episode on 31 March.

The deepest events are spread around the cavern borders. We also observe that to the west, events are concentrated essentially under the dolomite bed. To the east and to the center they are located on either side of this rigid bed. Their presence in the overburden, to the east, significantly increased during the last episode. Lastly, this distribution of events around the dolomite bed illustrates the major concentration of stresses, along this bed, at the center of the cavern.

As a general interpretation of this data and bearing in mind the relative precision of localization, it clearly appears that:

- The microseismic energy corresponds primarily to a vertical propagation from the cavern dome towards the surface. This is shown by the high density of events in the figures. These episodes correspond to a failure of the more or less anhydrite- marl beds overlying the salt layer.
- A significant part of the microseismic events is located in line with the episodes directly above the western part of the cavern. This dissymmetry is clearly visible in the figures indisputably accounts for a dissymmetrical development of the cavern during the first years of operations. Note that in early 2007, the top of the cavern had reached the roof of the salt layer in its eastern part while it was still covered by 10 meters of salt in its western part. This activity can therefore be explained by the localized failures induced by concentration of high stresses at the interface between the salt layer and the marl beds.
- These three microseismic episodes that marked a major turning point in the evolution of the system resulted in the failure in less than five months of some 30 meters of marls located above the salt layer. These dynamics show the very low mechanical strength of this thick bed in contact with the brine. The localization of induced seismicity along and above the dolomite bed caused the appearance the major impact in terms of stress fields and in induced motion, of the progression of this cavern along the upper strata, very probably an early warning sign of the generalized collapse mechanism.
- Finally, it is necessary to keep in mind that these evolutions can be attributed for a part to the dissolution that took place in the cavern for the last two years.

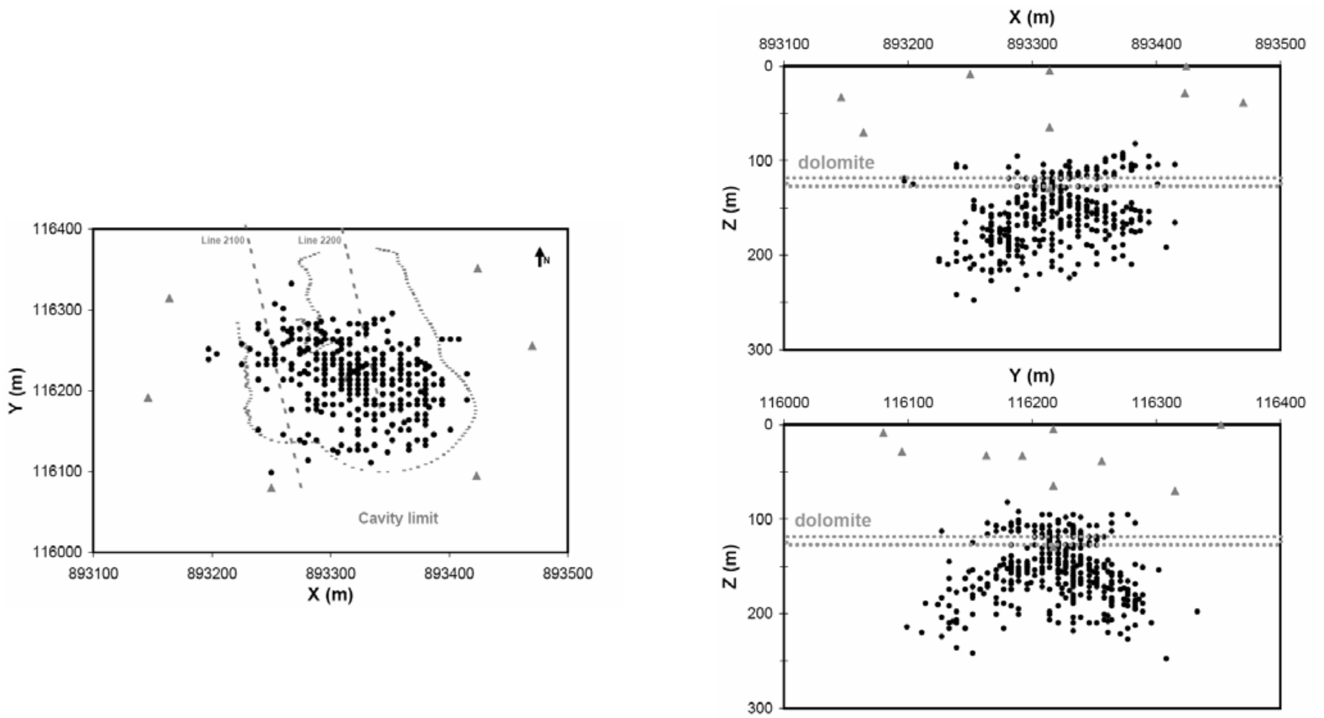

Figure 5: Positions of the microseismic events (black symbols) and of the microseismic sensors (grey triangles) along cross sections XY, XZ and YZ for the episode on 12 March 2008.

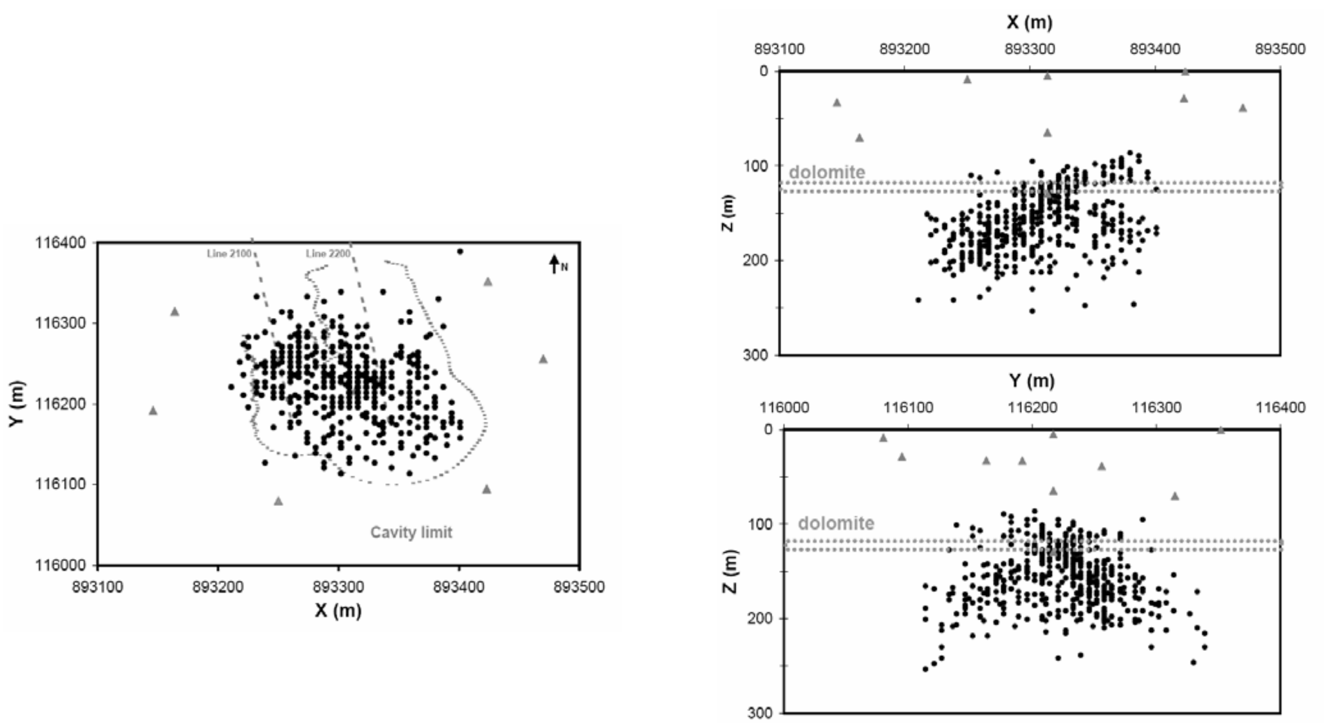

Figure 6: Positions of the microseismic events (black symbols) and of the microseismic sensors (grey triangles) along cross sections XY, XZ and YZ for the episode on 25 March 2008.

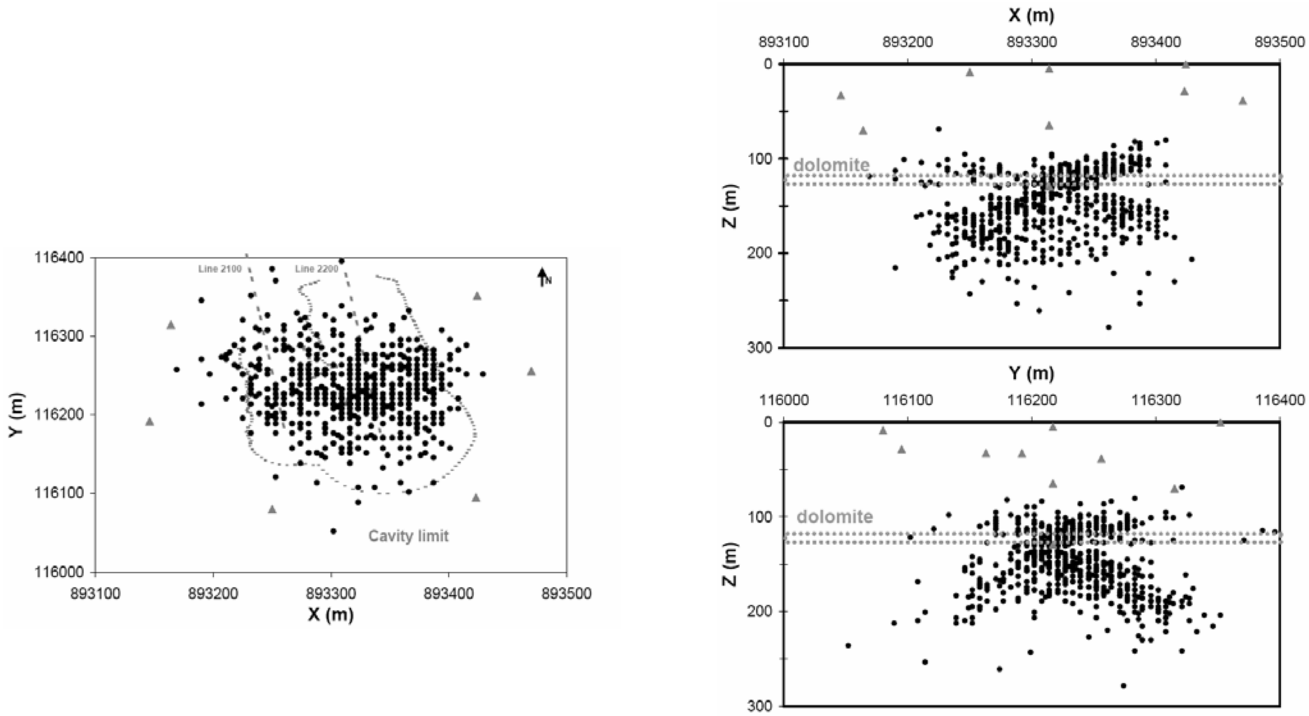

Figure 7: Positions of the microseismic events (black symbols) and of the microseismic sensors (grey triangles) along cross sections XY, XZ and YZ for the episode on 31 March 2008.

Correlation with the Pressure Measurements

For the first three episodes listed in Table 1, the mine operator observed a slight variation in the level of the brine level during the hour that followed the triggering of the episode during which the number of records hit its maximum. This shows that the activity peak is linked to a massive falling of blocks at the floor of the cavern. The events recorded subsequently are probably linked to re-adjustments of the stresses in the roof, but also to the continuing splitting of the marls, observed more locally and on more limited layers.

Regarding the three major episodes in March 2008, this phenomenon was clearly observed despite the episode having lasted for a number of days. For example, for the episode on March 31, a first pressure build-up was detected on 3 April at 21:09 then a second on 4 April at 08:34. The latter peak led to a spectacular variation in the brine level of more than 13 meters downstream from the cavern, i.e. more than 1,200 meters away. This level returned to its initial value nearly 8 hours later. In this case, the pressure sensor makes it possible to determine with certainty any large-scale avalanche phenomena. A detailed analysis of microseismicity is underway so as to use the waveforms to identify and quantify these specific phenomena, which are actually very rare in relation to all of the induced seismicity recorded.

Correlation with the Surface Measurements

The surface readings in line from mid-March 2008 in-line with the cavern, that are available and have a good degree of precision show a progressive subsidence of low amplitude affecting the overburden, between 16 March and 15 May 2008 with an acceleration on 5 and 6 April (Figure 8). A sudden movement of about 3.5 mm in nearly 24 hours was recorded in line with the cavern, at precisely the end of the microseismic episode on 31 March. It should be stated that the measurements taken regularly by the mine operator prior to March 2008 had not indicated any significant movement affecting the surface. Based on the measurements made by Solvay on similar sites, the expected movements on the surface before the generalized failure of the dolomite bed should reach a few centimeters.

One has to notice that the reflector line is used to observe the formation of a subsidence developing along the cavern line (Figure 9). The extension of the surface movements is consistent with the estimated limits of the cavern in 2008 and in line with an overall deformation of the overburden.

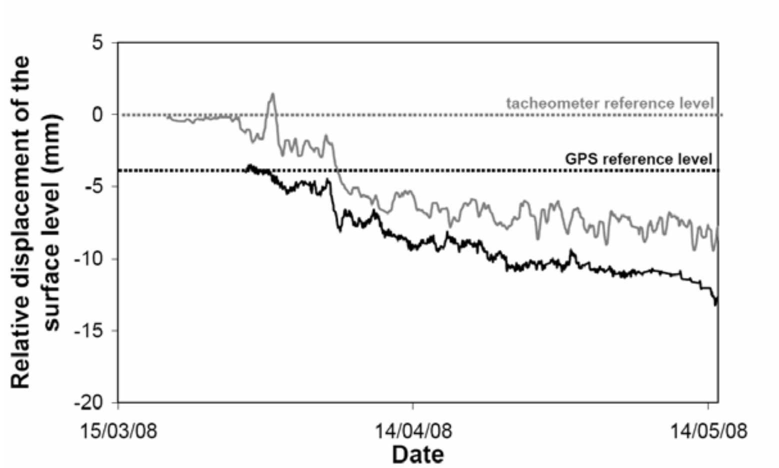

Figure 8: Relative variation in the surface level at target point 9 (in grey) and at the GPS measurement point (in black) close to it between 16/03/08 and 15/05/08.

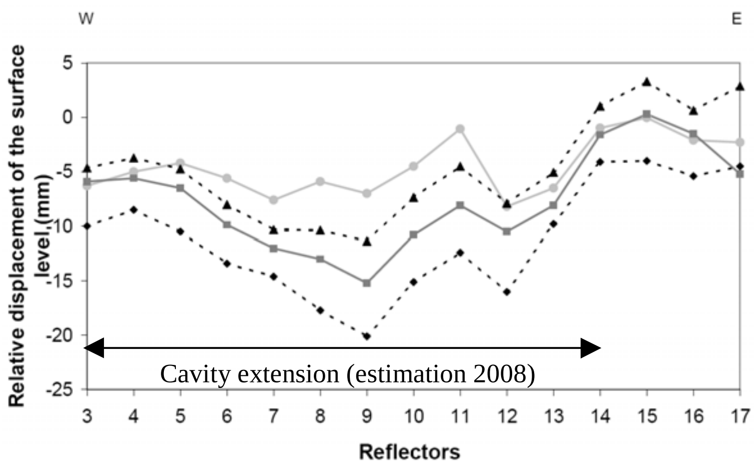

Figure 9: Change in the subsidence trough between 16 March and 1 April (grey dots); 1 May (black triangles); 1 June (grey squares) and 2 July 2008 (black diamond shapes).

Correlation with the Well Log Measurements

The spread of the events depths observed in Figures 5 to 7 is consistent with the well log readings made at regular intervals by the mine operator (Figure 10). On the west flank along the 2100 line, the cavern roof is deeper than at the east, along the 22 00 line, explaining the dissymmetry in the di stribution of events in terms of depth.

More generally, these readings confirm the capacity of the continuous microseismic monitoring to detect the cavern evolution: the assumption made is that th e episode on 6 February 2008 is linked to the roof heave by a few m eters observed between the profiles taken in November 2007 and in late February 2008. The episodes in March 200 8 can be linked to the very significant evolution observed betwe en the end of February and the end of May 2008; this resulted in a massive separation of marls from the cavern roof at a height of about 35 meters along close to 200 meters on the eastern part of the cavern and a rise of almost 20 meters in the height al ong nearly 100 meters on the western part, i.e. a vo lume estimated at 500,000 m^3.

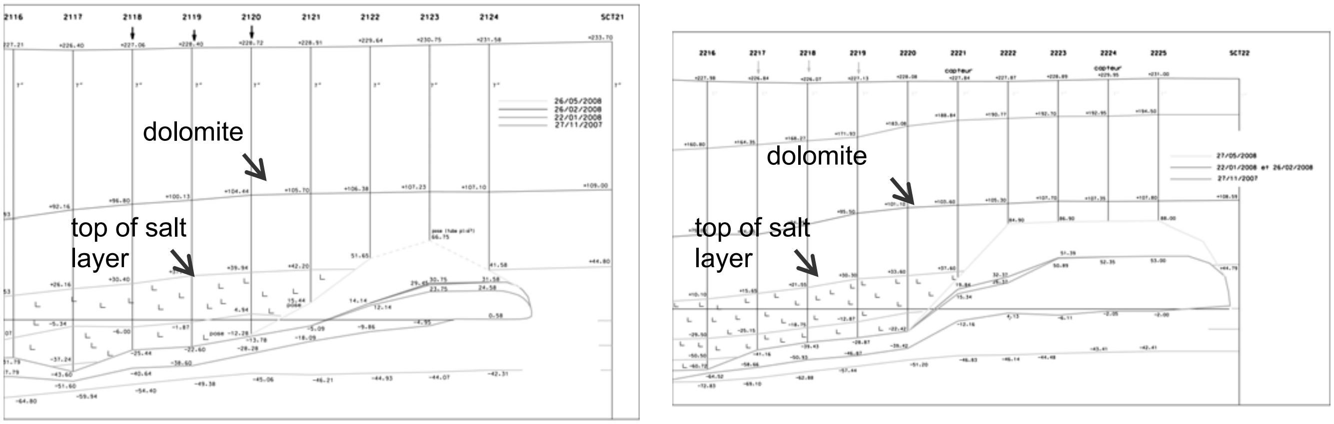

Figure 10: Data from well log readings taken by Solvay along lines 2100 (on left) and 2200 (on right) in November 2007, January-February 2008 and May 2008.

The evolution in the upper limit to the cavern as measured by well log corresponds very closely to the spatial localization of the microseismic activity during this period. The dimensions, which the cavern obtained in this manner, explain the impact on the surface level and on the microseismic background noise after the episodes in March 2008.

Discussion / Conclusions

On the basis of the measurement data collected and on the preliminary results obtained, the lessons that can be drawn from this stage of the experiment are as follows.

The recorded data has made it possible to monitor with relative precision the various steps in the evolution of the cavern, where the rate and amplitude of change have increased considerably during the past few months. These steps have been assessed directly and confirmed by the well log measurements made by the mine operator, thereby validating the monitoring data collected continuously.

Among the various remote measurements and observations methods implemented since the onset of the experimentation, microseismic monitoring has turned out to be the finest continuous monitoring method, in terms of both resolution and precision. The simple cumulative microseismic energy parameter has systematically made it possible to anticipate by a few hours or a few days the remote measurements of displacement, hydrostatic pressure or even the well log observations run at intervals of a few months in the operational drillings. Furthermore, numerous microseismic sequences have been recorded without any other data showing up significant variations.

The calculated 3D localization parameters for the microseismic events make it possible to properly check the dynamic geometric evolution of the cavern, in terms of extension and amplitude. This is clearly shown up by both the correlation with the site's known geology and the well log measurements that regularly mark up the cavern roof position.

During accelerated evolution phases, all of the collected data highlights two kinds of phenomena: diffuse failures affecting the host rock, linked to fracturing and falling of roof rocks and rare phenomena of massive block avalanches that may generate a hydraulic pressure wave of a few bar for a number of hours. Consequently, a displacement field takes place in the overburden that results in a measurable subsidence rate that comes to a number of millimeters per day, for the time being.

Although the average error made when localizing the microseismic events is clearly more than the thickness of the monitored dolomite bed, it clearly appears that the upper beds with the thick and marl roof of the salt layer have already been impacted by major deformations and failures. To this end, automatically processing microseismic data through differential localization should make it possible to better refine the assessment of the dynamic evolution affecting the geological overburden.

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