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INDUCED SEISMICITY MONITORING OF AN UNDERGROUND SALT CAVITY UNDER A TRANSIENT PRESSURE EXPERIMENT

MERCERAT Diego (1)(3), DRIAD-LEBEAU Lynda (2), BERNARD Pascal (3), SOULEY Mountaka (2)

(1) LAEGO - Ecole des Mines de Nancy, 54000 Nancy cedex

(2) INERIS - Ecole des Mines de Nancy, 54000 Nancy cedex

(3) Equipe de Sismologie - IPGP, 4 Place Jussieu, 75005, Paris cedex

Abstract

Within the framework of a research project launched to assess the feasibility of seismic monitoring of underground growing cavities, this specific work focus on the analysis of the induced microseismicity generated by a controlled pressure experiment recently carried out in a salt mine environment. A local seismic array has been installed over a stable underground cavity within a salt layer located in the Lorraine basin (north-east France). The array includes four 3D components and three 1D component geophones deployed at depths between 30 m to 125 m in cemented boreholes drilled in the vicinity of the study area. The underground cavity under monitoring is located within a salt layer at 180 m depth and it presents a rather irregular shape that can be approximated by a cylindrical volume of 50 m height and 180 m diameter.

Presently, the cavity fully saturated with brine inducing a significant pressure on its walls (~2.5 MPa) to keep the overburden mechanically stable. Nevertheless some small microsesimic events were recorded by the array and analysed (~500 events in two years of recording). In October 2005, a controlled pressure transient experiment has been carried out in the cavity in order to analyse the mechanical response of the overburden by tracking the induced microseismicity. The recorded events are mainly grouped in clusters of 3 to 30 seconds of signal duration with non-emergent first arrivals and rather low frequency content (between 20 to 120 Hz). Some of these events have been spatially located by travel-time picking close to the actual cavity and its immediate roof. Preliminary spectral analysis suggests sources possibly related to resonant fluid-filled cracks, and/or cavitations due to the dynamic excitation of the brine-filled cavity. Rock-debris falling into the cavity from delamination of clayey marls in the immediate roof is possibly another source of seismic excitation. No clear evidence of classical brittle ruptures in the competent layers of the overburden has been observed up to now. Current work is focused on the discrimination of all these possible mechanisms to better understand the damage processes within the rock mass.

Key words: Cavern Operation, Instrumentation and Monitoring, Seismic

Introduction

A large research project within the GISOS¹ program has been launched in order to identify and evaluate the potential of geophysical (microseismic, hydroacoustic) and geotechnical (extensometer, inclinometer) techniques for monitoring underground growing cavities due to salt dissolution (solution mining). A part of this program focus on two complementary axes: (1) the validation of induced seismicity monitoring techniques in salt mine environments, and (2) the numerical modelling of deformation and failure mechanisms with their associated acoustic emissions, as well as the induced microseismicity (Mercerat *et al*, 2007). In this article, we present the analysis of the microseismic activity induced by a transient pressure experiment carried out in a stable cavity of the Lorraine basin (France).

¹ Research Group for the Impact and Safety of Underground Works involving French institutions INERIS, BRGM, INPL and Ecole des Mines de Paris.

Previous studies on induced seismicity of underground growing cavities (Mendecki et al. 1999) confirm the presence of microseismic events associated with the progressive damage of the overburden until its final collapse. Continuous monitoring of such microseismicity may provide crucial information for stability analysis of the area surrounding the cavity. It is in this optics that a local microseismic network has been installed over a site test at Cerville-Buissoncourt (Lorraine, France), where a stable brine cavity is nowadays found. When the salt exploitation restarts, the spatial and temporal evolution of the seismic event locations and magnitudes will be recorded, and further analyzed to identify, and eventually quantify, the damage progression in the overburden. The experimental results are expected to be correlated with the geomechanical modelling to confirm back-analysis results about rock strength parameters (Cai et al, 2006).

The microseismic monitoring is operational since January 2005. Although the salt dissolution operation is stopped and the whole overburden is relatively stable, microseismic activity has been recorded by the array and it can be associated to the initial state of the salt cavity until the future mining operations. Moreover, in October 2005, a transient pressure experiment has been carried out in the brine filled cavity, in order to check the instrumentation layout and to calibrate some other monitoring techniques deployed on the site. This paper presents the first results of the microseismic analysis, and discusses some possible causes for the induced seismicity recorded up to the present days.

The site test

Brine cavity and overburden characteristics

The brine cavity of Cerville-Buissoncourt (Lorraine, France) is actually located within a salt layer at about 180 m depth and presents an irregular shape that, in first approximation, can be considered a cylindrical cavity of 180 m of diameter and 50 m high. A plan of the instrumented site with a schematic geological section of the area is shown in Figure 1. Typically, the overburden is characterized by a series of intercalated anhydritic marls lying over the salt layer, and on top of them, the presence of a competent dolomite layer of 8.5 m thickness which presents elasto-brittle mechanical behaviour, and it is located approximately 60 m above the salt layer. This layer corresponds to what is known as the 'Beaumont dolomite', and it represents the level where most of the seismic damage is expected, when the salt exploitation restarts and the cavity will migrate towards the surface.

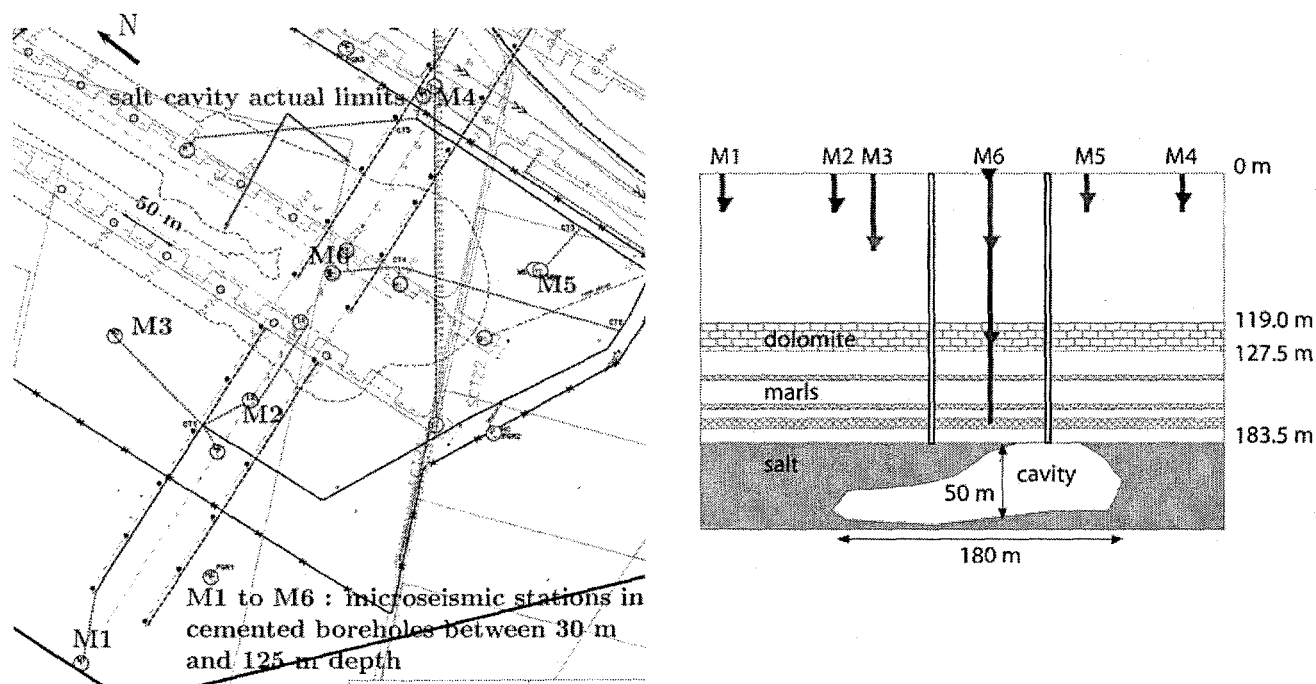


Figure 1 (Left) Plan of the instrumented salt cavity (Right) Scheme of the E-W vertical section with main lithological units and location of microseismic 3D stations (red triangles) and 1D stations (blue triangles)

Microseismic network

A microseismic network has been installed over the stable underground brine filled cavity of Cerville-Buissoncourt. The network includes four 3D components and three 1D component seismometers located at different depths (between 35 m and 125 m) in cemented boreholes distributed around the study area (see Figure 1). The frequency band of the geophones is between 40 Hz and 1 kHz. There is one station per borehole, except for the deepest one at the centre of the array right above the cavity (M6), where one 1D station at the surface and two 3D stations are located at 60 m and 125 m depth (Beaumont dolomite level). The lateral extension of the array is about 400 m by 600 m, and it presents reasonable azimuthal coverage (major gap of $\sim 130^\circ$ at the centre of the array).

Recorded microseismicity

More than 500 microseismic events were recorded between January 2005 and November 2006. As an *event*, we denote in this work, a recorded file by the acquisition system used in trigger mode with recording time window of 0.8 seconds. In fact, more than 75 % of the events are grouped in clusters of time duration between 3 to 30 seconds (recorded by almost continuous triggering of the acquisition system). This activity is clearly not related to classical shear slip mechanisms induced by hard rock fracturing. The frequency content of these long events is between 20 Hz and 100 Hz, and they present an emergent P wave onset, which is in general immersed in the coda of the previous event, hence it results in hardly possible P wave manual picking. In Figure 2, we can appreciate the time frequency analysis of 6 seconds of one of these recordings. It must be stressed that the amplitudes are well above the noise level in the study area, estimated from recordings with clear isolated events to be less than 10^{-7} m/s.

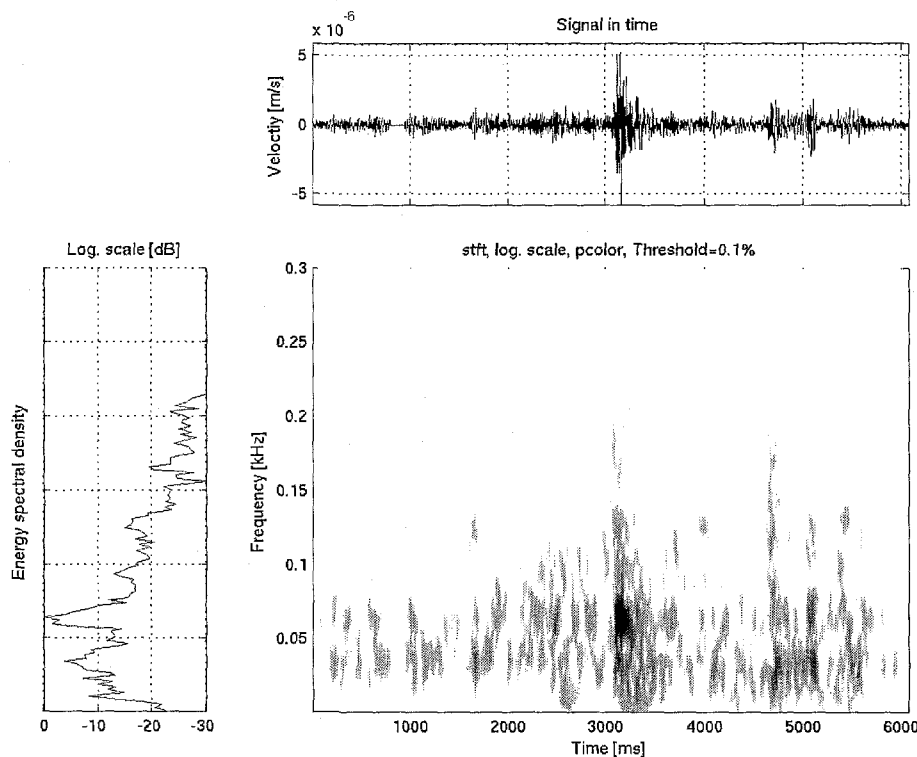


Figure 2 Example of long event recording (vertical component M62) of 6 seconds of time duration. Time frequency analysis by short time Fourier transform (Hanning time window of 0.1 seconds)

In addition, some small isolated events (less than 0.5 sec of time duration) were also recorded by the array. For these events, the frequency content is sensibly higher, with P wave onsets better resolved that allowed more precise manual picking of first arrivals. Polarization analysis of the waveforms indicates the presence of S waves in some recordings around 40 – 80 msec after the P wave arrival. Despite the higher uncertainties, they were also manually picked and used to better constraint the spatial localisation of these events.

Transient pressure experiment

Currently, the cavity is full of saturated brine inducing a significant pressure on its walls (~2.5 MPa) to keep the overburden mechanically stable. In October 2005, a transient pressure experiment has been carried out in the cavity, in order to analyse the mechanical response of the overburden and to check the sensitivity of the whole instrumentation. The experiment consisted of a pressure drop of around 0.4 MPa (30 m of brine column height), followed by a stable phase of one week, and a latest phase of pressure raise up to the original level of 2.5 MPa (see Figure 3). During the pressure raise, two of the clustered groups of events were recorded by all the stations (16 and 18 seconds of duration, respectively). While the pressure drop did not produce any significant seismic activity, except for a small cluster of 3 seconds of duration. This observation suggests that the increase in pressure within some fractured layers on top of the cavity could produce the observed induced seismicity.

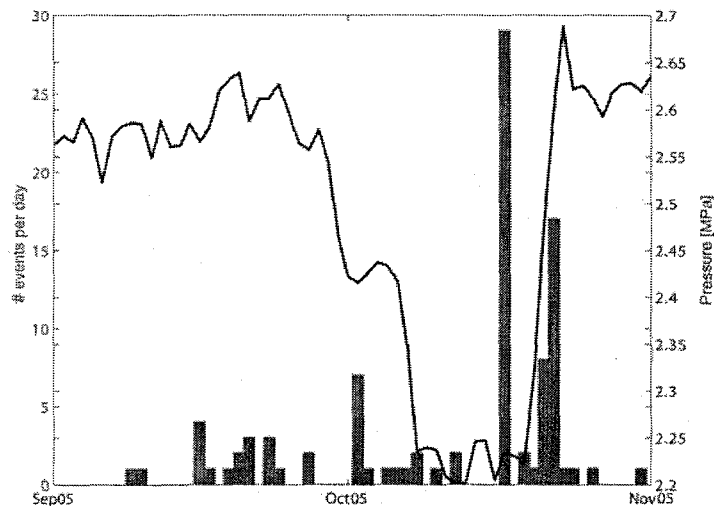


Figure 3 Number of *events* per day recorded while the transient pressure experiment in the cavity. The activity is concentrated in the pressure raise (two clusters of 16 and 18 seconds of duration).

Spatial Localisation

For the hand-picked events (isolated and/or immersed in continuous clusters), the hypocentral localisation was possible using the NonLinLoc software based on the Oct-Tree global search approach (Lomax, 2006). The 1D velocity model of the monitored area was defined on the basis of vertical seismic profiling data, acoustic laboratory measurements carried out on samples from the site, and a geological log of the study area. The model includes three layers, the first one with a uniform vertical gradient from the surface ($V_p=2400$ m/s) up to 120 m depth ($V_p=3000$ m/s), then the Beaumont dolomite of 10 m thickness ($V_p=5000$ m/s), and finally the marls-salt formation ($V_p=4000$ m/s) up to the bottom of the model. A fixed V_p/V_s ratio of 1.73 is assumed for all layers. We can assume that layer depths are relatively well constrained, but the largest uncertainties lie in the absolute values of the acoustic velocities of each formation, and possible lateral variations not taken into account in the model.

From the hypocentral location results, supposing a travel-time picking error less than 10 msec, we estimate an uncertainty of 20 m to 30 m in the horizontal hypocentral coordinates. In Figure 4, all microseismic events that could be satisfactorily located (maximum station residual < 0.05 s and maximum semi-axis length of the 68% confidence ellipsoid < 50 m) are shown. The vast majority of them have been spatially located close to the actual cavity and in its immediate roof. Up to the present days, there is no further evidence of ruptures near, or through, the Beaumont dolomite. The spatial correlation with the actual cavity limits in the horizontal plan is quite consistent.

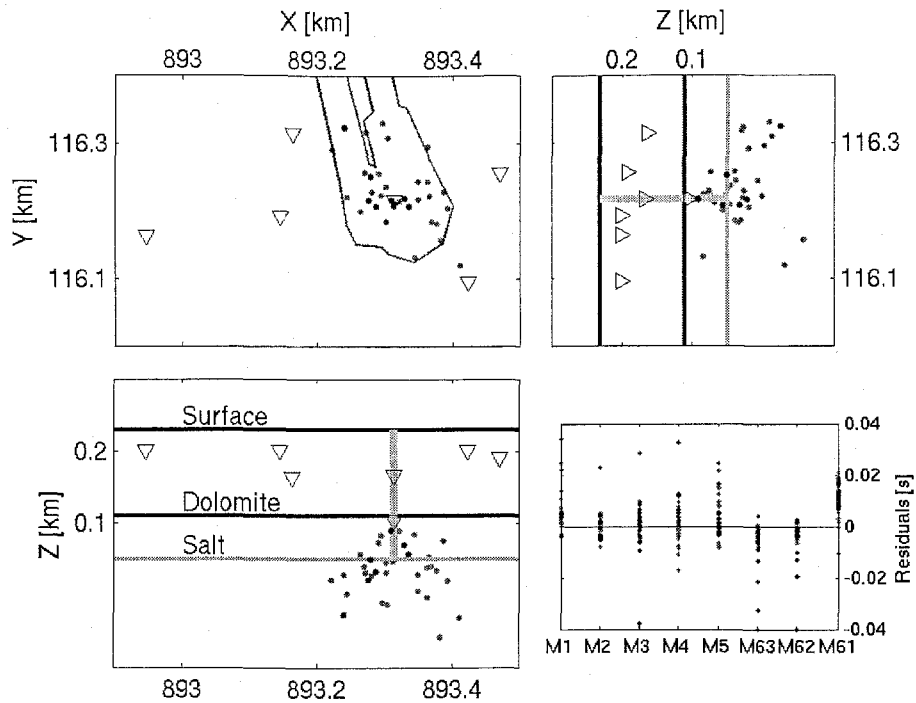


Figure 4. Spatial localisation of hand picked events (maximum likelihood locations). In pink, the events recorded during the transient pressure experiment (October 2005), in black some others from April, September and November 2005. Actual limits of the cavity in red. At the bottom right corner, the time residuals at each station are plotted.

Discussion

The brine filled cavity is in a rather stable period where the overburden does not deform considerably. The microseismic activity recorded, in particular during the transient pressure experiment, can be related to delamination of the clayey marls on top of the salt layer, followed by bloc drops within the cavity. As a possible example, we show in Figure 5 a group of four isolated events recorded on October 2, 2005, just at the beginning of the transient pressure experiment. In Figure 6, we plotted the spatial location of two of them (picked events) with its location uncertainties. The events may be associated to cavity roof detachments. From the time frequency analysis, although the inelastic attenuation has not been taken into account, we can observe a relatively high frequency content at the beginning of each event, followed by lower frequency content in the coda.

Note that the current cavity has a rather irregular shape and its base is partially filled by non-soluble rock debris that was found in the salt layer during the mining operation (salt dissolution). The signal expected from falling blocs of degraded material in a highly irregular surface is far from being simple, but some clues can be found in the recent work of Wust-Bloch and Joswig (2007), where field experiments of falling blocs in both brine filled and empty superficial salt caverns (less than 30 m depth) were carried out. They have used a time-frequency analysis to discriminate between them. Although their conditions are rather different from ours (in particular cavity depth and pressure), the frequency range and general signal characteristics are quite alike. Very similar seismic activity has been also recorded on a local seismic network in Northridge (England) to monitor an abandoned underground salt mine (Styles, 2005). The hypothesis concerning the origin of this activity (progressive delamination of clayey marls and bloc drops) is quite similar to the one described in this paper. In addition, Fortier *et al* (2006) studied the microseismicity of brine filled cavities used for hydrocarbon storage in the Geosel-Manosque exploitation, where they found evidences of small brittle ruptures followed by falling blocs within the underground cavities that generate clear monochromatic resonant waves.

In our case, it must be stressed that the cut-off frequency of the array sensors (40 Hz), tuned to register microseismic activity generated once the solution mining restarts, is just too high to neatly record resonant frequencies corresponding to cavitations. The current cavity dimensions are between 20 m to 50 m height and 180 m width. Therefore, assuming a P wave velocity in the brine of 1600 m/s, gives fundamental frequencies between 4.4 Hz and 40 Hz, exactly the frequency range that is highly damped by the geophones. Even if some evidences of roof detaching, followed by falling in the brine cavity, can be argued from the recorded signals, some extra work should be done in order to clarify the rupture mechanisms.

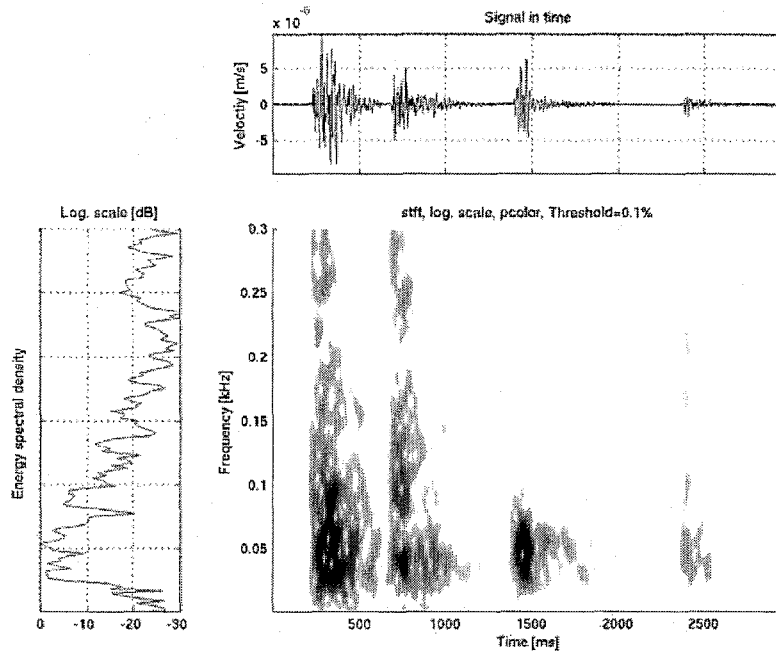


Figure 5 Example of isolated events (vertical component M63) less than 0.5 seconds of time duration. Time frequency analysis by short time Fourier Transform (Hanning time window of 0.1 seconds)

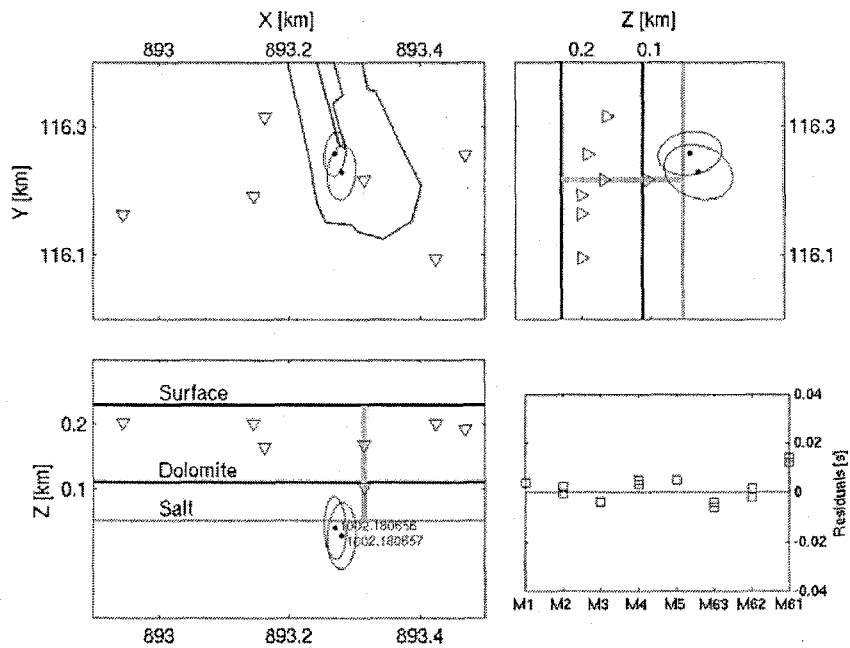


Figure 6 Spatial localisation (maximum likelihood hypocenters) with 68% confidence error ellipsoids of two picked events of Figure 5.

Conclusions

A local seismic network has been installed and further calibrated in the site test of Cerville-Buissoncourt (Lorraine, France). This site has been chosen by the GISOS working group to test and validate some monitoring techniques that could be used in the future in other salt mine environments, and not to pronounce about the consequences, in terms of environmental impact or security, of some specific salt exploitation methodology implemented in the test site.

Up to the now, the cavity is full of saturated brine what causes a significant pressure on its walls. The seismic activity recorded by the local network, after the transient pressure experiment, is probably related to cavity roof detachments and delamination of clayey marls on top of the salt layer. There is no clear evidence of classical fragile ruptures in the overburden, in particular in the competent layer of Beaumont dolomite. Therefore the whole system remains mechanically stable. Further research work will be carried out to analyse the microseismic activity induced by the cavity growing until the final overburden collapse. The resumption of the salt dissolution will offer a unique opportunity to record precursor phenomena, which is actually the most interesting part of the running program.

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