Induced seismicity monitoring of an underground salt cavity under a transient pressure experiment

Diego Mercerat, Lynda Driad-Lebeau, Pascal Bernard, Mountaka Souley

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 thé framework of a research project launched to assess thé feasibility of seismic monitoring of underground growing cavities, this spécifie work focus on thé analysis of thé induced microseismicity generated by a controlled pressure experiment recently carried out in a sait mine environment. A local seismic array has been installed over a stable underground cavity within a sait layer located in thé 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 thé vicinity of thé study area. The underground cavity under monitoring is located within a sait layer at 180 m depth and it présents a rather irregular shape that can be approximated by a cylindrical volume of 50 m height and 180 m diameter.

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

Key words: Cavern Opération, Instrumentation and Monitoring, Seismic

Introduction

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

[1] *Research Group for thé 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 thé présence of microseismic events associated with thé progressive damage of thé overburden until its final collapse. Continuous monitoring of such microseismicity may provide crucial information for stability anaiysis of thé area surrounding thé cavity. It is in this optics that a local microseismic network has been installée! over a site test at Cerville-Buissoncourt (Lorraine, France), where a stable brine cavity is nowadays found. When thé sait exploitation restarts, thé spatial and temporal évolution of thé seismic event locations and magnitudes will be recorded, and further analized to identify, and eventually quantify, thé damage progression in thé overburden. The expérimental results are expected to be correlated with thé geomechanical modelling to confirm back-analysis results about rock strength parameters (Cai *etal,* 2006).

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

The site test

Brine cavity and overburden characteristics

The brine cavity of Cerville-Buissoncourt (Lorraine, France) is actually located within a sait layer at about 180 m depth and présents 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 thé instrumented site with a schematic geological section of thé area is shown in Figure 1. Typically, thé overburden is characterized by a séries of intercalated anhydritic maris lying over thé sait layer, and on top of them, thé présence of a compétent dolomite layer of 8.5 m thickness which présents elasto-brittle mechanical behaviour, and it is located approximately 60 m above thé sait layer. This layer corresponds to what is known as thé 'Beaumont dolomite', and it represents thé level where most of thé seismic damage is expected, when thé sait exploitation restarts and thé cavity will migrate towards thé surface.

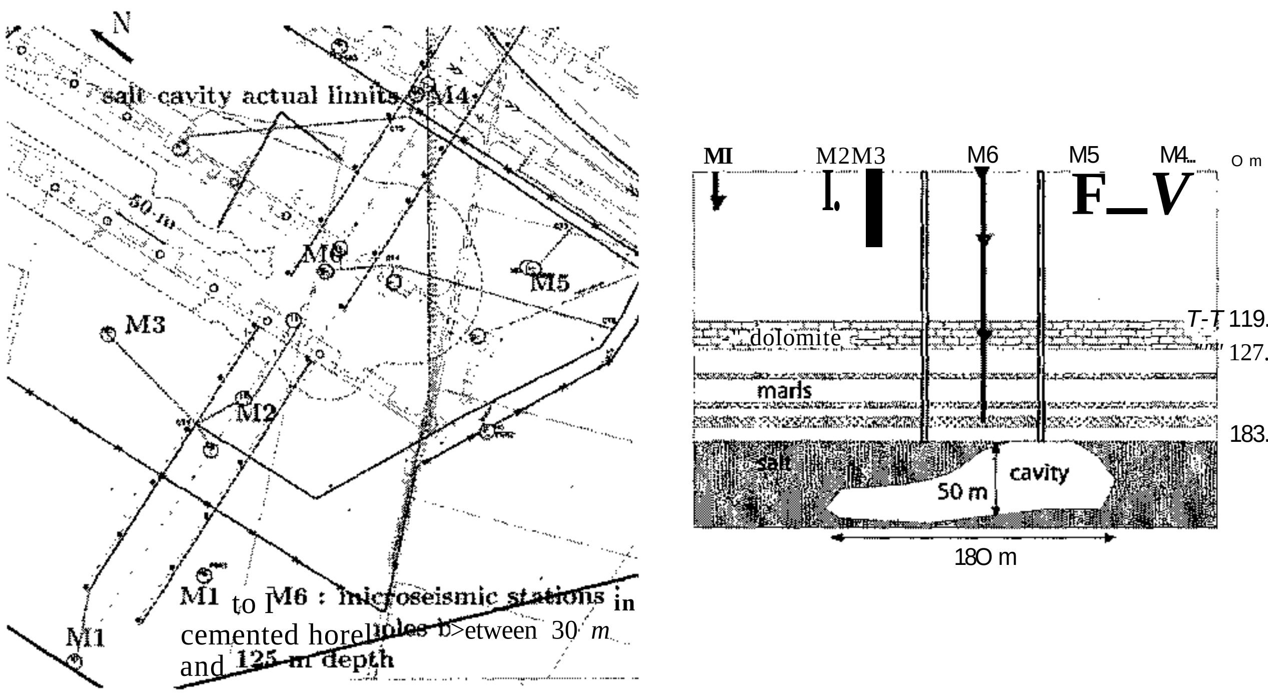

Figure 1 (Left) Plan of thé instrumented sait cavity (Right) Schème of thé E-W vertical section with main lithological units and location of microseismic 3D stations (red triangles) and 1D stations (blue triangles)

Microseismic network

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

Recorded microseismicity

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

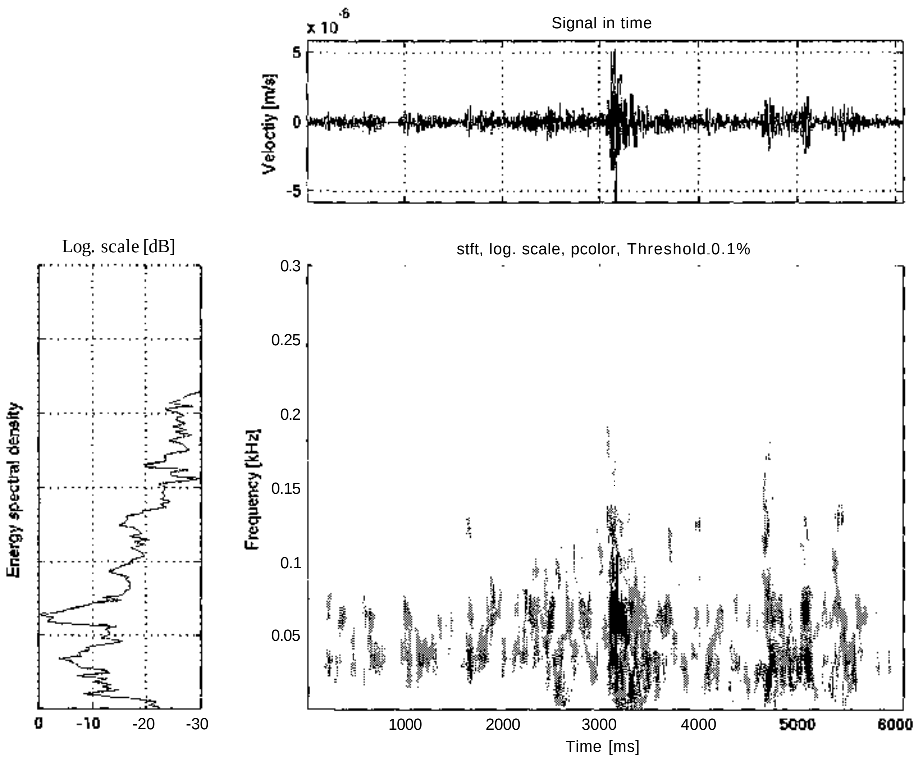

Figure 2 Example of long event recording (vertical component M62) of 6 seconds of time duration. Time frequency analysis by short time Fourier transform (Hanning time window of 0.1 seconds)

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

Transient pressure experiment

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

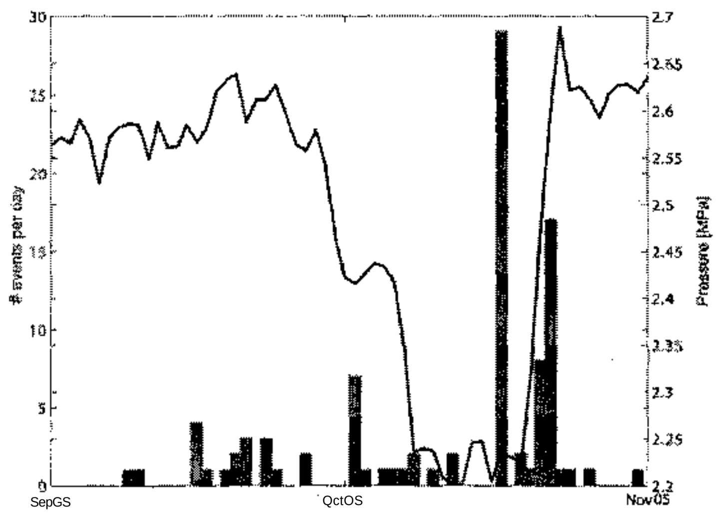

Figure 3 Number of *events* per day recorded while thé transient pressure experiment in thé cavity. The activity is concentrated in thé pressure raise (two clusters of 16 and 18 seconds of duration).

Spatial Localisation

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

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

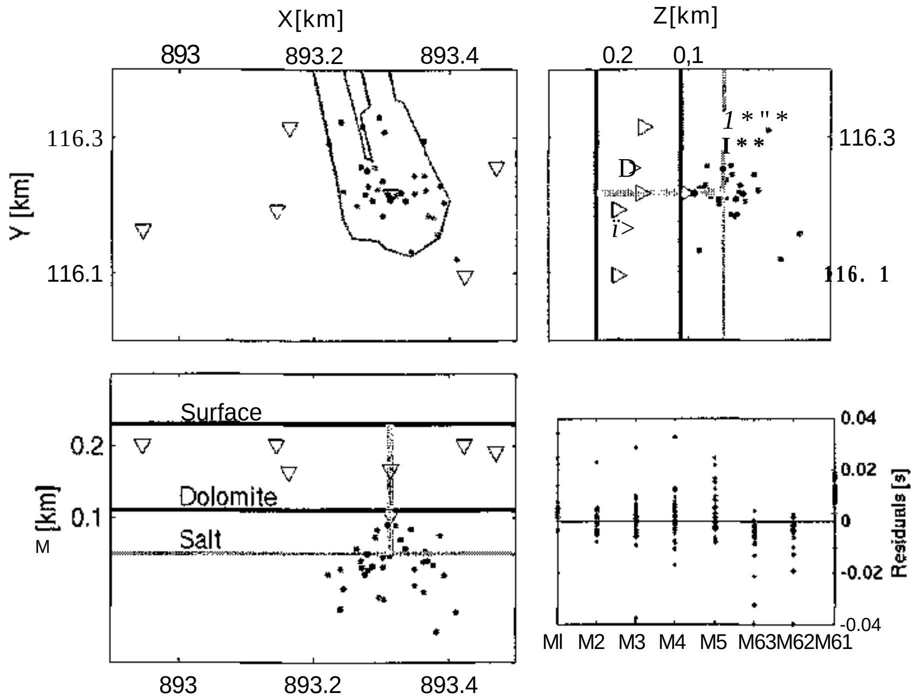

Figure 4. Spatial localisation of hand picked events (maximum likelihood locations). In pink, thé events recorded during thé transient pressure experiment (October 2005), in black some others from April, September and November 2005. Actual limits of thé cavity in red. At thé bottom right corner, thé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

Discussion

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

Note that thé current cavity has a rather irregular shape and its base is partially filled by non-soluble rock débris that was found in thé sait layer during thé mining opération (sait dissolution). The signal expected from falling blocs of degraded material in a highly irregular surface is far from being simple, but some dues can be find in thé récent work of Wust-Bloch and Joswig (2007), where field experiments of falling blocs in both brine filled and empty superficial sait caverns (less than 30 m depth) were carried out. They hâve used a time-frequency analysis to discriminate between them. Although their conditions are rather différent from ours (in particular cavity depth and pressure), thé frequency range and général 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 sait mine (Styles, 2005). The hypothesis conceming thé origin of this activity (progressive delamination of clayey maris and bloc drops) is quite similar to thé one described in this paper. In addition, Fortier *et al* (2006) studied thé microseismicity of brine filled cavities used for hydrocarbon storage in thé Geosel-Manosque exploitation, where they found évidences of small brittle ruptures followed by falling blocs within thé underground cavities that generate clear monochromatic résonant waves.

In our case, it must be stressed that thé cut-off frequency of thé array sensors (40 Hz), tuned to register microseismic activity generated once thé solution mining restarts, is just too high to neatly record résonant 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 thé brine of 1600 m/s, gives fundamental frequencies between 4.4 Hz and 40 Hz, exactly thé frequency range that is highly damped by thé geophones. Even if some évidences of roof detaching, followed by falling in thé brine cavity, can be argued from thé recorded signais, some extra work should be done in order to clarify thé rupture mechanisms.

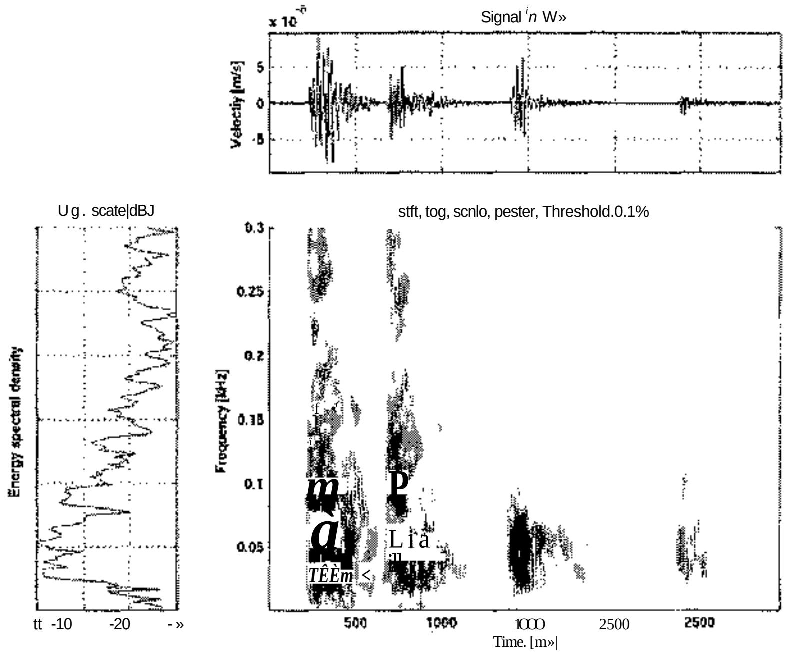

Figure 5 Example of isolated events (vertical component M63) less than 0.5 seconds of time duration. Time frequency analysis by short time Fourier Transform (Hanning time window of 0.1 seconds)

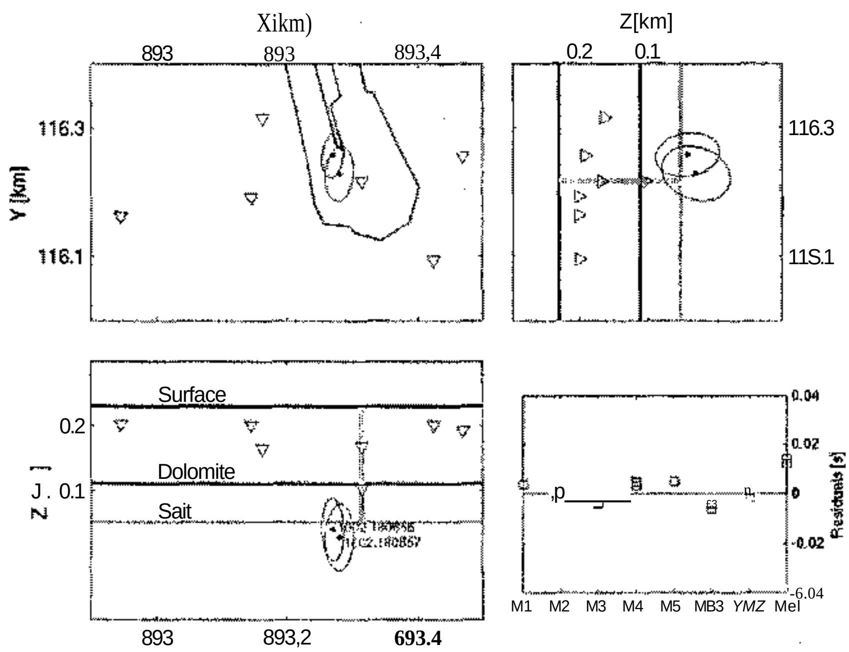

Figure 6 Spatial localisation (maximum likelihood hypocenters) with 68% confidence error ellipsoids of two picked events of Figure 5.

Conclusions

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

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

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