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GEOPHYSICAL DETECTION OF UNDERGROUND CAVITIES

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ABSTRACT: In this paper, we present a synthesis of the geophysical investigations conducted on experimental sites selected in the Lorraine salt basin and Haute-Normandie marlpits. These investigations were carried out in the frame of a partnership (scientific and industrial) research program on cavities detection and characterization using techniques of high resolution seismic, microgravity and electric resistivity. The objective of the research is three folds: (1) to develop and optimize P and S seismic vibratory sources with an enhanced procedure of generation and optimization of sweeps (2) for each technique, to define the privileged application field and limitations regarding the general context of the considered site (3) to progress in the joint interpretations of the geophysical data. Despite the good quality of the data, the results evidence the complexity in the interpretation of the geophysical response in cavities environment due mainly to the compromise between the resolution and the ratio depth/dimension of the cavities, and the nature of the filling (brine, water, air). In the case of the marlpit mines, the corresponding geophysical anomalies could be correlated to the exact position of the marlpit known according to the archive records. Drilling campaign has confirmed a local collapse of the marlpit identified on the only High Resolution Seismic data.

KEYWORDS: Cavities, detection, HRS, microgravity, resistivity, resolution.

RÉSUMÉ: Ce papier présente une synthèse des investigations géophysiques menées sur des sites expérimentaux du bassin salifère lorrain et les marnières de Haute-Normandie. Ces travaux ont été réalisés dans le cadre d'un programme de recherche partenarial axé sur la détection et la caractérisation des cavités à partir des techniques de Sismique Haute résolution (SHR), de la microgravimétrie et de la résistivité électrique. L'objectif du programme est triple : (1) développer et optimiser des sources vibratoires en ondes P et S avec une Procédure de Génération et d'Optimisation de Sweep adapté ; (2) définir pour chaque technique le champ d'application privilégié et les limitations en fonction du contexte général des sites considérés ; (3) progresser dans les interprétations conjointes des données géophysiques. Malgré la bonne qualité des mesures, des difficultés ont été rencontrées lors des interprétations de la réponse géophysique de l'environnement des cavités avec, pour raison essentielle le compromis entre la résolution de l'imagerie et le rapport profondeur/dimension de la cavité ainsi que la nature du remplissage (saumure, air, eau). Dans le cas des marnières, les anomalies géophysiques ont été carrelées à la position exacte de marnière pilote bien documentée dans les archives. Une campagne de forage a *permis de confirmer un éboulement local de la marnière observée sur les données de sismique haute résolution.*

MOTS-CLEFS : Cavités, détection, SHR, microgravimétrie, résistivité, résolution

1. Introduction

The detection and characterisation of underground cavities represent an essential technical and scientific stake in the process and setting up risks prevention plans related to ground movements. Scientific research on geophysical techniques aiming to detect, locate and characterize the underground cavities at depths ranging between ten meters and a few hundred meters is still a matter of debate and remains more than ever of topicality. Indeed, for this range of depth, the majority of these techniques presents a lack of resolution and requires being adapted to investigate site and wanted target, namely delineation and the characterisation of the abandoned underground works and the overburden. Nevertheless, some of these techniques appear promising on a condition that progress is made to optimise and enhance the performance of the acquisition and interpretation tools such as they are implemented today. The use of the geophysical techniques, such as the High Resolution Seismic, the microgravity and the electric resistivity, for the detection of the underground cavities is not a new approach. During the last 20 years, published applications recall the potential of these techniques to detect and locate shallow cavities (depth < 100 m) in various geological and mining contexts (Piwakowski, 1991 ; Lagabrielle and al. , 1994 ; Lagabrielle and Al, 1995 ; Piwakowski, 1998 ; Watelet, 1996 ; Bishop and Al, 1997 ; Driad and Piwakowski., 2002 ; Grandjean and Al, 2002 ; Baker et al., 2004 ; Styles, 2004). In the majority of the cases, these publications are matched examples of detected of known cavities, on which the effectiveness of the geophysical technique is tested. However, the problem remains complex taking into account, on the one hand, of heterogeneities and the geological stratifications of the crossed grounds and on the other hand, of the cavities target often under-dimensioned compared to the investigation depth. A shallow and voluminous spherical cavity (depth of the roof of the order of the radius) is a priori detectable with all geophysical techniques. However, under the real site conditions and beyond 20 m of depth, the effectiveness of these the measurements decreases notably because of heterogeneities of the loading medium whose geological noise limits the theoretical depth of investigation. The feedback of these various studies and research made it possible certainly to ensure, a scientific and technical progress in the field of the geophysical detection of the cavities, but also to emphasize the gaps as well as limitations which are always of topicality.

The technique based on the high-resolution seismic reflection imaging has shown an interesting potential in detecting underground works in particular cavities. It is indeed the only geophysical method that makes it possible to provide a continuous image of the succession of the grounds and their structural fitting. The success of this technique rests on the performances of the acquisition, the processing and the analysis means available today. The HRS was particularly applied to the sounding of mining underground works (galleries, rooms and pillars...) and to the civil engineering structures (tunnels, foundations, drains.... Husband et al., 1998, Knapp et al., 1986a, Miller and Steeples, 1995). Research and development works were carried out to improve the resolution of the HRS imaging and to increase the capacity to detect cavities which size is restricted compared to the depth of investigation. It was in particular shown that the “type” and the parameters of the seismic source constitute the principal factor of progress in this domain (Piwakowski, 2004b, Swoboda et al., 2000, Portolano and Odin, 2004).

The scientific questioning related to the problems of detection of the underground cavities are thus located around two aspects: (1) is it possible to improve the seismic resolution to enable it a positive detection of sub-surface structures, in particular of the underground cavities? (2) What is the contribution of each geophysical technique (HRS, microgravity, Eletric resistivity) and what is the relevance of a joint analysis? In this research program, we have attempted to answer the mentioned questions through new HRS developments and experimental measurements in abandoned mines where the cavities are known. After a short note on the HRS developments, the paper focus on the geophysical imaging and the interpretations obtained from the HRS reflection, microgravity and electric resistivity measurements for cavities detection in salt and marlpit mines.

2. Development of HRS acquisition tools

2.1. Vibratory sources

It is commonly known that, to obtain a good resolution of the seismic image it requires the exploitation of waves the shortest possible, i.e. of the high frequencies. Taking into account the fact that the absorption of the medium increases with the frequency, the exploitable frequency is limited. According to universal principles, the optimisation of the frequency requires the use of powerful seismic sources and/or broadbands, able to generate very short impulses. The experience shows that each investigated site requires an individual choice of the type of source and its power. The requirements concerning the choice of the source are sometimes contradictory: (1) a broad band source must emit an impulse as short as possible; (2) a short impulse induces a weak energy which generally implies a weak signal to noise ratio; (3) in theory, the power of the source is limited by the local conditions (site) and by external factors (cost, noise, vibratory harmful effect, safety, possible damage of the site...) and cannot be increased without limits; (4) during the data processing, the stacking operation makes it possible to approach an equivalent power, but because of non repetitivity of the source, the summation is reduced to a low-pass filtering, which limits the exploitable frequency (high frequency). Vibratory source type used successfully in seismic investigations for oil exploration can bring a solution to the mentioned problems. Indeed, the development of mini-vibrators adapted to the specificity of the HRS proved to be necessary taking into account their limited number in Europe. Thus, within the framework of this program[1], three vibratory sources were developed within the laboratory “Electronic Acoustic” of the Central School of Lille (Fig. 1), scientific partner for the HRS investigations.

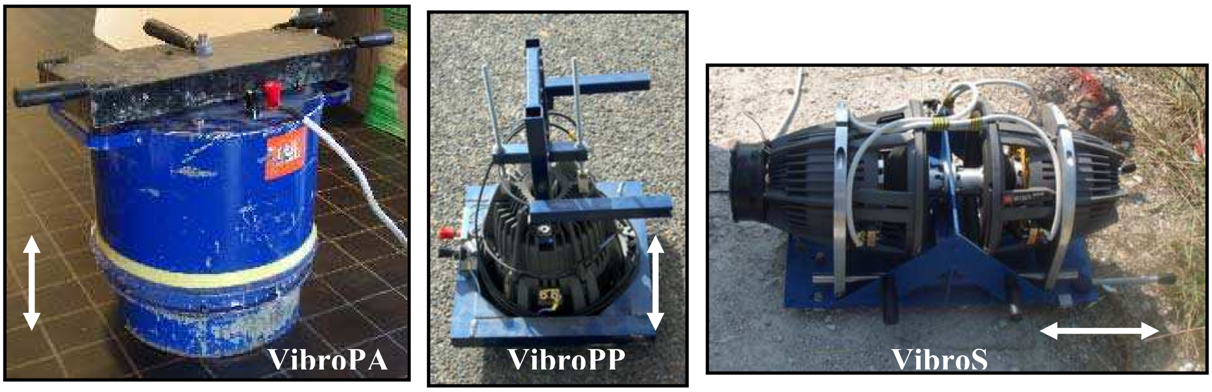

Figure 1. P and S wave vibratory sources allowing acoustic (VibroPA) and mechanical (VibroPP) coupling

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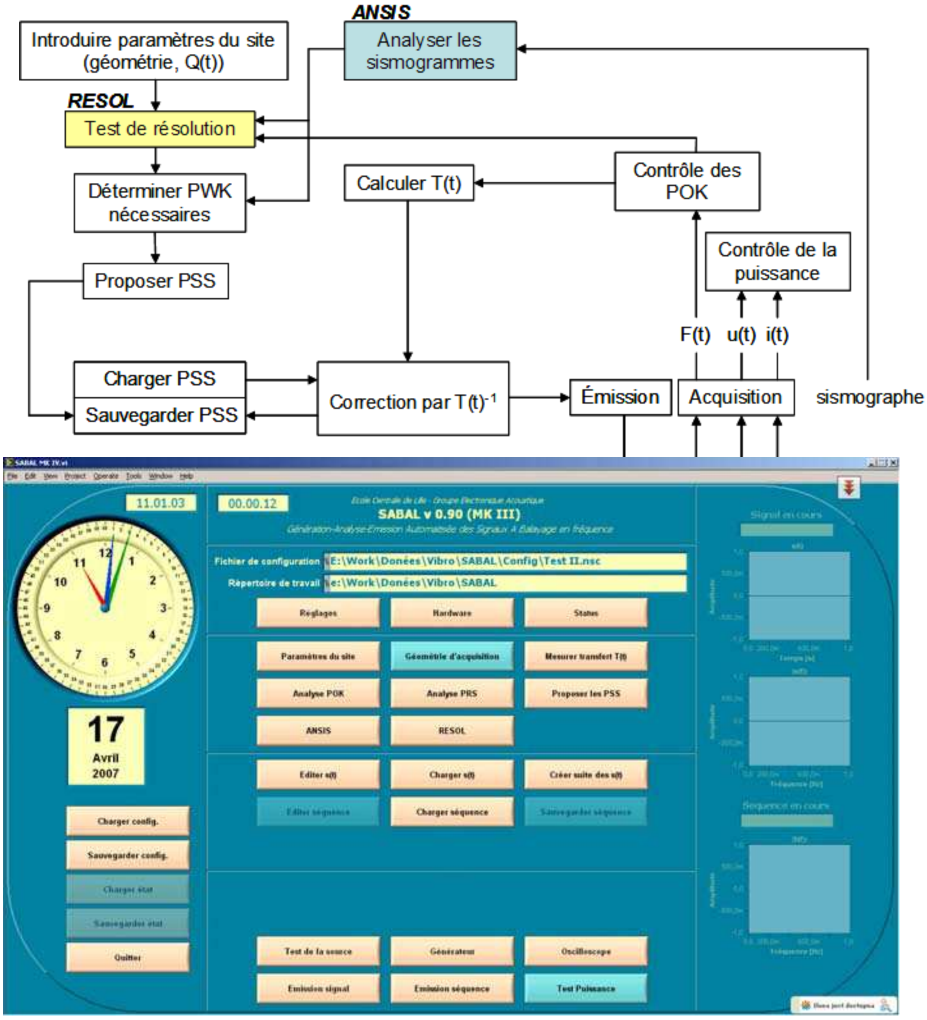
[1] *The research work was carried out within the Ph.D. thesis of Arkadiusz Kosecki with the close collaboration of the Central School of Lille (North France)*

2.2. Procedure of Generation and Optimisation of Sweeps (PGOS)

The selection of the input signal is governed by the dependencies existing between the emitted vibratory signal and the parameters of the seismic records. Indeed, the input signal is fixed according to the quality of the seismic image obtained during the test phase and evaluated according to well-defined criteria's. The adopted solution was to develop (1) a Procedure of Generation and Optimisation of Sweep (PGOS), an algorithm allowing an optimal selection of the input signal (or a series of signals) in comparison with the objectives of the measurements; (2) a program package baptized "SABAL" shown in the figure 2, a complete solution integrating the PGOS, the piloting system of the vibrator and a parametric analysis, in particular the design of the measurements. The theoretical basis and the procedures relating to the design and the development of the PGOS are inspired by work of Brouwer et al., 1997 et Brouwer & Helbig, 1998.



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Répertoire de travail e:\Work\Donées\Vibro\SABAL

Figure 2. Principle (top) and the front face of the program SABAL including the PGOS and the parametric analysis

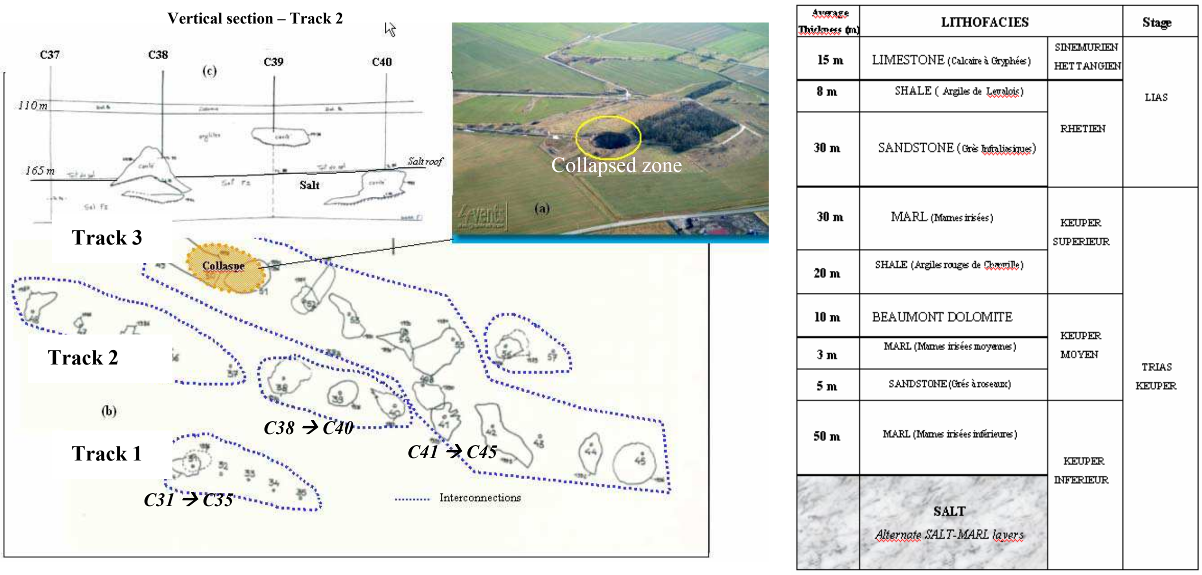
It should be noted that this software of the figure 2 is operational and applicable to the sources developed within the framework of this research program, but also on any P and S vibrator.

3. Geophysical investigation

3.1. Experimental sites

The selected sites belong to two different geological and mining contexts. (1) *Salt mine* exploited by dissolution between 1971 and 1993 in the Lorraine basin (North-east France).

The wells[2] split into three tracks were drilled into the base of the first salt seam and connected together by hydro-fracturing. The salt cavities that resulted from the workings are located at depths of 110 to 180 m. In addition, the variety of their geometrical forms, the various geological setting and the nature of the infilling (brine, air) have given a particular interest to the selected site. Indeed, the cavities progress naturally through the marls until they reach a stiff and resistant layer called "Beaumont Dolomite"; as soon as this banc breaks, than the global collapse of the cavity occurs. Note that in December 2004, less than one year before the geophysical measurements, a major collapse (expected) has affected the site along the track3 at the cavities 50 and 51 (Figure 3).



Average Thickness (m)	LITHOFACIES		Stage
15 m	LIMESTONE (Calcaire à Gryphées)	SINEMURIEN HETTANGIEN	LIAS
8 m	SHALE (Argiles de Levalois)	RHETIEN	
30 m	SANDSTONE (Grès Infraliasiques)		
30 m	MARL (Marnes irisées)	KEUPER SUPERIEUR	TRIAS KEUPER
20 m	SHALE (Argiles rouges de Chaeville)		
10 m	BEAUMONT DOLOMITE	KEUPER MOYEN	
3 m	MARL (Marnes irisées moyennes)		
5 m	SANDSTONE (Grés à roseaux)		
50 m	MARL (Marnes irisées inférieures)	KEUPER INFERIEUR	
	SALT *Alternate SALT-MARL layers*		

Figure 3. Experimental site selected in an old salt mine (North-East France). Sonar imaging of the salt cavities, situation of the collapsed zone on the track 3(left) and the geological setting (right)

(2) *The Marl-pit mines* exploited during the last two centuries in the Haute-Normandie regions (North-West France) to extract "soft chalk" used to compensate for the natural acidity if the silt ground. The risk of collapse related to the voids left by the marl-pits affect, in a considerable way the entire region, which appears among the French areas most, affected. The major resulted cavities are situated at depth of 20 to 45 m covered by altered chalk, shale and silt (alluvium) near the surface. For the geophysical investigations, an experimental site (Eturqueraye, department of Eure) overlays a known marpit for which the exact position (on the surface and in depth) has been not revealed before the data analysis was completed.

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[2] Water injection and salt extraction wells

3.2. Detection of salt cavities

HRS analysis: The acquisition design and parameters were defined with respect to the general context of the investigated site and the targets (see Kosecki et al, 2008b for more details). The first step consisted in *testing the new acquisition system* composed by the vibratory sources and the related software. Reference vibratory sources in P and S waves have used for comparison on the test profile crossing the cavities 37, 38 and 39 along the track3 (Fig. 3).

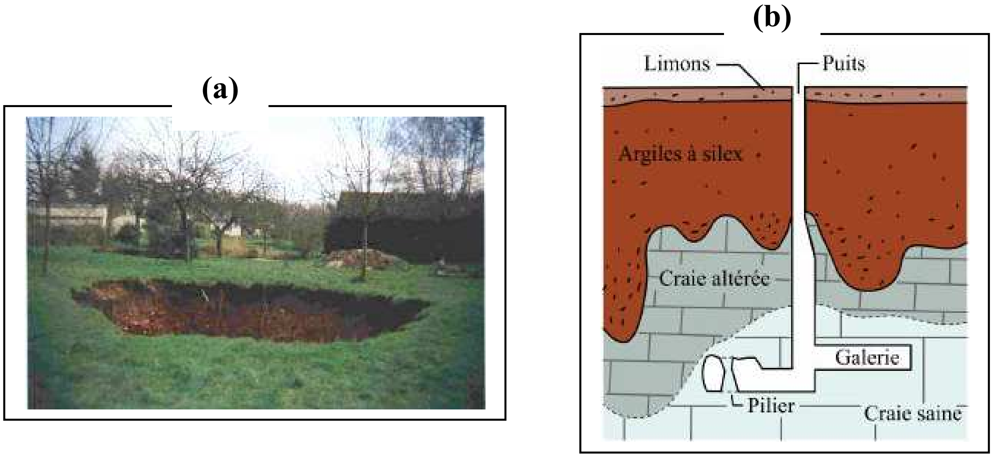

Figure 4. Marlpit mines in the Haute-Normandie (North-West France). (a) Example of collapsed marlpit in private garden, (b) vertical section of typical marlpit

The results of the comparative analysis of the seismic profiles obtained from 6 sources (impulsive and vibratory sources) revealed the performance of each source and made it possible to identify the factors limiting the resolution of the seismic image. The combination of the two operations (tests source, comparison section SHR) showed how the characteristics of a source influence the quality of a seismic image (Kosecki et al, 2008a). Furthermore, three HRS reflection profiles have been carried out along each track. The longest profile overlaying the major cavities was done using the VibroPA source along the track 3 up to the position of the cavity 42. The resulted time section shows masking effects of the deep reflectors and signal perturbation of the salt roof interface (Fig. 5). The described seismic behaviour is observed mainly at the positions of the known salt cavities suggesting a positive detection. In the case of the cavity 37 whose sonar image is not available, it would be of low dimension, located in salt and embanked mud saturated with brine, it might be "acoustically" hidden, the detection is, thus, not possible. Note that majority of cavities are filled of brine, the masking effect is not highlighted accurately as it would be seen if the cavities were empty; the experience in data processing made it possible to come out with interpretable sections (Kosecki et al, 2008b).

Microgravity analysis: the measurements were carried out with Scintrex CG-5 allowing a resolution of 1 µGal and a standard deviation lower than 5 µGal (Styles, 2005). The design of measurements was optimised to detect cavities at depth greater than 100 m profiles on tracks 1, 2 and 3. In addition, a 3D-grid was applied above the cavity 41 (track1) believed to be instable and thus likely to induce variability in the gravity anomalies. The residual gravimetric anomalies, representative of local heterogeneities, were obtained after classical processing consisting in the different corrections (tide, drift, regional geology…). The residual map of the figure 6 highlights (1) a dominant negative residual anomaly in the collapsed zone (tracks 3) expressing the gravitational field induced by the crater (deficit of mass) following the collapse; (2) a negative anomaly at the Eastern border of the investigated zone that would act of a geological fault not indexed but identified on the electric resistivity map (see further); (3) a correlation (large wavelength) between a slight negative corridor of the residual anomalies and presence of cavities 36 to 45 along the main track. It should be noted that the correlation between presence of cavities and negative anomalies is in fact not striking. In addition, it is not easy to “individualise” the gravimetric anomalies in association with the isolated cavities; (4) just as on track 3, cavity 31 belonging to the track 1 is translated by a hardly negative anomaly with a light side shift.

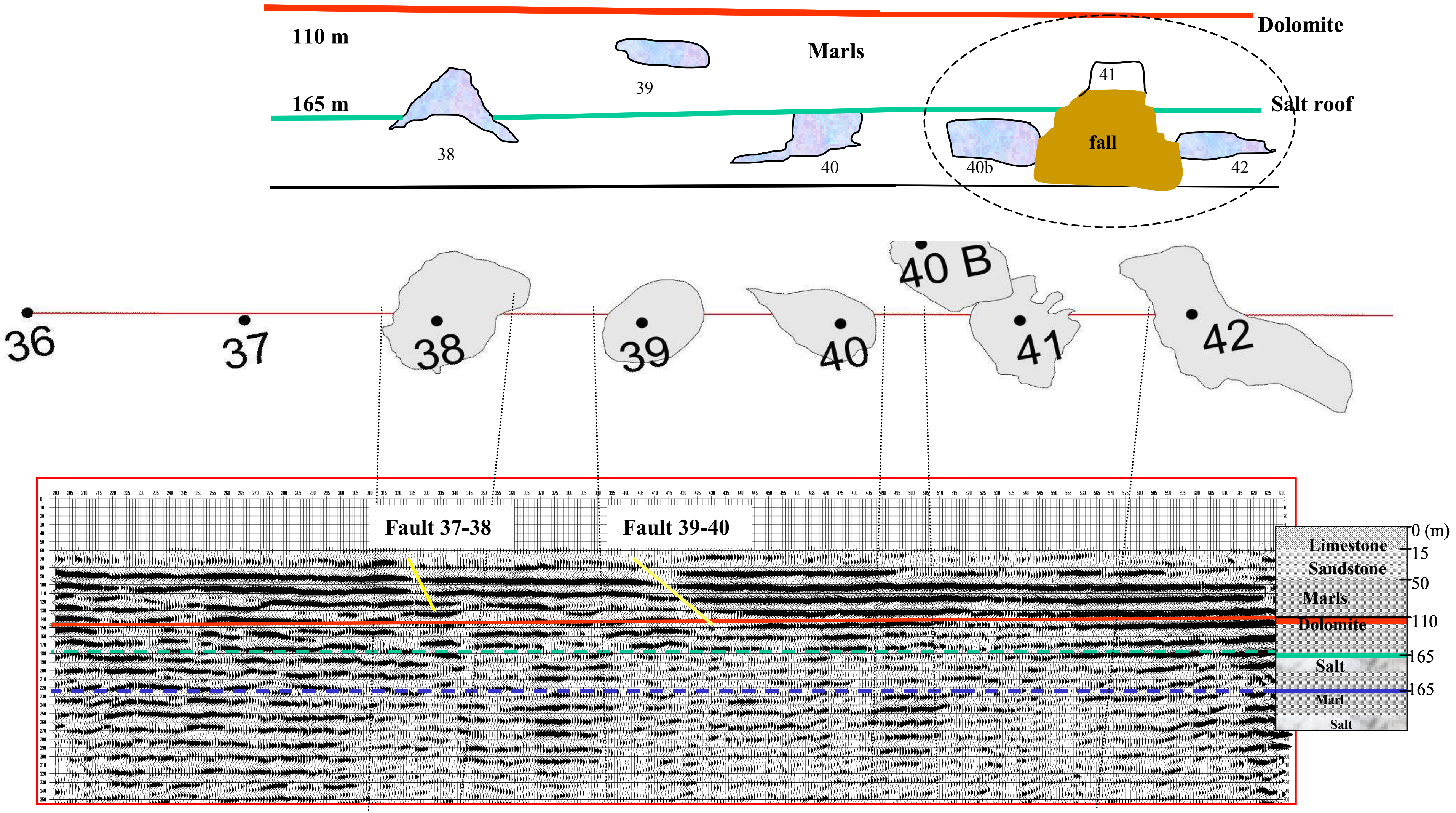

Figure 5. Interpreted High Resolution Seismic reflection time section obtained for the long profile of the track 3.

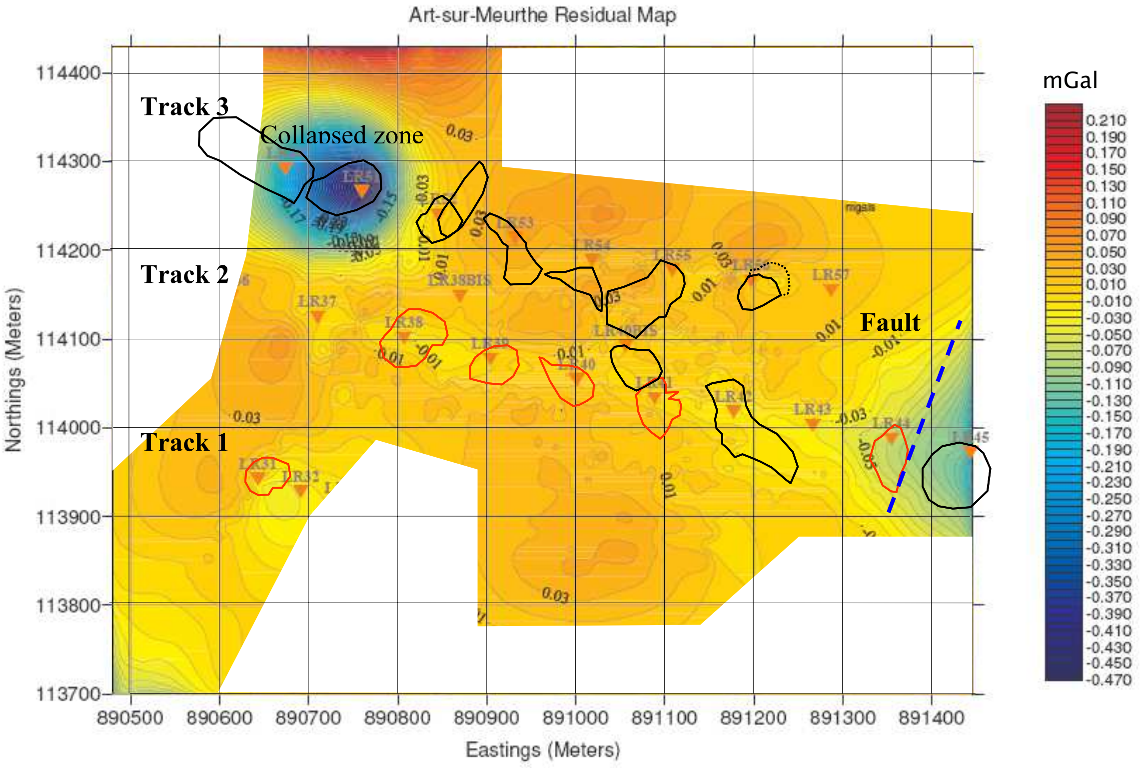

Figure 6. Residual map obtained from microgravity measurements. The collapsed zone corresponds to the dominant negative anomaly on the track 3.

Electric resistivity analysis: the method known as "rectangle" was used to attempt the detection the salt cavities. It consists in injecting the current on a pair of fixed electrodes, relatively distant one from the other (bipole injection), and maping the distribution of the electric field which results from it inside a rectangle centered between these two electrodes. After transforming the measurements into apparent resistivities, an empirical topographic correction was applied to suppress the strong correlation observed between the measured apparent resistivity and the altitude given by a differential GPS. A map of apparent resistivity corrected for the topographic effect was thus obtained ((Fig.7). Globally, we we identify two types of anomalies: (1) geological structures such as a “graben” and faults oriented according to the direction of regional fracturing. It is interesting to note that the major fault identified on the western side of the graben is prolonged to the collapsed zone. According to the owner of the mine, it is probable that this fault contributed to the evolution of cavities 50-51 towards surface until its collapse. In addition, the secondary fault detected in the East of the track 2, near cavity 45, is known from the owner, it probably had an impact on the evolution of this cavity which up to now under observation; (2) anthropic structures including a large conducting zone which includes two parallel tracks of cavities and a resistive zone associated to the collapsed zone.

Joint geophysical analysis: the isolated cavity on the track 1 has been selected for the joint measurements. The cavity of 35 m X 10 m is located at the base of dolomite to 110 m of depth and would be filled with water unsaturated with salt. If one considers individually the geophysical images, none the techniques could detect the cavity in a convincing way. In addition to the nature of the infilling, we believe that the ratio between the dimension and the depth of the cavity is not optimal for geophysical detection.

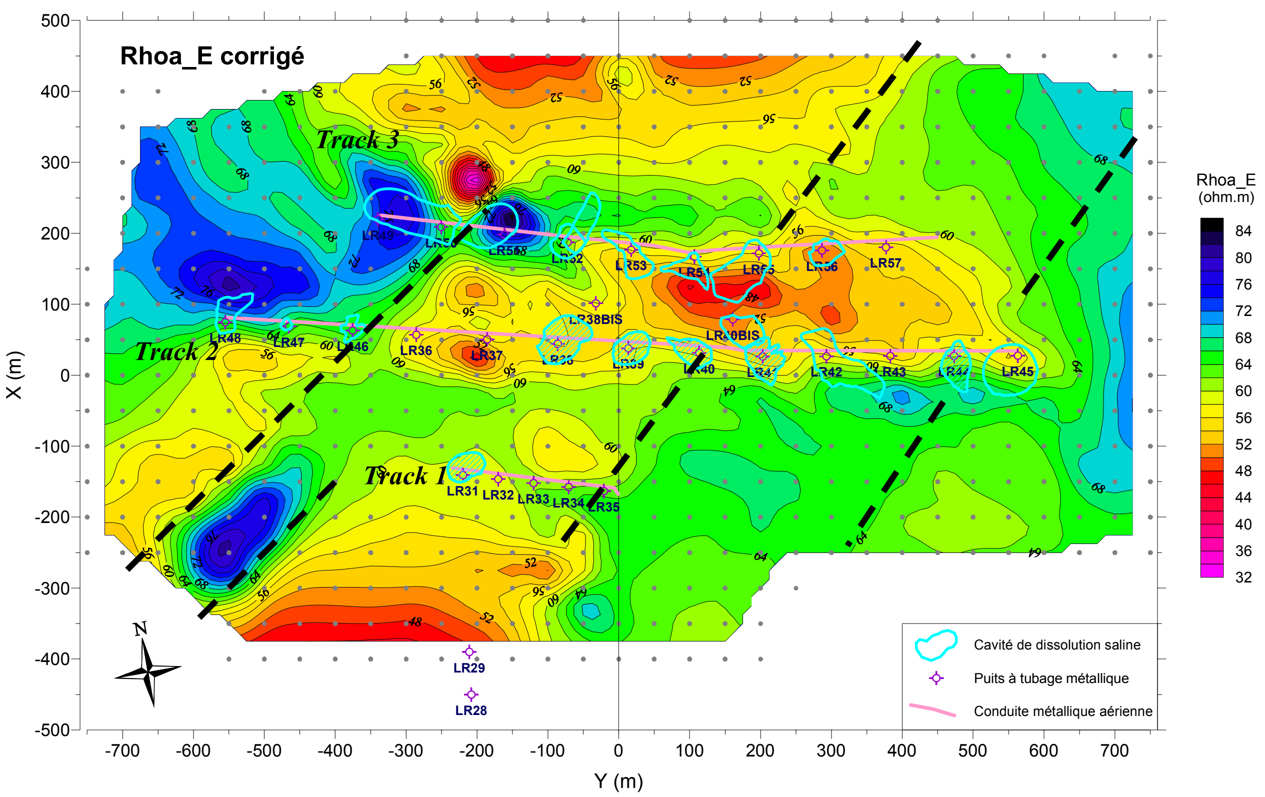
Résistivité apparente obtenue à partir du champ électrique total

Figure 7. Apparent resistivity map obtained for the salt mine

3.3. Detection of marlpit

The geophysical surveys were conducted on selected experimental site (Eturqueraye) where the marlpit mine location was known. The information on the exact position of the mine was purposely "hidden" during the measurements and the data analysis.

<u>HRS analysis: </u>two perpendicular profiles have been designed and deployed on the only basis of depth range of 20-45 m the marlpit. Taking into account the unfavourable geological context (strong absorption due to the local geology) the data processing was confirmed very complex, the exploitable frequency is indeed particularly weak (Figure 8). However, it was possible to identify on the two profiles, an anomalous zone which corresponds to a relatively significant attenuation of the amplitudes in the first 20 meters of the basement. Although this zone is very attenuated, it seems that the waves crossed the disturbed medium. The HRS images do not evidence the presence of cavity, the observed anomaly could be related to collapsed zone in the first 20 m of the cover. Finally, the correlation to the marpit real position and the drilling data confirmed the seismic interpretation. Indeed, the marlpit was found collapsed at the drilling point on the first 23 m (depth of the marlpit).
The local conditions of the selected site did not enable the use of the vibratory source therefore the latter has been tested on another site located in Goderville (Haute-Normandie) where the marpit is well known and was subjected to HRS reflection measurements in 2002 (Driad, 2004). The first

HRS investigations were carried out using impulsive source providing an uncompleted section due to the inaccessibility of an inhabited zone (private houses). Thus the same profile as in 2002 has been measured with a non-destructive vibratory source allowing the access in private garden. The comparative results shown in figure 9, evidence a better seismic image with the vibratory source confirming undeniably the advantage in using a non-destructive source.

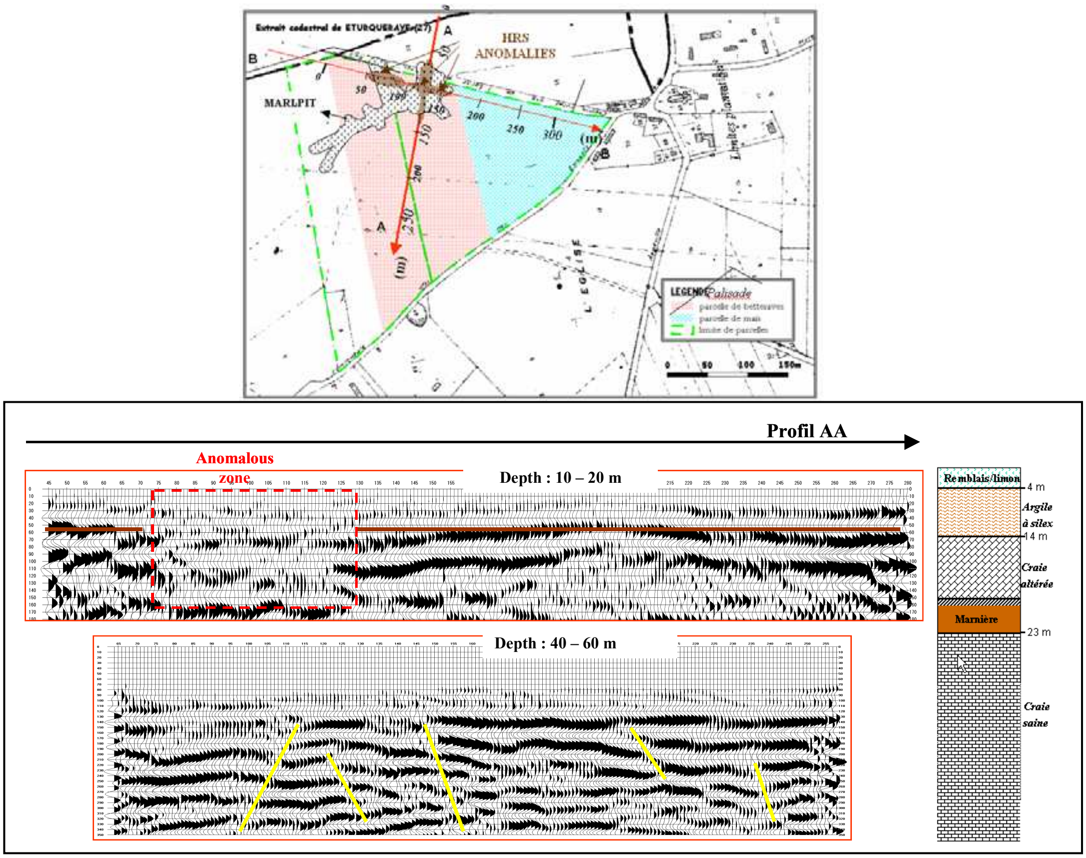

Figure 8. Interpreted HRS reflection time section obtained for one profile crossing the marpit. The position of the marlpit and the seismic profiles and anomalies (top) seismic section for depth ranges of 10-20 m and 40-60

<u>Microgravity analysis</u>: the measurements were carried out following a grid of dimension 200 x 400 m^2 with 10 m spacing in order to detect the marlpit situated at depth range of 20-40 m. The obtained map of residual gravity anomalies shows two negative anomalies of –25 µgal, located at the east and the west of the investigated zone (Fig. 10). These two anomalies are separated by a central positive anomaly, which reaches +22 µgal. The negative anomaly, located in the western part, is correlated with the presence of the marlpit. The drilling data made it possible to associate the negative anomaly to decompressed zone corresponding to the local collapse of the marlpit. This interpretation would not have been validated without the drilling information. The negative anomaly located more in the east does not correspond to a known cavity; it is associated to a locally decompressed zone identified by drilling. Finally, the positive anomaly located at the centre, would correspond to stronger density than the embanked rocks; related probably to a more significant concentration of flint in this zone. Indeed, the flint has a density of approximately 2600 kg/m3 whereas the density of soft chalk is of the order 2000 kg/m3. The accumulation of flint might also be connected to the exploitation of the marlpit, which could be rejected at this place by the owners.

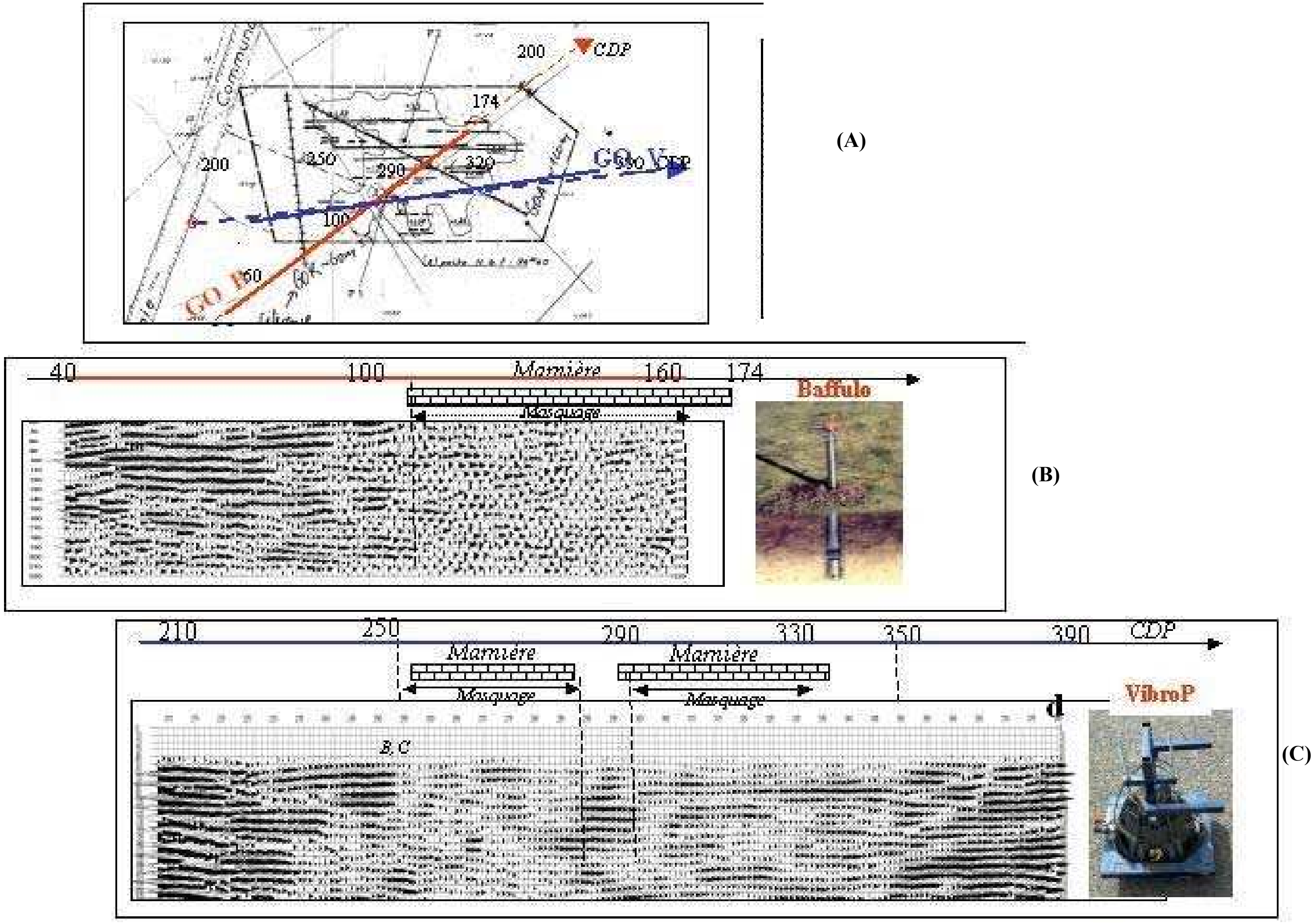

Figure 9. HRS sections of Goderville marlpit situated at 45 m depth. (A) Topographic delineation of the marlpit and the position of the seismic profile in 2007 (red) and in 2002 (blue). (B) the time section from the impulsive source, (C) The time section obtained in 2007 using the new seismic acquisition system.

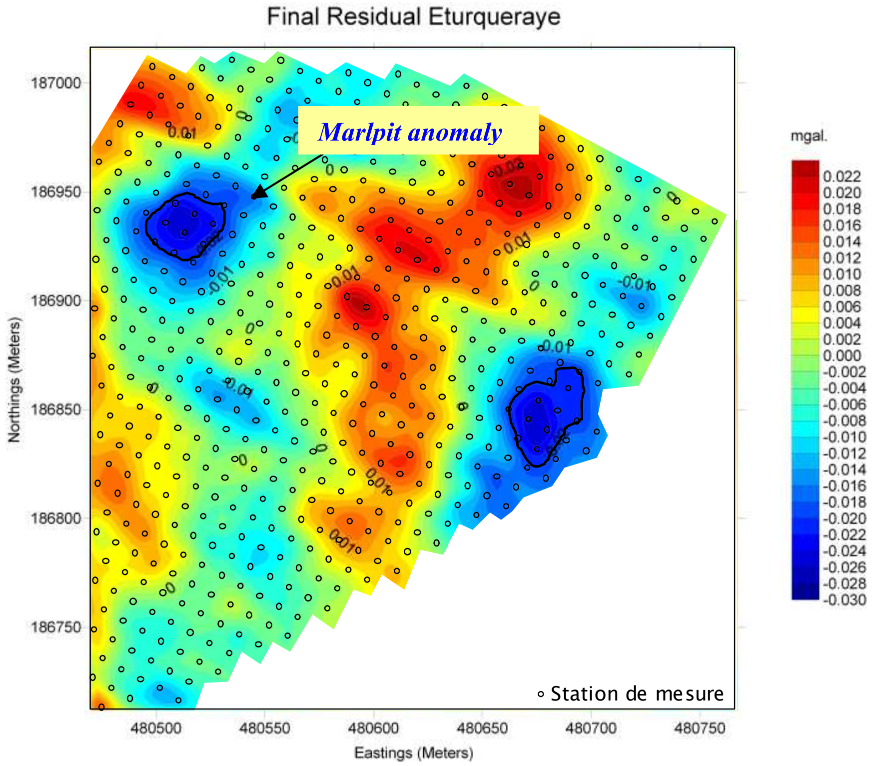

Figure 10. Gravity residual anomalies obtained for the marlpit site Etruqueray

Electric resistivity: three profiles A, B, C were implemented, of which the profile C is located out of the influence zone of the marl-pit (reference profile). The analysis of the resistivity tomography for the three profiles is obtained from pole-pole and pole-dipole measurements; the latter device is generally the more used since it provides a good resolution. It should be noted that the expected anomaly related to the presence of the marl-pit should be very resistant; the contrast of resistivity is theoretically less significant when the cavity is stowed. The tomography model obtained after from data inversion of the three profiles is shown in the figure 11. It arises a resistant anomaly located directly above the marlpit with a slight side shift on profile A. It would have been simple to interpret this anomaly as being the effect of the marlpit if this same anomaly were not observed on the other profiles, in particular the reference profile C. The various approaches of modelling unfortunately did not succeed in bringing more precise details. Moreover, the differences observed between the profiles carried out in the marlpit zone and outside this zone are not sufficiently contrasted to distinguish without ambiguity the resistive anomaly (i.e. marlpit) in a relatively conductive medium. This observation probably reflects the limit of the technique in term of resolution in the context of marlpit mines all the more reason that the expected anomaly would represent a collapsed zone (i.e decompressed ground).

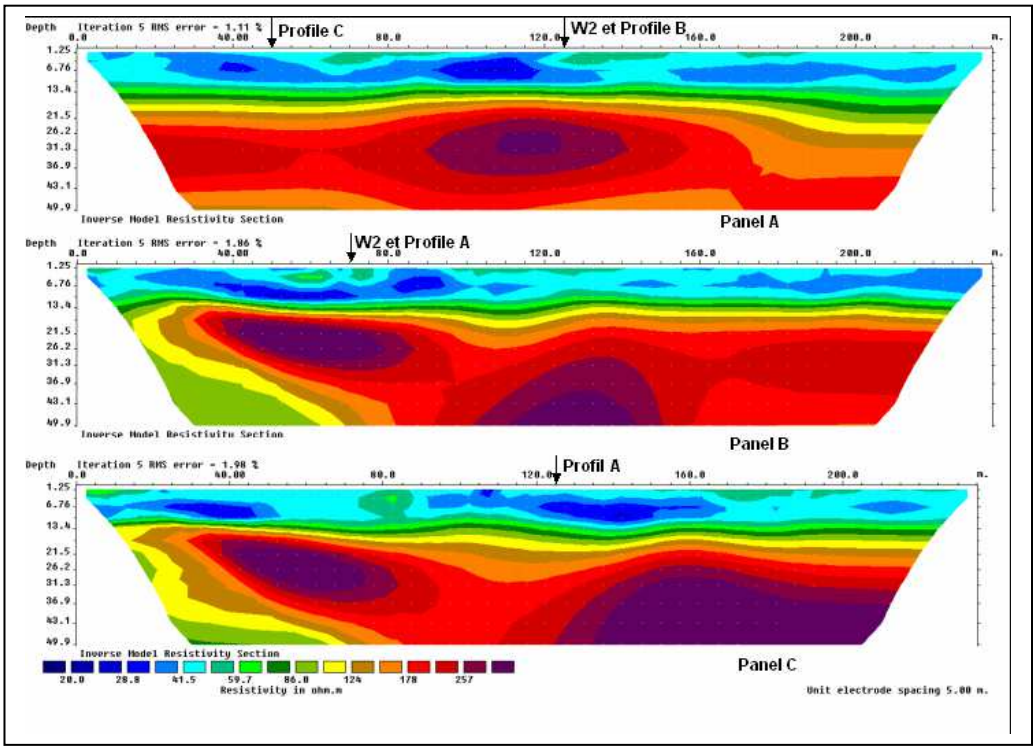

Figure 11. Tomography of the electric resistivity obtained for panels A, B and C (reference profile) using acquisition device pole-dipole.

Joint geophysical analysis: since the electric measurements were not conclusive, the joint analysis was limited to the superposition of the seismic and microgravity anomalies. The results evidenced a positive correlation of both seismic and residual gravity anomalies corresponding to the marlpit position (Fig. 12). This encouraging result can be regarded as a validation of the interpretation, but does not draw aside a control by drilling in order to associate the geophysical anomaly the target i.e. marl-pit.

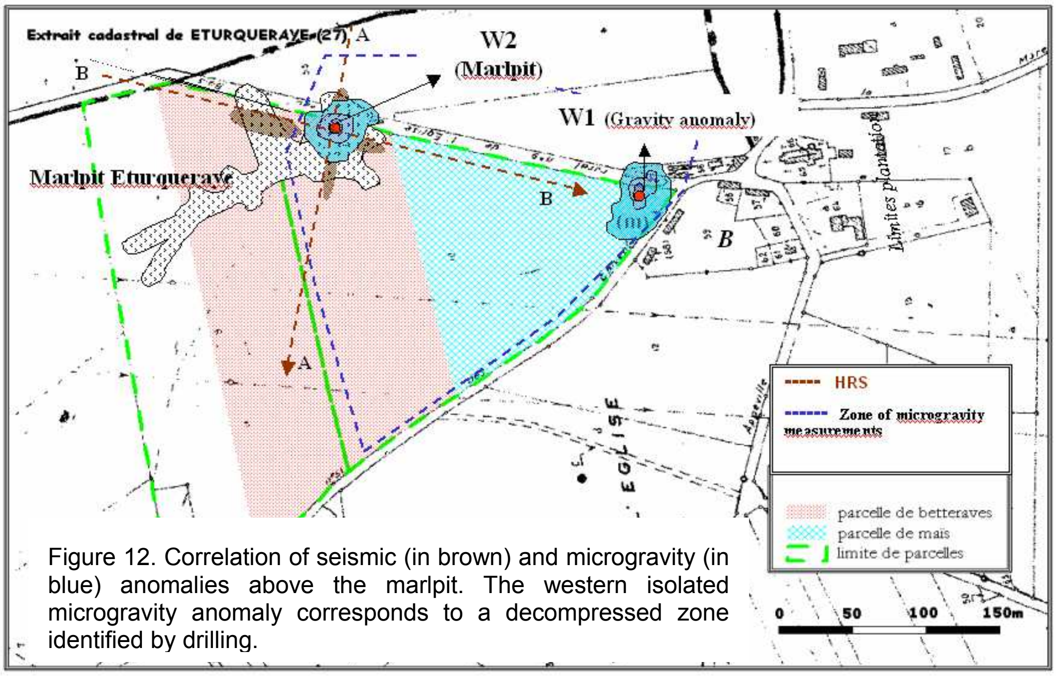

Figure 12. Correlation of seismic (in brown) and microgravity (in blue) anomalies above the marlpit. The western isolated microgravity anomaly corresponds to a decompressed zone identified by drilling.

4. Discussion and conclusions

This partnership research program on geophysical detection of underground cavities offered the opportunity of developing new acquisition system for High Resolution Seismic (HRS) investigations, and of testing joint measurements of HRS, microgravity and the electric resistivity in the context of salt mines of the Lorraine (North-east France) and the marlpits of Haute-Normandie (North-West France).

The experimental site of salt mine, where the cavities were known, was the object of many seismic tests to validate the newly developed acquisition system (vibratory sources in wave P and S, PGOS). The results obtained from exhaustive and comparative analyses revealed the interest of the developments carried out and confirmed the contribution of the adopted technical solutions (electronic, mechanical, algorithms...) and methodology for obtaining a better resolution of HRS imaging. The tests source showed that the VibroPP vibrator can have a potential similar to that of an explosive source which gets objectively the best resolution, but must be used (VibroPP) in an optimal way in order to exploit all the advantages, of which the non-destructive character. It is in particular a question of ensuring an acceptable and repetitive coupling and of carrying out preliminary tests in order to select the source appropriate to the site conditions and target. Although the vibratory sources at the stage "prototype" were developed for research, it was shown that the detection of salt cavities at depth greater than 100m is possible by analysing the masking effects of deeper reflectors. Taking into account the nature of the infilling (brine), the interpretation of the HRS sections was not simple. Indeed, the masking effect is less marked than if the cavities were empty (air). Note that the lack of resolution to great depth did not make it possible to precise the position of cavities. In addition, the HRS highlighted anomalies related to the collapsed zone (not shown in this paper) and geological faults observed on resistivity and microgravity images.

The microgravimetric detection of the salt cavities turned out less effective taking into account the depth of investigation (110-180 m) compared to the dimensions of the cavities. Moreover, the fact the cavities are mainly filled with brine, the density contrast is smaller than if the cavities were empty (air); thus, the lack of mass is not sufficient for an accurate detection. The electrical measurement made it possible to obtain a complete and interesting image of the global structure in particular geological faults, but the precise and individual detection of the cavities was not possible. Indeed, the limitation is due essentially to the compromise between dimensions of the cavities and the depth of investigation, which is not optimal.

In the context of the marlpits , the geophysical measurements were carried out on a marl-pit whose exact position was revealed only after the data analyses. The HRS and microgravimetric imaging highlighted both individually and jointly anomalies associated with the presence of the marlpit. The observations were validated by drilling which identified decompressed zone up to 24 m depth corresponding to a partial collapse of the marlpit. In addition, complementary HRS measurements on the Goderville marlpit using the new acquisition system enabled an accurate detection since the non-destructive character of the vibratory source made it possible to access inhabited zone and implement a longer profile. The detection attempt of the marlpit by resistivity tomography was not conclusive; this technique indeed came up against its limits of resolution in this geological and mining context.

Finally, through this research program we could evidence the limitations and the potential of the investigated geophysical techniques but also the necessity to progress in new developments and increase the performance in acquisition, processing and analysis. In comparison to the past investigations, it has been shown that the research work carried out on the HRS acquisition system contributed strongly to the detection underground cavities in the condition of the selected sites. Further more, other geological and mining context should be considered to come out with a complete methodology applied to the geophysical detection of underground cavities.

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