

# *Ground-penetrating radar prospection over a gallery network resulting from Neolithic flint mine (Borownia, Poland)*

N. Boubaki<sup>1</sup>, A. Saintenoy<sup>1</sup>, S.Kowlańczyk<sup>2</sup>, R. Mieszkowski<sup>2</sup>, F. Welc<sup>3</sup>, J. Budziszewski<sup>3</sup> and P. Tucholka<sup>1</sup>

<sup>1</sup>UMR IDES 8148, CNRS - Université Paris Sud, Faculté des Sciences,  
Bâtiment 504, 91405 Orsay Cedex

<sup>2</sup>Institute of Hydrogeology and Engineering Geology, Faculty of Geology, University of Warsaw, Al. Zwirki i Wigury 93, 02-089  
Warsaw, Poland

<sup>3</sup>Institute of Archaeology, Cardinal Stefan Wyszyński University in Warsaw, St. Woycieckiego 1/3, no. 23, 01-938 Warsaw,  
Poland

**Abstract**— A Ground-penetrating Radar has been used to map a 100 m<sup>2</sup> area suspected to be above a network of galleries remaining from flint prospection during the neolithic period. Twenty profiles have been acquired. Their interpretation, gives evidence for banded flint layers dipping to the North, and underground remaining galleries.

**Keywords**-component; cave archaeology, flint, geophysical prospection, GPR survey.

## I. INTRODUCTION

Krzemionki is an area in Poland (Fig. 1) presenting many remains of flint mines. In Neolithic and Bronze Age times (about 4000-1500 B.C.) people dug some mines to get at a beautiful banded flint, used mostly to make flint axes (chipped then ground), spotted flint for large core blades, and chocolate flint for axes and bifacial tools. There are above four thousand of mines shafts in this area. Some are simply pits while others consist of a vertical shaft that penetrates the limestone to a level where there are large flat nodules of flint. Once this was reached (sometimes as much as 9 meters below the ground surface) drifts were dug in a radial pattern from the shaft. These drifts (55 to 120 cm in height) followed the flint layer and expanded into low chambers (Fig. 2). Some of these have been scientifically excavated and were found to contain numerous antler picks, other digging tools, and ingenious methods of ventilation and lighting. The depth of mines depends on the flint location. More information can be found on different web sites as <http://en.wikipedia.org/wiki/Krzemionki> and <http://www.primtech.net/flint/poland.html>.

Krzemionki site is similar to Grimes Graves flint mines in eastern England and a site close to Falaise in France. The Polish flint site is the largest in its extension. The mining area is 4.5 km long and 25–180 m wide and covered 78.5 ha (<http://en.wikipedia.org/wiki/Krzemionki>). The flint mining in Krzemionki began to decline at least since 1800-1600 B.C. Archeology studies began in 1922 and in 1967 the Krzemionki

mines were stated as archeological reserve and in 1995 as natural reserve. Archeological information can be found in [1].

Ground-Penetrating Radar (GPR) is a geophysical method using electromagnetic (EM) waves to prospect underground. The tool description and many examples of its applications can be found in [2] and [3]. EM wave's propagation depends on EM parameters of the sounded medium. Massive limestone is known to be a medium not too absorbing for EM waves. Different GPR prospections have been carried out on over such a medium. Henson et al. [4] studied one GPR line over a karstic environment doing some precise velocity analysis using common-midpoint data. Martinez et al. [5] used GPR with a 500 MHz antenna to analysis the first 3 to 4 m part of a petroleum-reservoir-analog limestone unit. Chamberlain et al. [6] demonstrated the GPR with a 100 MHz antenna to be an effective method for detecting caves in limestone down to a depth of 20 m. El-Qady et al. [7] imaged the path of two adjacent caves in the first 7 m in limestone doing a 3D acquisitions with a 200 MHz GPR system. In those two last studies, adjacent profiles were acquired to make a 3D localization of the caves. A preceding GPR study has been carried out on Krzemionki site in 1983 [8]. They used a SIR system emitting a 80 to 100 MHz EM wave. They discovered underground works down to 8 to 10 m and their geophysical data analysis was confirmed by excavations.

In this study, we investigated an area close to Borownia, 12 km south from Krzemionki (Fig.1), where archaeologists suspect flint mine remains, underground of a plot field. They argue that many caves resulting from the neolithic flint prospection remain undiscovered because they do not reach the ground surface or because their entrances are obscured by unconsolidated surface deposits. Several GPR profiles were acquired parallel to each other to cover an area of 100x150 m<sup>2</sup>. Additional 500 m long profiles were acquired next to this area. We made some numerical simulations to help us with GPR data interpretations.

## II. GPR DATA

We acquired in June 2011, fifteen 100-m long GPR mono-offset profiles parallel to each other with 10 m in between them (Fig. 3). Additional 500 m long profiles were acquired next to this area for comparison. GPR data were acquired using the system RAMAC with 250 MHz antenna. Data were collected in continuous mode with readings every 5 cm. Each trace consists of 1008 samples (stack 8) adding to a 223 ns time window. Basic processing was applied to those data using ReflexW [9]. De-wow filtering was applied first, then data were bandpass filtered in between 7 and 800 MHz for noise reduction. Time-zero was set to the arrival time of the maximum of the direct air wave and each profile was cut to 200 ns. For better visualization, we gained the amplitude using an energy decay gain and we subtracted the average trace inside a running window of 50 traces. The first four processed radargrams are shown Fig. 5.

## III. NUMERICAL SIMULATIONS

To interpret our GPR data, we simulated radargrams using GprMax which solves Maxwell's equations using the finite-difference time-domain method [10]. EM parameters describing each medium were chosen according to published work [2].

We simulate a radargram acquired above galleries with rectangular section connected like on Fig. 4. Dimensions were chosen from galleries descriptions like in Fig. 2. It shows the complexity of the radargrams due to the high difference of EM wave velocity between air and limestone. Reflections on entrances are not spatially linked to reflections on the top of the horizontal gallery. Even in this simple model many hyperbolas appear resulting from edge diffractions. In our model the limestone is low-loss and multiple reflections are distinguishable. In the reality we suspect that some galleries are filled with boulder remaining from the excavation. Those boulders would be a source of additional scattering compared to the simplified model presented Fig. 4.

## IV. GPR DATA INTERPRETATIONS

From hyperbolas fitting using ReflexW software, we determined a radio wave velocity of 0.1 m/ns on the average. Using this velocity, the two-way travel time axis is converted to a depth axis and coherent signal is visible coming from down to 7 m. This depth of penetration is quite good considering that we are using 250 MHz antenna. Helped by our simulations our interpretation of four GPR profiles is shown on Fig. 5. Dipping reflectors are interpreted as reflection on flint veins. On a profile acquired in a adjacent field (not shown here), we see similar dipping event to the North. Profiles of Fig. 5 present numerous zones of high scattering that we interpret as underground galleries. A 3D visualization of 10 profiles (Fig. 6) confirms the lineament of the zone of scattering in a direction NW-SE in the continuity of the forest represented in green on Fig. 3. On Fig. 5, we underline in green a reflector whose depth varies about 1 m. It might come from

the bottom of the tillage layer. This reflector shows some deepening above some diffraction hyperbolas like at 55 m on profile 3 (Fig. 5). It is tempting to interpret this as a surface subsidence above a gallery entrance. Such an interpretation is encouraged by the fact that each deflection of the green reflector is correlated to the presence of some hyperbolas underground.

## V. CONCLUSIONS

GPR has proven to be an effective method to investigate the structure of the subsoil in limestone, with a depth of penetration of 7 m. A zone of multiple radar scattering was visible on 10 adjacent profiles with an alignment NW-SE. Numerical simulations help us to interpret dipping reflectors as coming from flint veins and we suspect the scattering zone to come from galleries remaining from the Neolithic flint excavations. No excavations were undertaken yet at the Borownia site yet to confirm our GPR interpretation. Although some electrical resistivity tomography could be undertaken as in [7] and [11] to add evidence for underground mining remains, we are confident enough in our interpretation of the GPR data to consider further investigations on the area to map the spatial extent of the Neolithic flint mines.

## ACKNOWLEDGMENT

The field experiment could take place with the help of the Warsaw University. We are thankful to Piotr Ziolkowski and Jerzy Trzcinski for their help for the data acquisition.

## REFERENCES

- [1] Borkowski W. and J. Budziszewski, 1995, The use of striped flint in prehistory, *Archaeologia Polona*, 71-87.
- [2] Davis and P. Annan, 1989, Ground- penetrating radar for high-resolution mapping of soil and rock stratigraphy, *Geophysical Prospecting*, 37, 5, 531-551.
- [3] Sagnard F and F. Rejiba, 2010, Géoradar - Principes et Applications, TE5228, *Techniques de l'Ingénieur*, 14 pages.
- [4] Henson H., J.L. Sexton, M. Henson, and P. Jones, 1997, Georadar investigation of karst in a limestone quarry near Anna, Illinois, *Society of Exploration Geophysicists Expanded Abstracts*, presented at SEG 67th annual meeting, Dallas, TX, 1997.
- [5] Martinez A., J. M. Kruger and E. K. Franseen, 1998, Utility of ground-penetrating radar in Near-surface, high-resolution imaging of Lansing-Kansas city (Pennsylvanian) limestone reservoir analogs, *Kansas Geological Survey, Current Research in Earth Sciences, Bulletin* 241, part 3.
- [6] Chamberlain A. T., W. Sellers, Ch. Proctor and R. Coard, 2000, Cave Detection in Limestone using Ground Penetrating Radar, *Archaeological Science* 27, 957-964.
- [7] El-Qady G., M. Hafez, M. A. Abdalla, and K. Ushijima, 2005, Imaging subsurface cavities using geoelectric tomography and ground-penetrating radar. *Journal of Cave and Karst Studies*, v. 67, no. 3, p. 174-181.
- [8] Borkowski W., 1990, Results of subsurface radar geophysical studies of the Krzemionki banded flint mines Poland, *Archaeometry*.
- [9] Sandmeier K. J., 1997, REFLEX Version 4 program for processing and interpretation of Reflection and Transmission Data, University of

Karlsruhe, Geophysical Institute, Environmental and Engineering Geophysical Society.

[10] Giannopoulos A., 2005, Modelling ground-penetrating radar by GprMax, Construction and Building Materials, 19, 10, 755-762.

[11] Boubaki N., A. Saintenoy and P. Tucholka, 2011, GPR profiling and electrical resistivity tomography for buried cavity detection: a test site at the abbaye de l'Ouye, (France), Proceedings of the 6th International Workshop on Advanced Ground Penetrating Radar, Aachen, June 22-24, pp. 1-5.

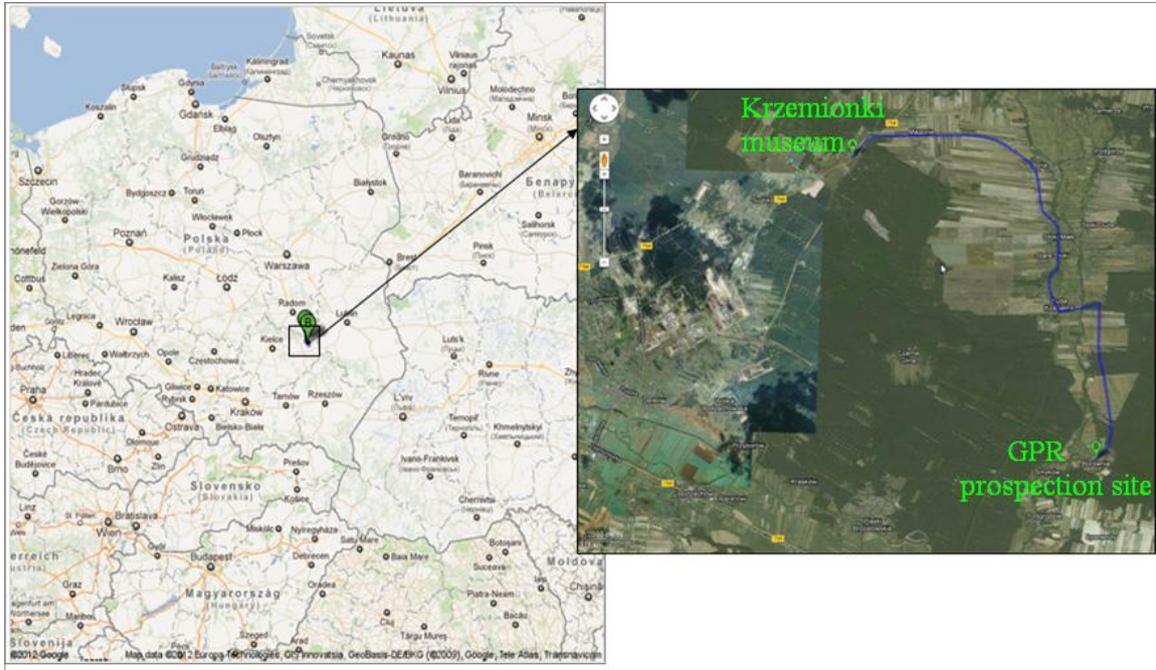


Figure 1. Krzemionki flint mines localisation in Poland.



Figure 2. Vertical shafts and radial galleries created by neolithic man for flint excavation (coming from the museum at Krzemionki).

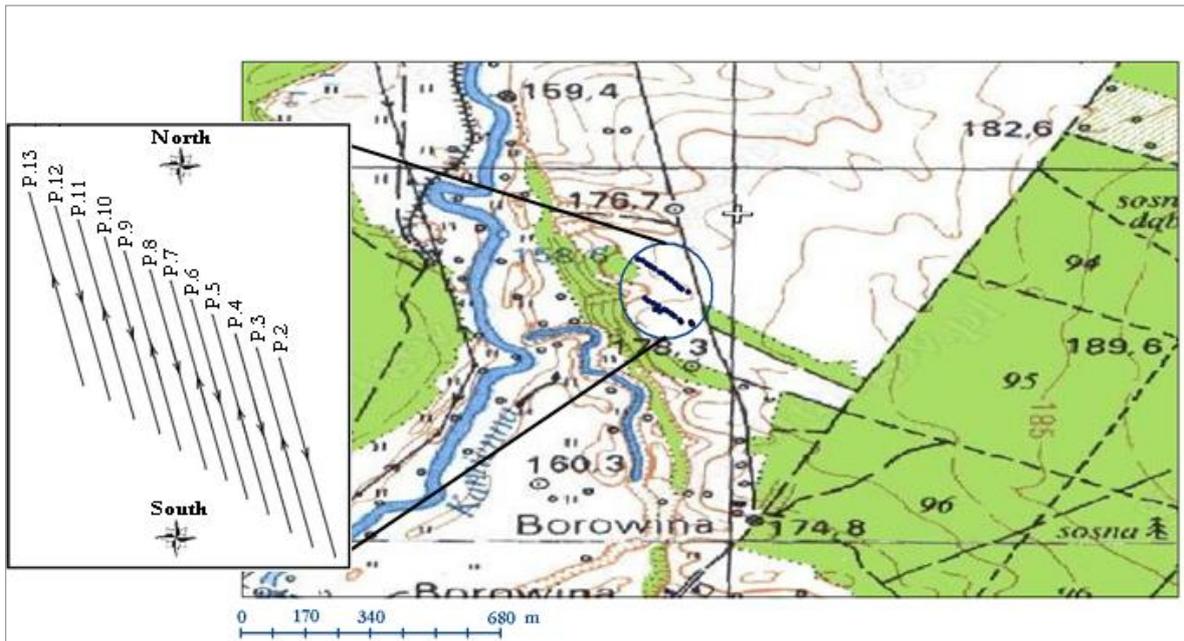


Figure 3. Location of the study area in the sedimentary basin of BOROWNIA, positioning of the radar profiles acquired in the site.

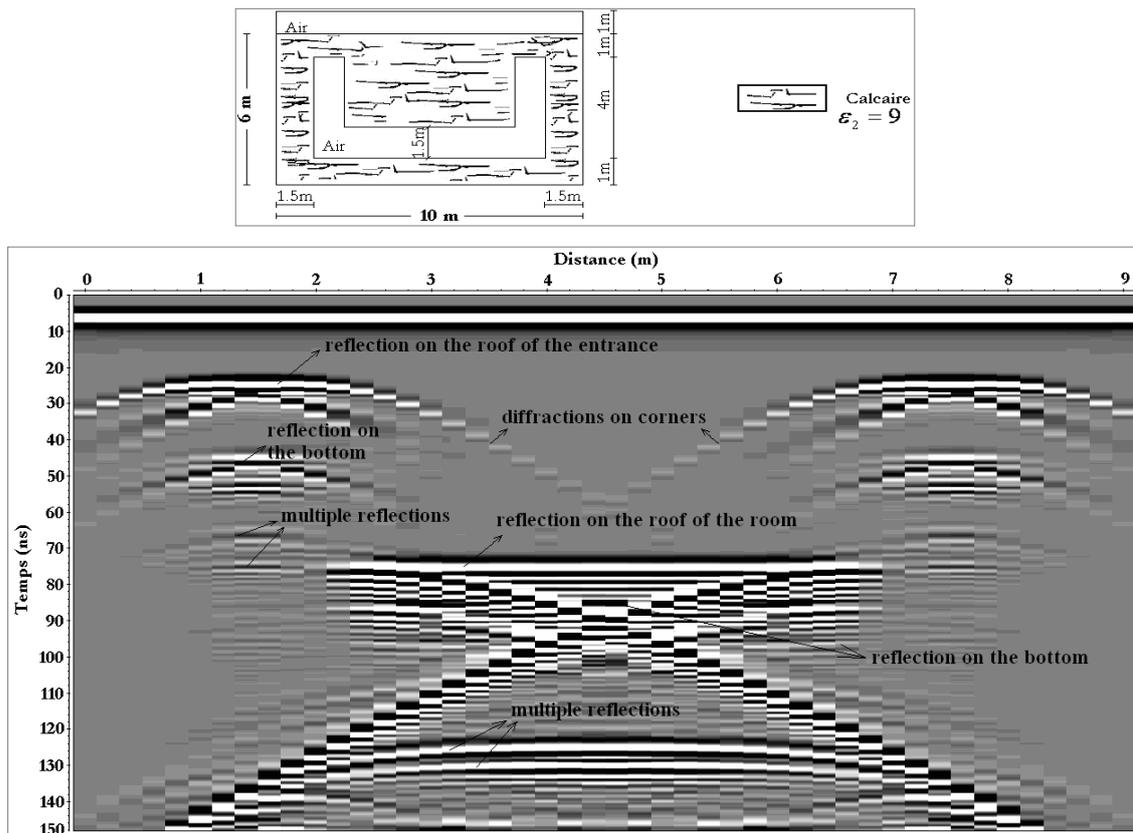


Figure 4. a) Model and b) simulated radargram.

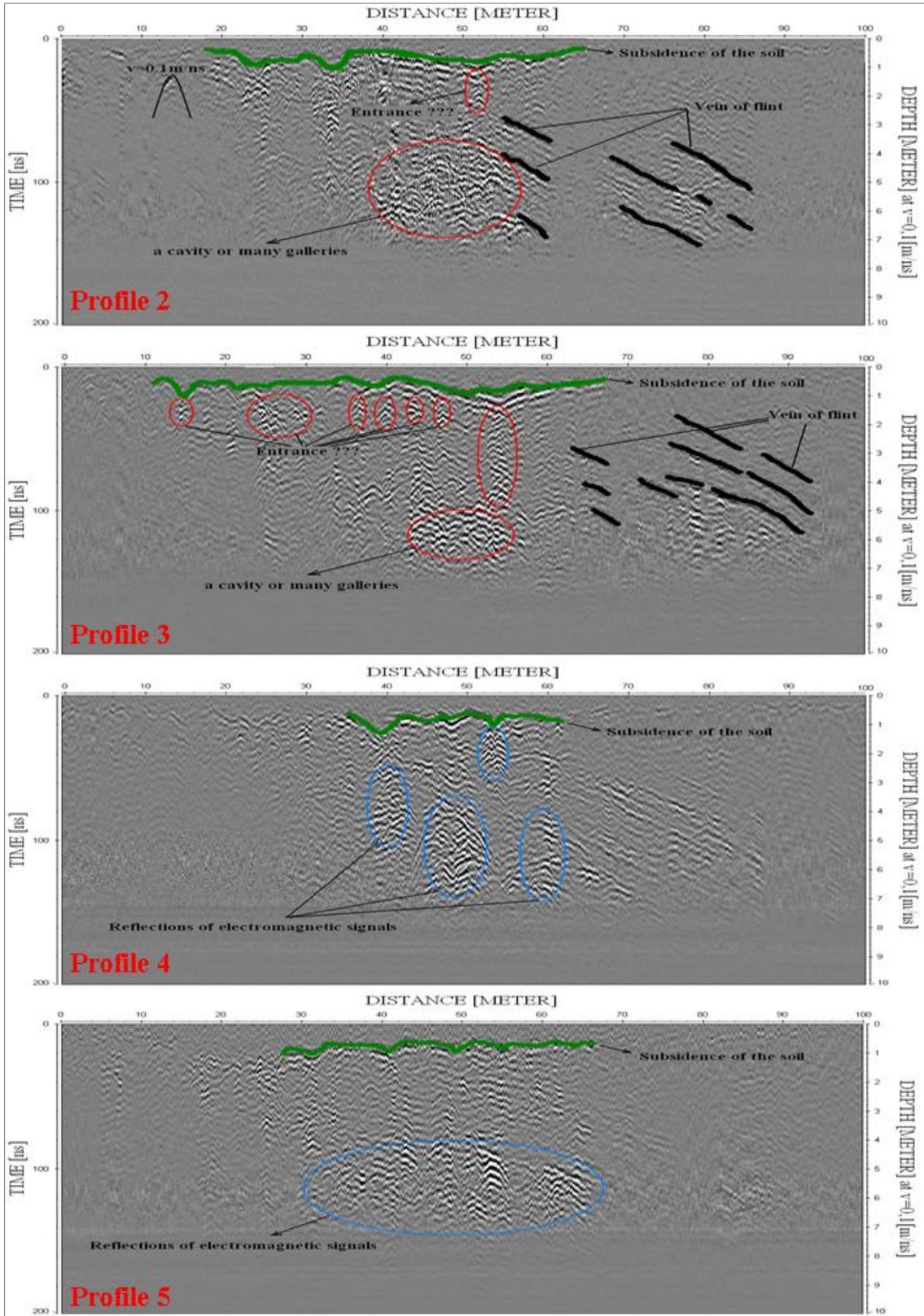


Figure 5. Four profiles acquired over the suspected underground cavities showing main interpreted features.

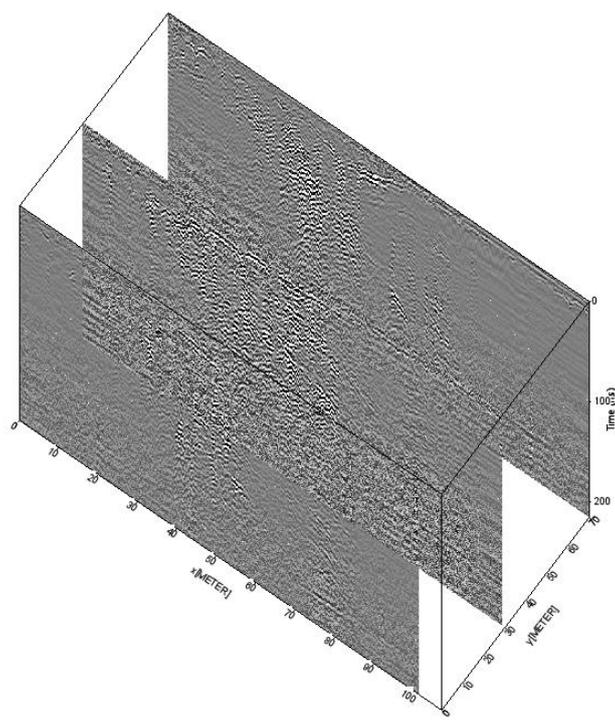


Figure 6: 3D visualisation of 3 GPR profiles.