Shallow GPR and seismic surveying in a carbonate environment: Belize, Central America

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ABSTRACT

The use of non-invasive geophysical techniques to assist archaeologists in focusing excavation activities has been steadily increasing world-wide. Over the last several years, ground penetrating radar (GPR) and near surface seismic surveys have been conducted at the ancient Maya site of Maax Na in Belize, Central America. Accurate spatial and topographic measurements were also recorded using a Leica TC805L total station survey.

Velocity determination based on the hyperbolic fitting of curves to point diffractors has resulted in a wide range of velocity measurements. These differences have been attributed to climatic conditions during surveying, ranging from wet conditions in 2002 and 2004, to dry weather in 2003. Measured velocities in 2002 and 2004 ranged from 0.072 - 0.106 m/ns. Conversely, velocities ranging from 0.122 - 0.140 m/ns were acquired in 2003. The maximum depth of penetration was approximately 2-3 m.

Processing of the GPR was achieved using Reflexw software. The flow consisted of a dewow filter and gain, a smoothing operator, a bandpass filter, a diffraction stack migration and a bulk shift. Processing challenges were encountered due to calibration problems, and skipped traces.

The GPR method provides coherent and interpretable images of the subsurface of the plaza with good signal penetration. To date, the GPR lines have highlighted a number of interesting features, one of which was excavated in 2004. No buried features were unearthed, but confirmation of the noticeable structure present on the feature will be investigated based on the archaeologist's description of the excavated pit.

A brief comparison between identical lines extracted from the GPR 3-D survey and the 3C-3D micro-seismic survey serves to illustrate the potential of combining these two methods to resolve and image deeper into the subsurface. The resolution of GPR records in the near surface is superior to that of the seismic in the depth range of 0.7 -1.75 m but the depth of penetration of the seismic is greater than the GPR. Ultimately, a combination of the two would be advantageous to archaeologists in their quest to understand the past.

INTRODUCTION

The Maya civilization flourished in Central America for close to a thousand years. During the Classic Period (A.D. 300 – 900), monumental architecture in the form of ornate palaces, pyramids and temples, adjoined by expansive plazas, were erected to honor gods and deities, and to highlight the lives and accomplishments of their rulers. Much of Maya life was centered on cosmology, and the perfect alignment of these structures to astrological bodies and events.

Maax Na is one of many Maya archaeological sites situated in the Rio Bravo Conservation area of the Programme for Belize (Figure 1). The site was discovered hidden within dense and remote jungle in 1995 by a group of surveyors. Subsequent excavation and mapping at Maax Na have revealed hundreds of intact structures within and around the site centre including temples, pyramids, stelae and caves (King, 2004). Archaeologists now consider this site to be ceremonial in nature.

Maax Na is situated in the Corozal Basin of the geological province of Northern Belize, and consists of a thick sequence of marine carbonates, primarily limestone (Aitken, 2003). The near surface layering of the plaza is comprised mainly of soil and humus, with assorted limestone detritus above limestone bedrock. Building supplies were easily obtained from the abundant soft-limestone beds, materials that could be cut into blocks or reduced by burning to produce lime for plaster (Sharer, 1994).

The University of Calgary was invited to participate in the Maax Na Archaeological Project in 2001, and has been acquiring a number of near-surface geophysical surveys each field season. These methods are particularly useful in that they generate images of near surface stratigraphy and structure, and may delineate possible buried features. The 2002-2004 field seasons have involved surveying several 2-D lines and three 3-D grids across the plaza using both GPR and surface seismic, a seismic tomographic survey circumnavigating a pyramid and a total station survey. This report will focus mainly on the results from the GPR survey with a brief discussion on a comparison between the GPR and the 3C-3D micro-seismic survey.

GPR SURVEY

The term 'ground penetrating radar' (GPR) refers to a technique designed primarily to detect "the location of objects or interfaces buried beneath the earth's surface or located within a visually opaque structure" (Daniels, 2004). GPR constitutes the propagation of electromagnetic energy into the subsurface. The resultant GPR image represents a series of reflections indicating changes in the impedance of one or more electrical/magnetic properties namely, dielectric permittivity, magnetic susceptibility and electrical conductivity. The recorded signal is generally measured in nanoseconds.

The success of GPR surveys is dependent on the composition of near surface materials and conditions, such as the clay content of soils and the saturation level of the material (Aitken, 2003). The saturation of the near surface results in vast changes in dielectric permittivity which translates into varying measurements in velocity. According to Table 1, significant differences in velocities were obtained each field season. These differences we now attribute to climatic conditions, namely wet conditions in 2002 and 2004, and dry weather in 2003. Measured velocities in 2002 and 2004 ranged from 0.072 - 0.106 m/ns. Conversely, velocities from 0.122 – 0.140 m/ns were acquired in 2003. This represents almost a doubling of velocities at the extremes of the various ranges.

As shown in Figure 2, a number of 2-D and 3-D grids have been surveyed during the past three years. In 2003, a GPR 3-D survey and 3C-3D seismic micro-survey were acquired over the same 3-D grid. The orientation and results of the 2002 and 2003 lines has already been discussed in previous reports. The 2004 survey featured reshooting a number of 2-D lines and extending them to the edges of the plaza for a total number of 21 lines, as well as a small 5 m x 5 m 3-D grid shot in orthogonal directions across what the archaeologists consider a ceremonial altar. Surficial conditions such as tree roots, depressions and large rocks impeded the ability to shoot the data in the desired spot and as a result necessitated some deviations in the survey.

The GPR equipment consisted of a Noggin® 250 and Smart Cart® system in which the transmitter and receiver antennae are housed in the same unit at a fixed interval of 27.94 cm. Due to the fact this instrumentation is monostatic, meaning the distance between the transmitter and receiver is fixed, a common mid-point velocity survey cannot be conducted. As a result, velocities are measured by fitting hyperbolic curves to point diffractors as shown in Figure 3. The unit is manufactured by Sensors and Software Ltd. The antenna has a frequency of 250 MHz with an associated bandwidth of 125-375 MHz. Resolution of the GPR survey is dependent upon the wavelength of the energy (i.e. frequency of the antenna) that is being pulsed into the ground. One may be able to resolve anomalies resulting from smaller features with higher frequency units but higher energy dissipation will mean that the depth of penetration into the ground will drop (Gaffney and Gater, 2003).

Spatial sampling (station interval) for all the GPR lines was set at 5 cm with temporal sampling (sample rate) at 0.4 ns. The 3-D surveys were acquired in a forward reverse set-up with line intervals set at 50 cm (Figure 4). In order to provide exact coordinates of many of the features delineated on the GPR records, a total station survey was conducted.

3C-3D MICRO-SEISMIC SURVEY

The 3C-3D seismic survey consisted of 60 channels using a split-spread configuration. The geophones were single-component omni-phones with a removable spike, allowing vertical or horizontal orientations of the sensor (Kaprowski and Stewart, 2004). A seismic signal was generated by a single blow of a 2.5 kg hammer striking the top of an aluminum cylinder. A trigger was attached to the handle of the hammer. Shot spacing was set at 50 cm with the receiver locations remaining stationary at 1 m spacing while the full shot spread was run three separate times for each orientation. A total of 225 shots were recorded.

PROCESSING

The GPR processing was accomplished using the Reflexw software package and involved several steps including the application of gain, filtering, and migration algorithms. The Reflexw program was designed for processing and interpretation of seismic, acoustic or electromagnetic reflection, refraction and transmission data (Sandmeier, 2004). The advantage of using this program is that many of the options available to the seismic processing user including 2-D and 3-D processing capabilities are available.

Challenges in processing the 3-D's in particular were encountered when the acquisition parameters, namely the length of each line, did not match the assigned input parameters due to calibration problems, and with the presence of skipped traces. Skipped traces are the result of the unit moving too fast for the collection of data, resulting in repeated traces.

Similar processing flows were established for the GPR lines for both the 2-D and 3-D lines. Due to the acquisition procedure for the 3-D, namely a reversal in the direction of all the odd lines, an additional step to essentially flip the line is necessary such that all lines are aligned in the same direction. The flow includes a step to ensure that each profile contains an equal number of traces (i.e. equal line length), a dewow filter and gain, a smoothing operator, a bandpass filter, a diffraction stack migration and a bulk shift to bring the start time to time zero.

Several different filters were applied to the data, each providing a distinct and necessary function in optimizing the GPR record displays. A brief explanation of each follows.

The dewow filter acts on each trace independently. A running mean value is calculated for each value of each trace within a specified time window, and is then subtracted from the central point. The dewow filter is used to eliminate a low frequency component common to GPR systems.

Due to the rapid attenuation of the high frequency GPR signal, it is necessary to apply some sort of gaining function to compensate for the decrease in the strength of the signal at deeper events on the GPR record. The AGC filter facilitates this through the generation of equally distributed amplitudes within a predefined time window (Sandmeier, 2004). Each sample is multiplied by a scalar derived from a window of data about the sample. The size of the window determines the severity of the equalization (Hatton et al, 1988). Small window sizes cause a strong equality distribution, large windows a weak. This option serves to emphasize low amplitude ranges against ranges with higher amplitudes, but true amplitude information is lost.

The running average filter is considered a smoothing filter and performs a running average over a specified number of traces for each time step. This filter method suppresses trace dependent noise and serves to emphasize horizontally coherent energy.

A simple time migration (diffraction stack) of a two-dimensional profile on the basis of a constant velocity was also performed on the GPR data. Velocity measurements were determined based on the hyperbolic fitting of curves to point diffractors. The goal of the migration is to collapse back the reflection and diffraction energy to their "original point source".

The diffraction stack is done in the x-t domain. It represents an unweighted summation for each point of the profile over a calculated hyperbola of preset bandwidth. The bandwidth represents the number of traces over which the summation is predicated. The existence of diffraction arrivals is a precursor to accurate velocity determination. In addition to the contraction of the diffraction energy, migration serves to shift the arrivals to their "true" position. This is especially important for steep dipping reflectors.

The merging and interpolation of the 3-D grids, and migration algorithms are still currently being tested using F-K migration, pre-stack migration, and inversion.

TOTAL STATION SURVEY

In the 2004 field season, we conducted a Leica TC805L total station survey across the entire plaza, and around the periphery of the pyramid. This survey tool allows for accurate spatial and topographic coordinates based on existing reference markers set in place by the archaeologists. In previous years, a GPS system was used but accuracy concerns due to satellite and tree cover issues have necessitated the need for more dependable systems, at least in this location.

Figure 5 represents the resultant topographical map of the plaza. Note the gentle slope of the plaza to the south-east. According to the archaeologists, the Maya applied advanced engineering techniques when building the plaza such that the slope allowed for the drainage of water away from pyramids and other structures during the torrential downpours associated with the rainy season. Mapping generated from the near surface seismic using the Hampson and Russell's Generalized Linear Inversion Software package (GLI3D) is shown in Figure 6. It represents the elevation plots of Layers 2 and 3 of the 3C-3D micro-seismic survey grid acquired in 2003. Even though the micro-seismic survey was conducted on a small subset of the total station survey grid, it also illustrates a gradual dip to the south east.

INTERPRETATION

The interpretation of GPR data is even more dependent on the skill and experience of the operator than any other geophysical near-surface method (Gaffney and Gater, 2002). Anomalous features recorded on GPR images can be caused by numerous natural, man-made and acquisition/processing "artifacts".

3-D volumes generated for the 2003 grid acquired at Maax Na are featured in Figures 7 through 9. Inline (X), cross-line or Xline (Y), and full volume views have been generated. As shown, processing with Reflexw has resulted in interpretable images of the plaza. Continuous reflectors and changes in amplitude allow one to infer structural and stratigraphic information about the subsurface. A number of minor faults or fractures, and anomalies are present. As these datasets have been migrated, diffractions are no longer visible. Figure 10 represents a series of time slices that have been generated at 12, 20, 30 and 38 ns respectively. Note the anomalies highlighted in black.

During our most recent visit to Belize, the archaeologists were interested in what they believed to be a ceremonial altar on the plaza surface. A 3-D GPR survey was acquired across the surface feature. Figure 11 represents a photo of the altar, and is recognized by the archaeologists by the placement of stones around a central depression. Figure 12 shows the GPR image of the subsurface at this location. A strong feature is present in the vicinity of the altar as outlined by the dashed oval.

One of the anomalies, namely a structural anomaly present on a 2-D line acquired in 2003, was highlighted for excavation (Figures 13 and 14). The archeologists did indeed excavate the site but found no evidence of buried artifacts. A detailed geologic description of the pit is forthcoming and will be compared to the anomaly to validate structural changes at least. One of the lessons discerned this year has been the need to look at the gain applied to the data during acquisition. This gain function is set in the initial stages as an input parameter. One of the best anomalies we have come across during the last few years didn't show up when reshooting the lines because the gain in the lower part of the section on the interactive screen was set too low. It was not until we processed the data once we returned to the processing lab that the anomaly was apparent.

A comparison between one of the 3C-3D micro-seismic survey and GPR survey lines is shown in Figures 15 and 16. The two sections show a slight depression or structural low. The seismic method traditionally is used for deep exploration and has been less successful at imaging the near surface due to low frequency and noise. GPR conversely is considered to be a viable geophysical tool in the shallow section due to its inherent high frequency which translates to finer resolution. The disadvantage of GPR is the inability to see deeper into the subsurface. Figure 17 represents a display of the GPR and micro-seismic surveys side by side. It serves to illustrate how much better the resolution and definition of the GPR record is compared to the micro-seismic record from a depth range of 0.7 – 1.75 m. However, the depth of penetration of the micro-seismic is superior to that of the GPR. The micro-seismic display shows recorded events up to 45 ms, an additional 25 ms below that of the GPR. This essentially translates into additional data that the GPR was unable to "see". A combination of the two would undoubtedly be advantageous to archaeologists. Continued research at the University of Calgary will attempt to do just that, by focussing on extracting more detail from the 3C-3D micro-seismic survey through processing, and applying more rigorous acquisition, processing and modelling techniques to the GPR data. With continued improvements, the hope is to one day strip away the layers of time and successfully image the plazas and other monumental structures before the actual excavation, thereby creating efficiencies in terms of manpower, time and expense.

CONCLUSIONS

The GPR records provide interpretable images of the plaza, in which structural, stratigraphic and other features can be resolved.

A number of interesting features have been highlighted for possible excavation. One must be cognizant that anomalous features recorded on GPR images can be caused by numerous natural, man-made and acquisition/processing "artifacts". The failure to unearth artifacts must not deter one from continuing to make recommendations to the archaeologists.

More care must be taken with distance calibration of each line within a 3-D survey.

Gain and other input parameters must be carefully looked at and possibly changed during acquisition.

A comparison between one of the 3C-3D micro-seismic survey and GPR survey lines serves to validate the idea of combining these two geophysical tools to better image and resolve the near surface.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the support of the members of the CREWES Project, the dedicated team of archaeologists engaged with the Maax Na Archaeological Project namely Drs. Eleanor King of Howard University, Washington, D.C., and Leslie Shaw, and Claire Allum of Bowdoin College, Brunswick, Maine, and the permit holder for the overall Programme for Belize Archaeology Project, Dr. Fred Valdez, and the Belizean Institute of Archaeology.

REFERENCES

Aitken, J.A. and Stewart R.R., 2003, Ground Penetrating Radar (GPR) imaging of a carbonate surface in Belize, Central America, CREWES Research Report, **15**.
Conyers, L.B., and Goodman D., 1997, Ground penetrating radar- an introduction for archaeologists: 232 p.
Daniels, D.J., 2004, Ground Penetrating Radar 2nd edition: The Institution of Electrical Engineers, London, England, 726p.
Gaffney, C., and Gater, J., 2003, Revealing the Buried Past: Geophysics for Archaeologists: Trafalgar Square Books, 200p.
Hatton, L., Worthington, M.H., and Makin, J., 1988, Seismic Data Processing - Theory and Practice: Oxford University Press, Don Mills, Ontario, 177 p.
Kaprowski, N.A., and Stewart R.R., 3C-3D seismic micro-survey at a Maya plaza ruin in Belize, Central America: CSEG Recorder
King, E., 2004, Personal Communication, Howard University, Washington, D.C.
Reynolds, J.M., 1997, An introduction to applied and environmental geophysics: John Wiley & Sons, New York.
Sandmeier, R., Reflexw help notes, Sandmeier Software, http://www.sandmeier-geo.de
Sharer, R. J., 1994, The Ancient Maya: Stanford University Press, 892 p.
The Ma'ax Na Archaeology Project, 2001, http://www.neararchaeology.or/project.

TABLE 1. Field Observations at Maax Na. Radar velocity determination based on hyperbolic curve fitting for years 2002 through 2004.

Year	Measured Velocities (m/ns)	Depth of Penetration * (m)	Field Conditions
2002	0.072 - 0.106	1.8	wet
2003	0.122 - 0.140	3.4	dry
2004	0.058 - 0.084	1.8	wet
* based on a 50 ns record			

FIG. 1. Location of the Maya site of Ma'ax Na in Belize, Central America (The Ma'ax Na Archaeology Project, 2001).

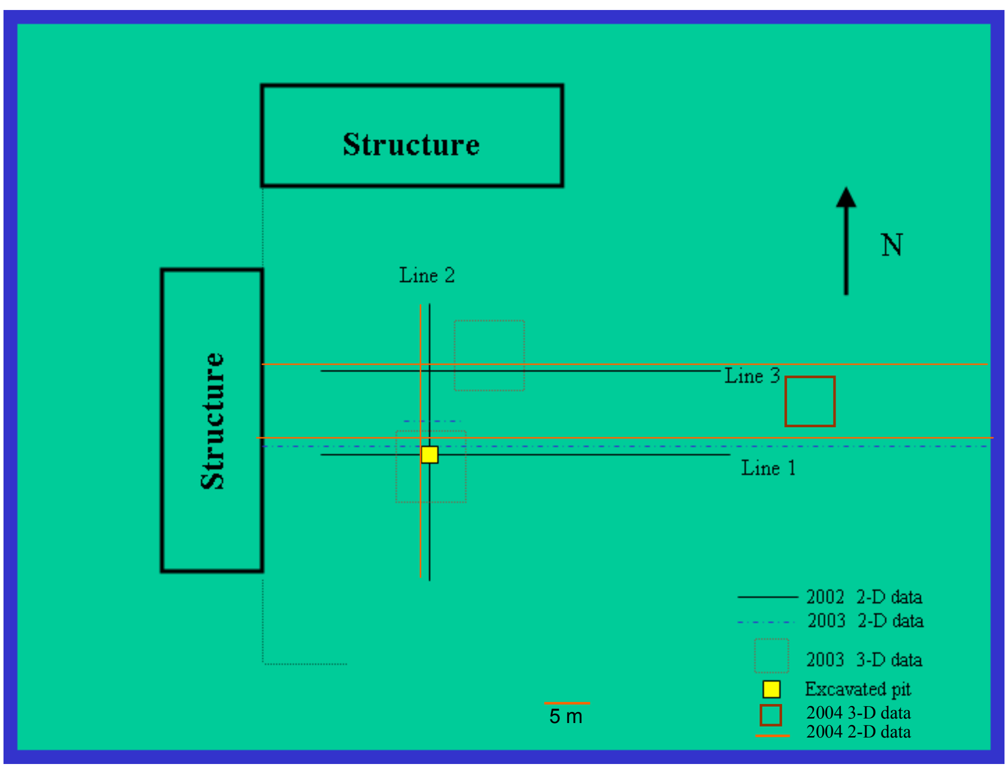

FIG. 2. Acquisition layout over the three last field seasons (2002-2004).

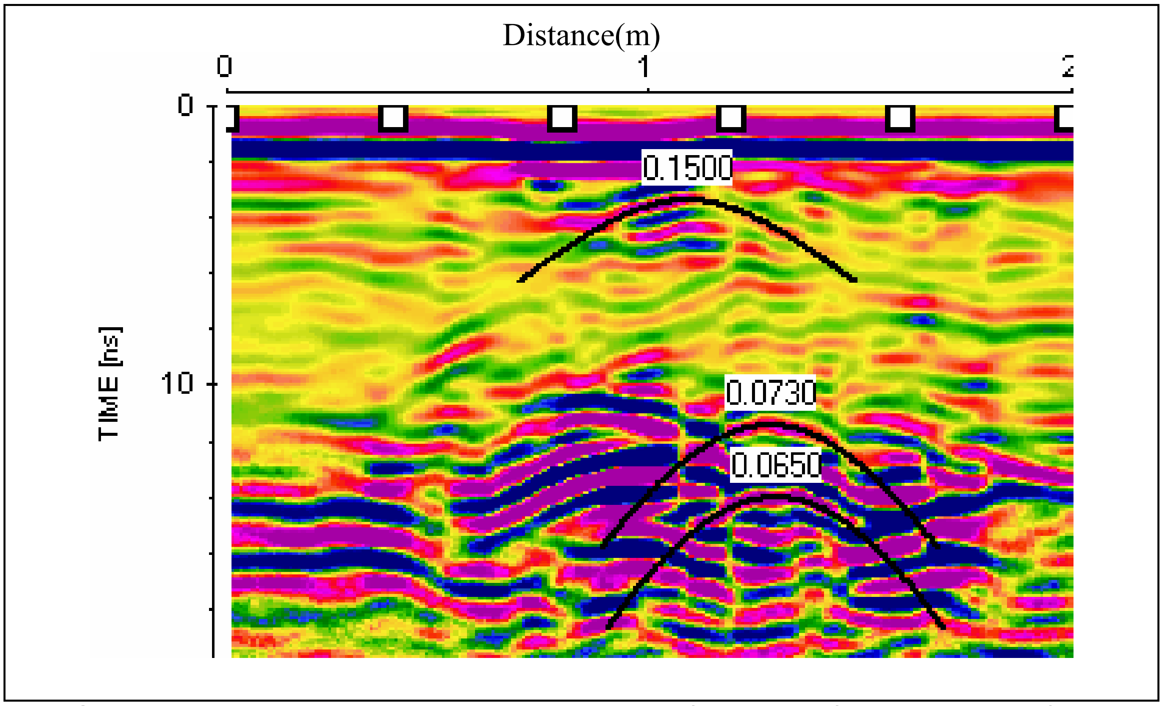

FIG. 3. Velocity determination using interactive curve fitting in the field and using Reflexw.

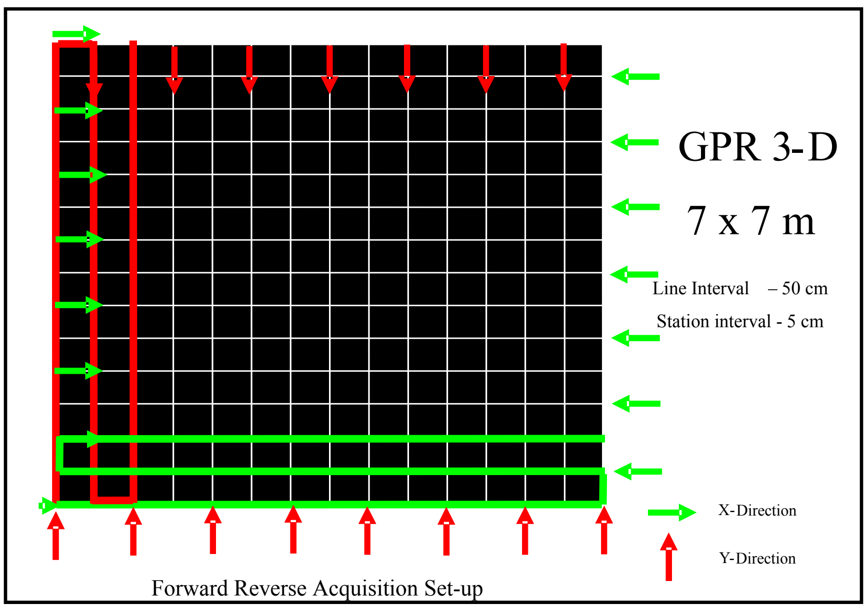

FIG. 4. Layout of 3-D grid with lines acquired in forward and reverse directions both in E-W and N-S orientations.

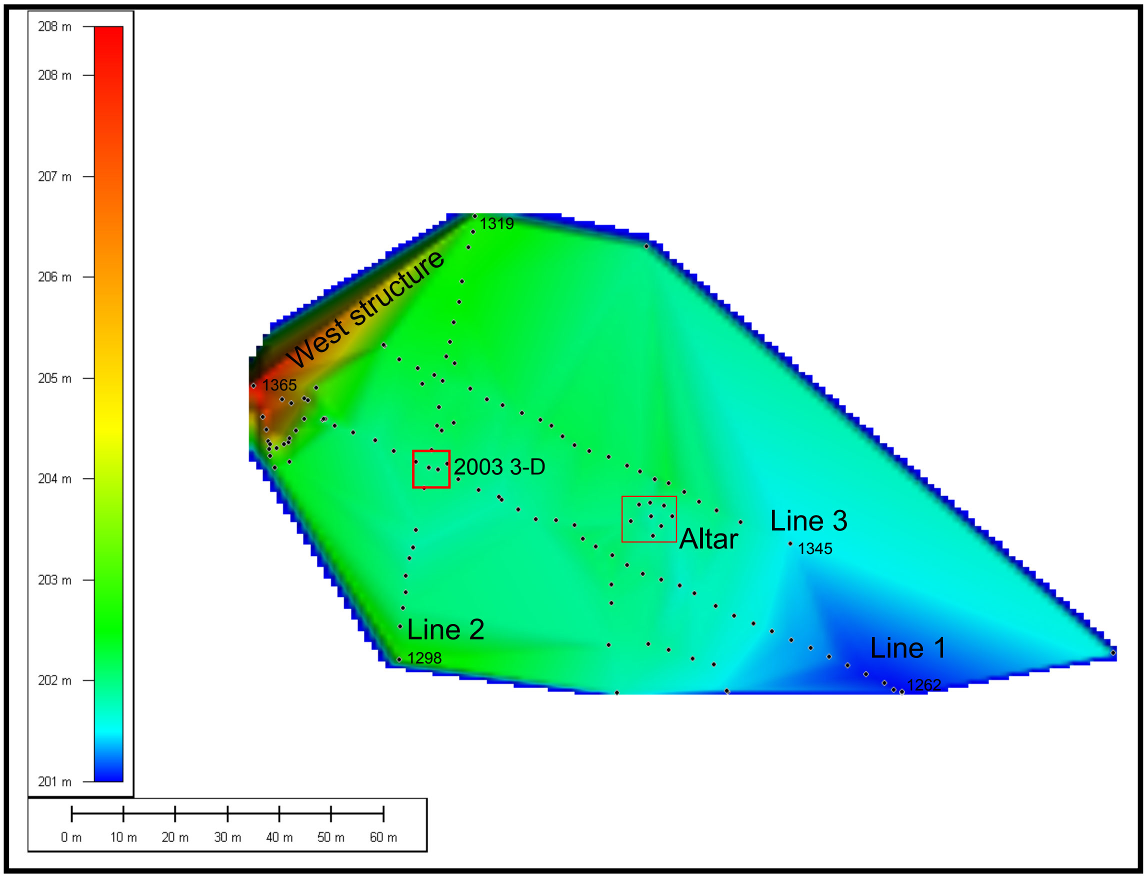

FIG. 5. Elevation and coordinate map for the plaza at Maax Na based on the Total Station survey.

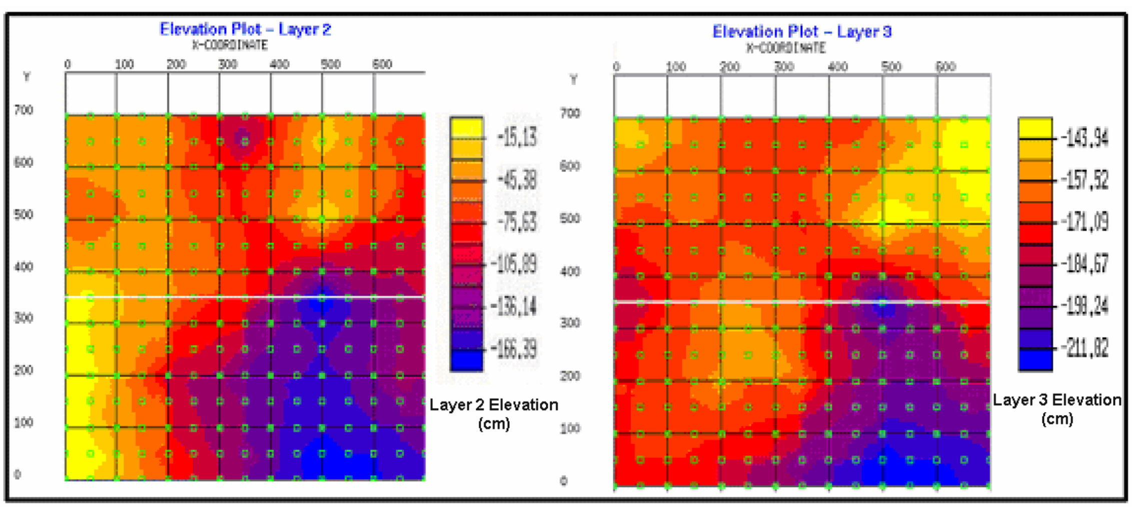

FIG. 6. GLI3D Elevation plots of layers two and three of the 3C-3D micro-seismic survey grid acquired in 2003.

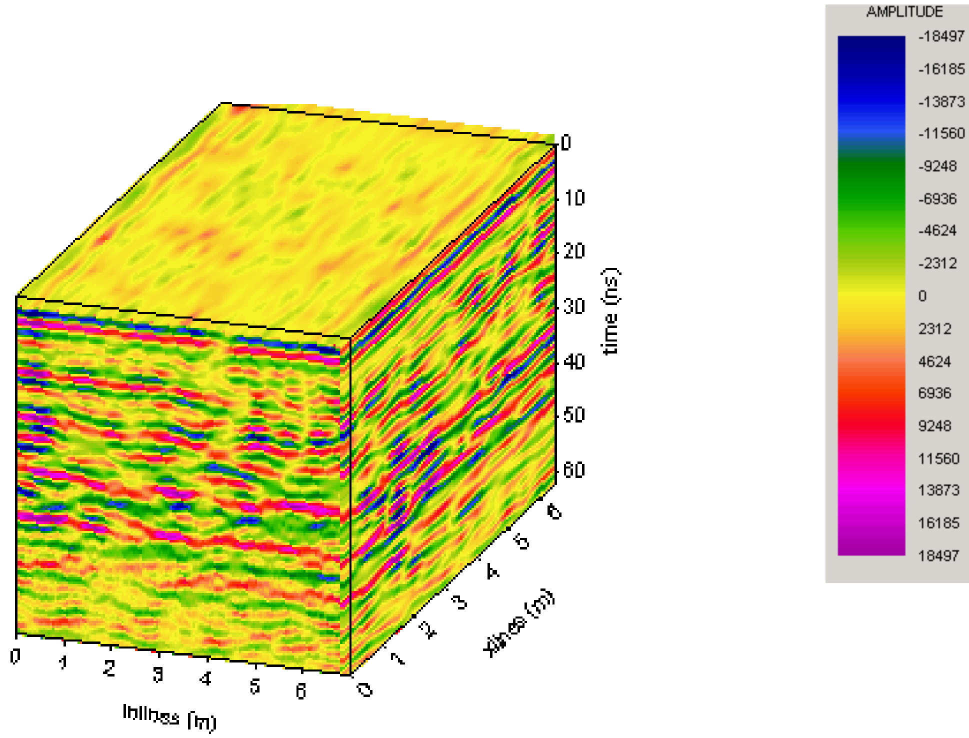

FIG. 7. 3-D cube of GPR data from the 2003 3-D shot over the excavated pit.

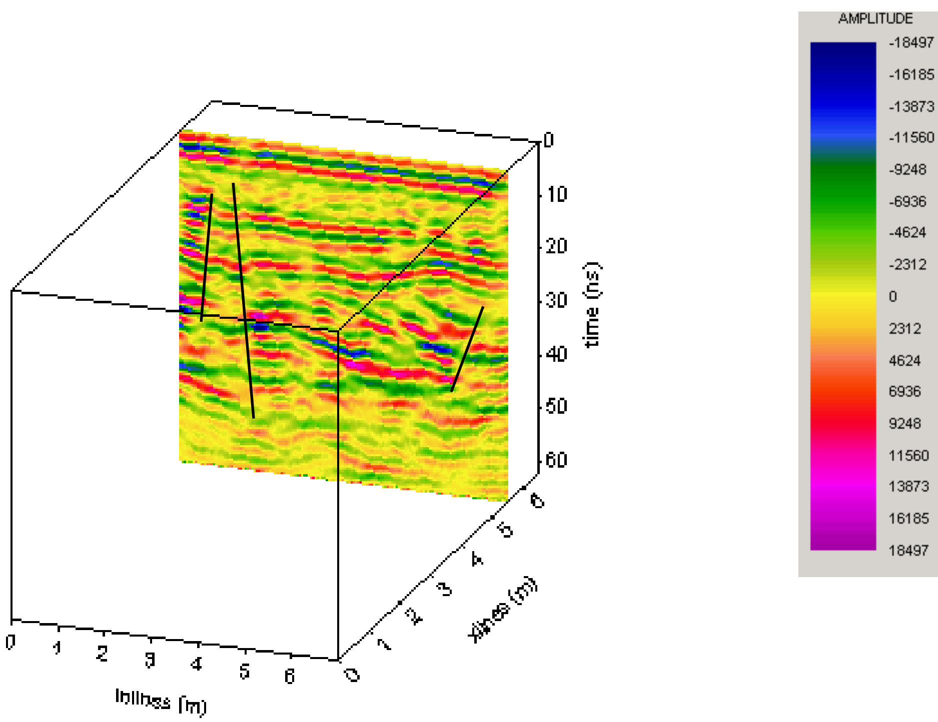

FIG. 8. Inline 3 from 2003 3-D GPR dataset with anomalies and highlighted discontinuities.

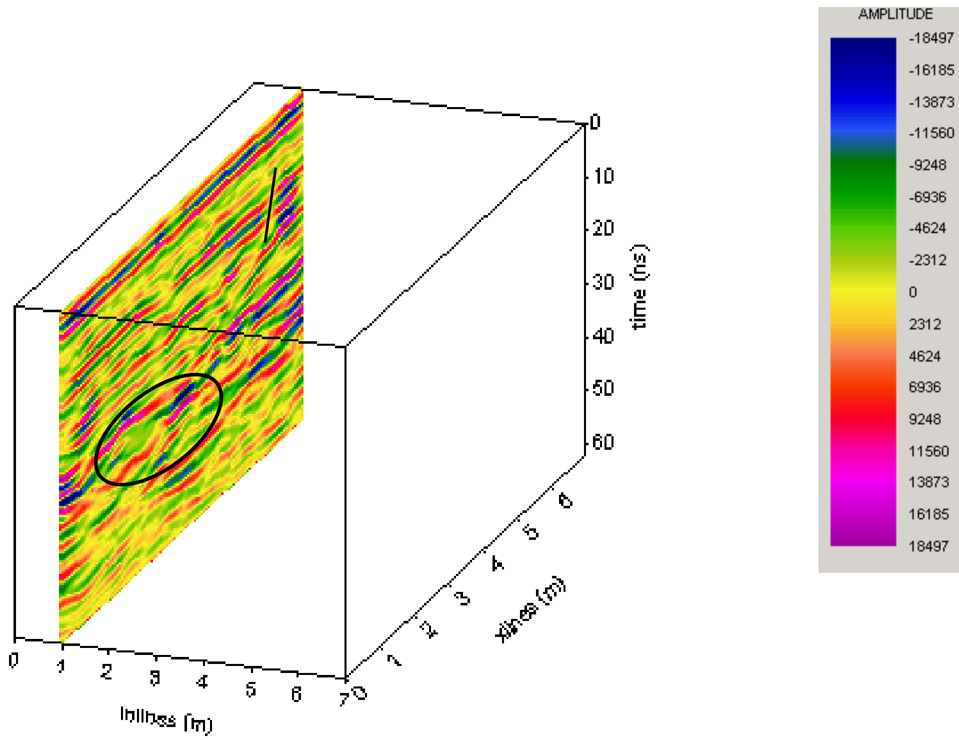

FIG. 9. Xline 3 from 3-D grid showing discontinuities and amplitude anomalies.

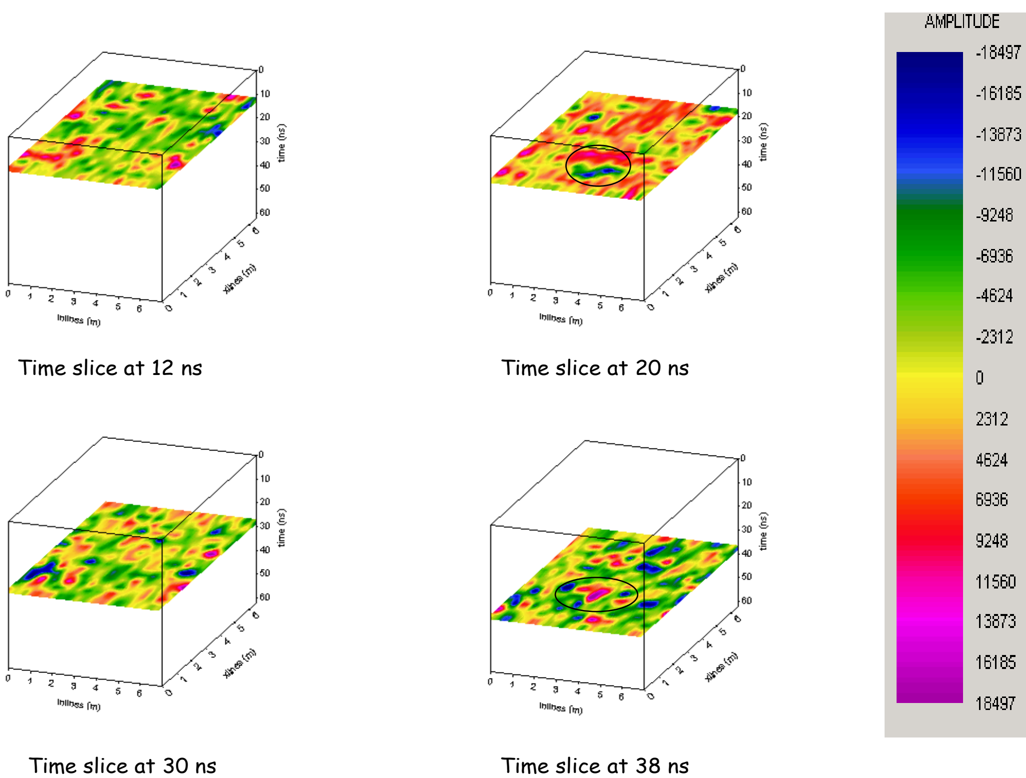

FIG. 10. Time slices from the GPR 3-D volume. Anomalies highlighted in black.

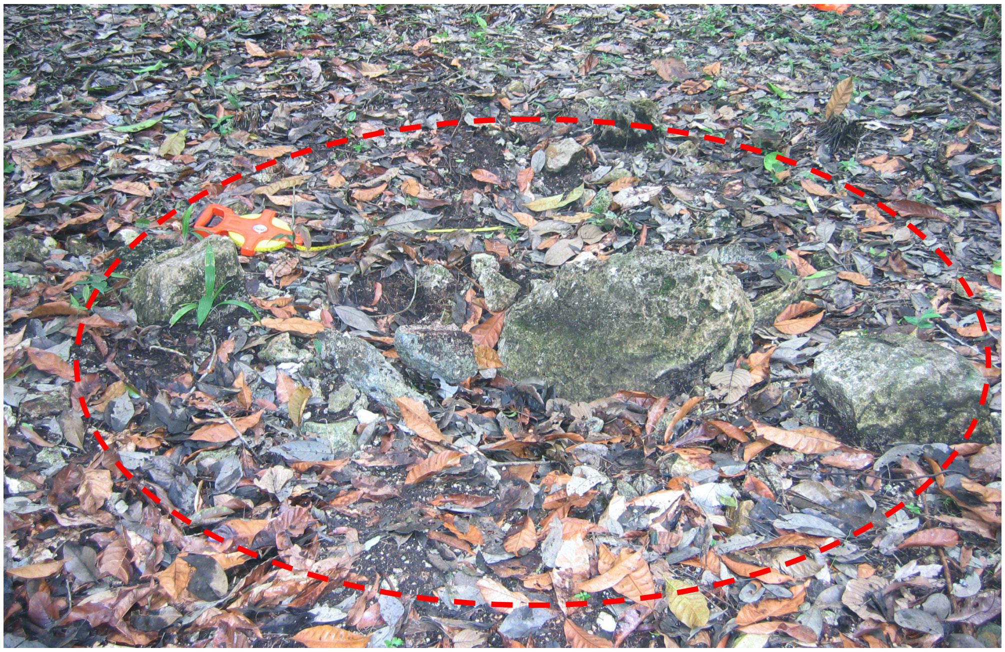

FIG. 11. Placement of the stones within a depression on the surface of the plaza marking an "altar" or ceremonial pit.

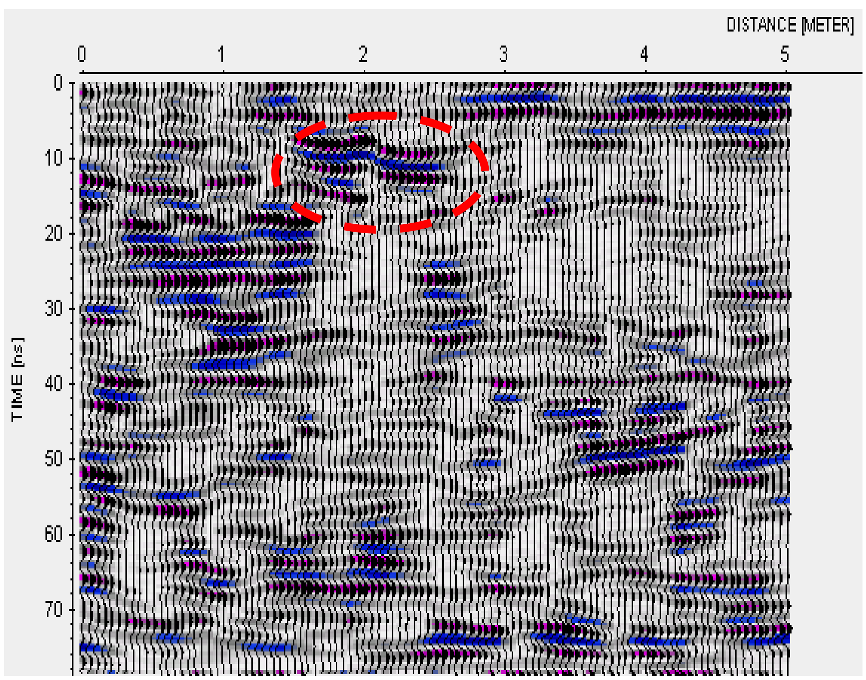

FIG. 12. Wiggle trace display of Grid 2 Line 4 showing structural anomaly in vicinity of "altar".

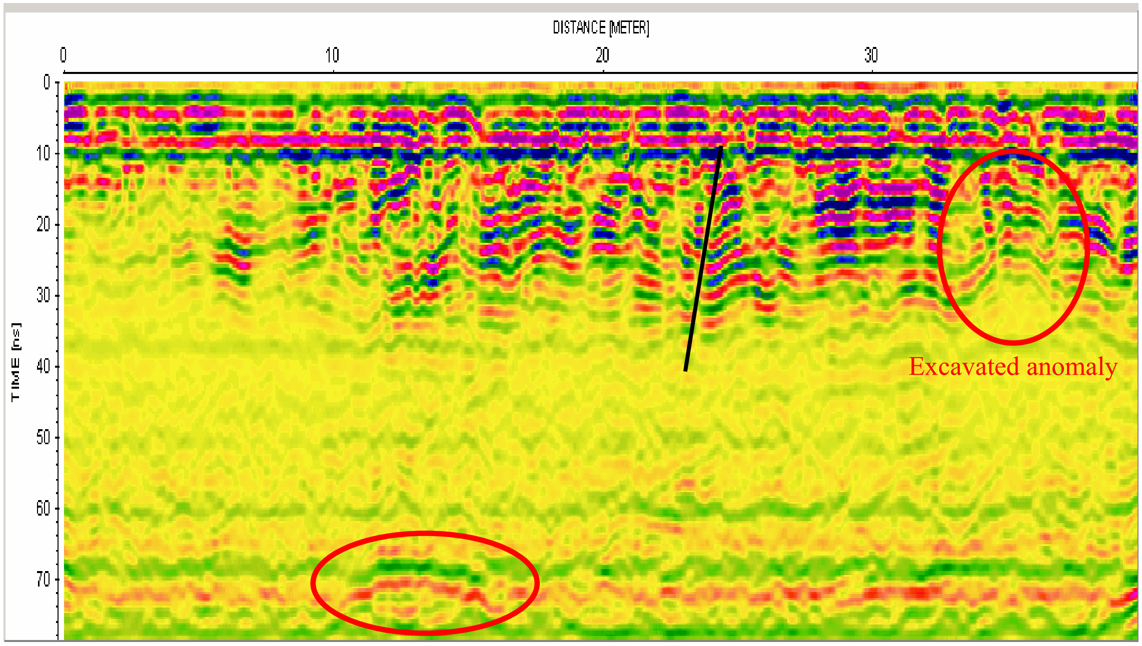

FIG. 13. Anomalies present on Project 6 Line 2. Upper anomaly was excavated by the archaeologists during the field school in 2004.

FIG. 14. Dr. Rob Stewart is pointing out the surface location of above noted anomaly in plaza to be excavated by archaeologists.

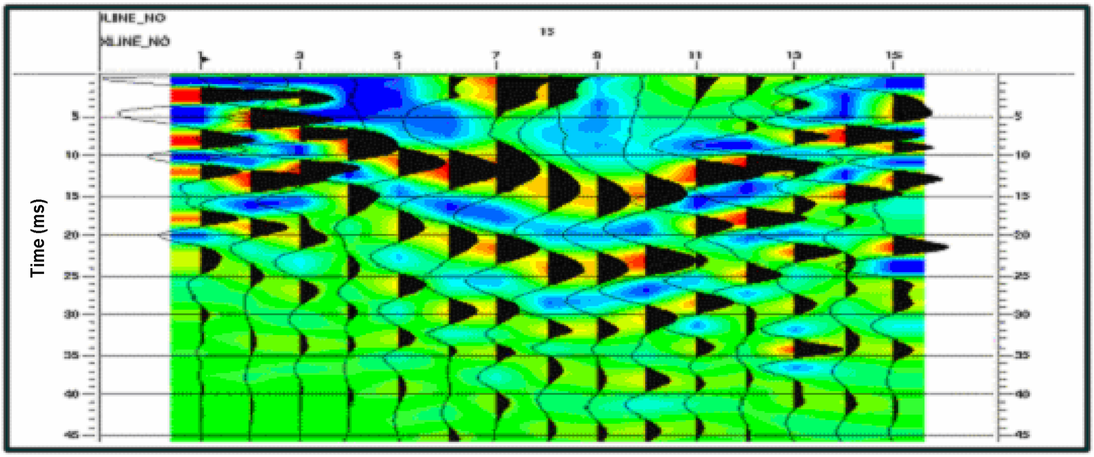

FIG. 15. Iline 15 stacked data, displaying variable density with trace overlay from 3C-3D micro-seismic survey.

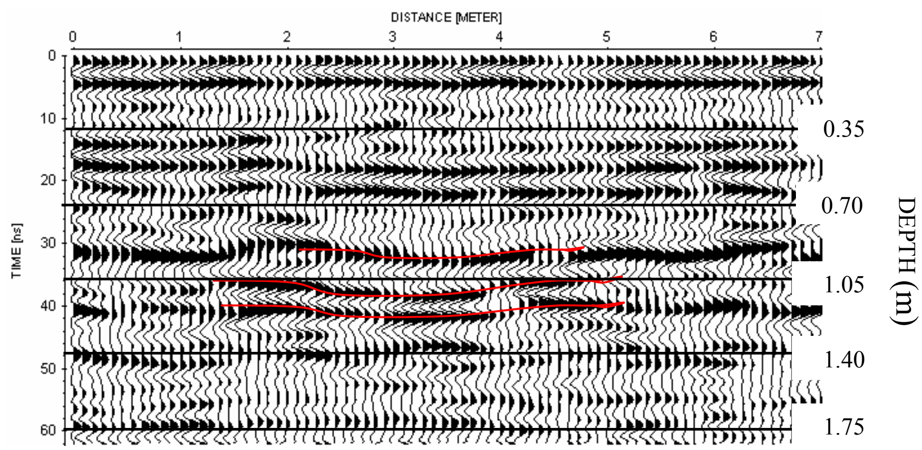

FIG. 16. Wiggle trace display of Inline 15 of the GPR survey. Note the similarity in structure between both lines.

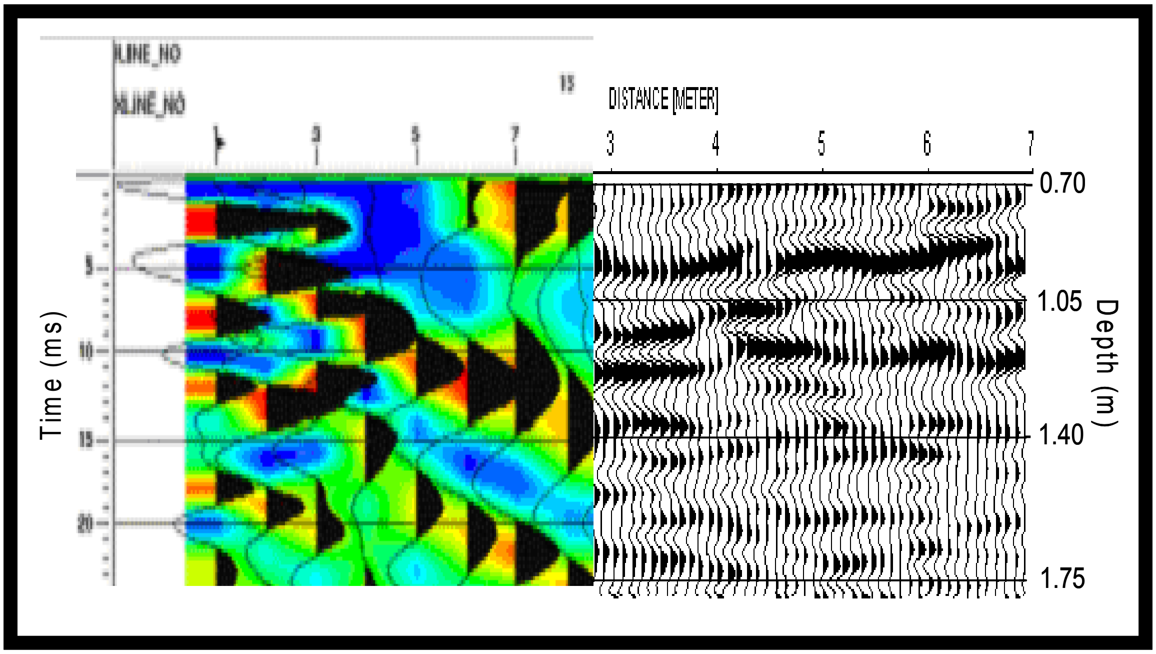

FIG. 17. Comparison of the micro-seismic (left) and GPR (right) surveys at depths 0.7 - 1.75 m.