Shallow imaging using ground-penetrating radar (GPR) data in a carbonate environment: Belize, Central America

Monica Moldoveanu, Robert R. Stewart, and Julie A. Aitken

ABSTRACT

During the summer of 2002, seismic and ground-penetrating radar (GPR) surveys were successfully conducted in northwestern Belize, Central America. The 2002 field season was initiated to explore more of the shallow section and two archaeological sites (Ma'ax Na site and Chan Chich). This paper describes the GPR surveys carried over the Ma'ax Na structures and analyzes the data acquired in this area. Thirty GPR lines were acquired during the 2002 field season, using Sensors & Software Inc.'s Noggin® system with a 250-MHz antenna. Most areas had loose soils and forest debris overlying rubble or competent carbonates.

Preliminary analysis of the data gives velocities from 0.072 m/ns (for a depth of 1 m) to 0.106 m/ns (for a depth of 0.7 m).

Different types of gain (true amplitude recovery, automatic gain control) and filters were applied on the data to enhance the deeper reflectors. Using the velocity values determined during the acquisition, we estimate that the maximum depth from which we have reflections is between 1 and 3 metres. Good comparison between two reversed lines indicates that the method provides repeatable results. A project conducted over a few caves provided good imaging of these structures and indicated the effective applicability of the method in a carbonate environment. The method was successful in interpreting the locations of the caves.

INTRODUCTION AND GEOLOGY

Belize is part of the North American plate. Geomorphologically and geologically the country of Belize can be divided into Corozal basin in the north and Belize basin in the south separated by the Maya mountains (GeoPO, 1995). Chan Chich and Ma'ax Na were built on the Eocene-age limestone that comprises the Yucatan Peninsula. The area of study is located in the Corozal basin, which is a continuation of the Yucatan Platform, and is stratigraphically associated with the north Peten basin in Guatemala. The Corozal basin is primarily composed of a thick sequence of non-clastic sediments deposited during a 50-million-year history of tectonic uplift and erosion, faulting, and marine transgressions. It is characterized by predominantly carbonate facies, specifically limestones and dolomites. Sediments in the Belize basin are over 7900 m thick, characterized predominantly by clastics. The Maya mountains form the highland part of this country with metamorphosed sediments and igneous intrusives. A generalized surface geology of the Yucatan peninsula is illustrated in Figure 1.

Geomorphically, the study area is a central pediplain with gentle topography and linear-trending lakes of Karstic origin. Drainage is fracture-controlled in a north or north-northeast direction. The terrain is typically covered by Lower to Upper Tertiary carbonates and marls of the Barton Creek formation (Figure 2).

The Ma'ax Na archaeological site is located in the Rio Bravo Conservation and Management Area (RBCMA) and the Chan Chich site is situated to the south (Figure 3). Situated just east of the Guatemalan border, the privately owned RBCMA contains 260,000 acres, and represents about four percent of Belize's landmass.

Discovered in 1995 by researchers from the University of Texas at Austin (Eaton, 2002), Ma'ax Na ("Monkey House" in Mayan) is large, approaching the size of Tikal in neighbouring Guatemala, and it contains 20 to 25 intact structures. Excavation of the site began in 1997. One of the purposes of the non-invasive seismic and GPR data acquisition is to improve the archaeological return from excavation sites at Ma'ax Na by shallow imaging prior to digging.

During May and June 2002, seven different ground-penetrating radar projects (each of them containing between 2 and 7 lines) were acquired over the Ma'ax Na and Chan Chich sites. Two seismic lines were acquired over the Uba He pyramid at different elevations.

In this paper, we will discuss the GPR surveys acquired on the Plaza and over the caves situated approximately 1 km from the Plaza (Figure 4). On the Upper Plaza three GPR lines were acquired: two parallel lines (direction of the survey was SE-NW) and a crossline (SW-NE). During the acquisition, velocity values were determined by fitting a hyperbola to a diffraction event: 0.072 m/ns (at 1 metre depth), 0.106 m/ns (at 0.7 m depth) for line 1; 0.082 m/ns (at 0.8 m depth) for line 2; and 0.072 m/ns (at 0.87 m depth), 0.074 m/ns (at 0.7 m depth), 0.082 m/ns (at 0.6 m depth), 0.1 m/ns (at 0.4 m depth). The objective was to analyze this data, to process it in a way that will lead to an optimum enhancement of the deeper reflectors and to interpret the lines. To process the data we used Landmark's ProMAX processing software. We tested different processing flows and the results are discussed in this paper.

GPR EQUIPMENT AND SURVEY

The measurements were conducted between May and June 2002. We used Sensors & Software Inc.'s Noggin® 250 and Smart Cart® system (Figure 5). This unit has a 250-MHz antenna (with 125 to 375-MHz bandwidth). The radar source is triggered every 5 cm (by a roller turned by one of the wheels) and the separation between the antenna is 27.94 cm. During the five days, 30 GPR lines were acquired. Those lines were grouped in 7 different projects, based on the area were the lines were acquired. Project 0 contains 4 lines acquired on the Uba He pyramid. Project 2 has 3 lines and it was acquired on the Plaza at the Ma'ax Na site. Project 3 represents project 2 reversed. Project 4 was also acquired on the plaza and it has two lines, shot to establish position of a test pit. Project 5, with 4 lines, was acquired over few caves located approximately 1 km from the Plaza. We focus on the Plaza, Test, and Caves projects for this paper (projects 2, 4, and 5).

DATA ANALYSIS AND PROCESSING

To display, analyze, and process the data we used Landmark's ProMAX processing software. Prior to the import into ProMAX, the data have been converted from the radar format to SEGY format. This involved converting the 2-byte integer data into 4 byte IBM data. From the headers of the data we were able to determine the sample rate for recorded data (0.4 ns), number of samples per trace (196 for project 2 and 4, and 508 for project 5), and the trace length (77.4 ns and 203 ns, respectively). This information, along with the velocity values determined during acquisition, was used to determine processing parameters (length of the AGC operator, dimensions of the spatial median filter) and the maximum depth of investigation. The processing flow used for analyzing the GPR data is shown in Table 1.

We display the data in ms although the actual values are in ns.

Note that radar velocity generally decreases with depth. Sensor & Software (1999) gives velocities values of 0.3 m/ns for air, 0.12 m/ns for limestone, 0.1 for soil, and 0.065 for wet soil. The velocities determined during acquisition (by fitting a hyperbola to a diffraction event) are between the values of 0.106 m/ns and 0.072 m/ns.

Plaza Project

This project, as the name indicates, was acquired on the Plaza at Ma'ax Na site. Plaza EW line is 49.45 metres long, has 990 traces, and the data is shifted 15 ms. The direction of the survey is SE-NW. Analysis of the data indicated that we have negative amplitude values where there is no signal. To correct this we applied a trace DC removal in the processing flow. Prior to this, data was bulk-shifted 15 ns. The results can be seen in Figure 6. In order to enhance the deeper reflectors we applied an Automatic Gain Control (AGC) in the flow. This proved useful for the enhancement of the deeper reflectors, but the result was far from the one expected.

AGC is not usually recommended because alters the amplitude information. To avoid this problem, a 2D spatial median filter was used. This filter sorts the samples and passes on the median sample of the sorted array. Initially, the length of this filter was 3 samples by 17 traces, but we found that a filter with the length of 9 samples by 17 traces gives a better image (Figure 7). The application mode was subtraction with the purpose of eliminating the coherent energy represented by the air and ground waves and enhancing the deeper reflectors energy. The application of True Amplitude Recovery in the processing flow had also a positive role in the enhancement of deeper reflectors.

In Figure 7, we also see that below 30 ns we do not have any information. Using the velocity value at 1 m depth (0.072 m/ns) and this time value, we determined that the maximum depth of investigation is ~1 metre.

Test Project

This project consists of two short lines (18.35 and 17.85 m respectively) also acquired on the plaza. Line 1 is line 0 reversed. They were shot to determine the position of a test pit that was used to collect information about the lithology. These lines correlate well, which proves the repeatability of the GPR method (Figures 8 and 9).

Figure 10 displays these two lines together for the purpose of comparison. Similar or identical structures can be identified on both lines. This is a good indication of the fact that the GPR method is a repeatable method in that, by acquiring a different survey over the same area, we obtain similar sections.

Caves Project

A similar analysis was performed for the caves project. This project was shot over caves at Ma'ax Na site and a plan view of the NS and EW lines, with the location of the caves, is shown in Figure 11. These caves can be seen on the preliminary processed section (Figures 12 and 13). The lack of signal on the section is an indication of the presence of the caves. Using the velocity value determined during acquisition (0.08 m/ns) and the time to which we can see reflections (~ 70 ns) we determined that the maximum depth of investigation for this project is ~ 3 metres. Sections correlate well with the field notes.

The caves can be also identified on the crossline (Figure 14). Surveys of the area on top of the caves indicates a substantial radar reflection anomaly located at a depth between 2 and 3 metres. We interpreted the top of one of the caves at 45 ns two-way time. This corresponds to a 2 metres depth and correlates with the field notes.

RESULTS AND CONCLUSIONS

Preliminary analysis and processing of three GPR surveys acquired over the Ma'ax Na site provides a good image of the near-surface.

We obtained similar images for two reversed lines acquired over the same structure at the Ma'ax Na site. Comparison of the two reversed lines demonstrates the "repeatability" of the method.

We were able to determine that the maximum depth of investigation for these surveys is between 1 (Plaza lines) and 3 metres (caves lines). We have information from a greater depth for the cave area, which indicates the effective applicability of the method for investigating subsurface structures in carbonate environments, with reflections obtained from voids within the caves system.

We interpreted the caves on the GPR sections and the sections correlate with the field notes. This indicates the reliability of the GPR method for high-resolution near-surface imaging.

ACKNOWLEDGEMENTS

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Table 1. ProMAX processing flow for the GPR lines

SEG-Y Input

Header Statics

Trace DC Removal

Automatic Gain Control/True Amplitude Recovery

Median Filter (and subtraction)

Deconvolution

Migration

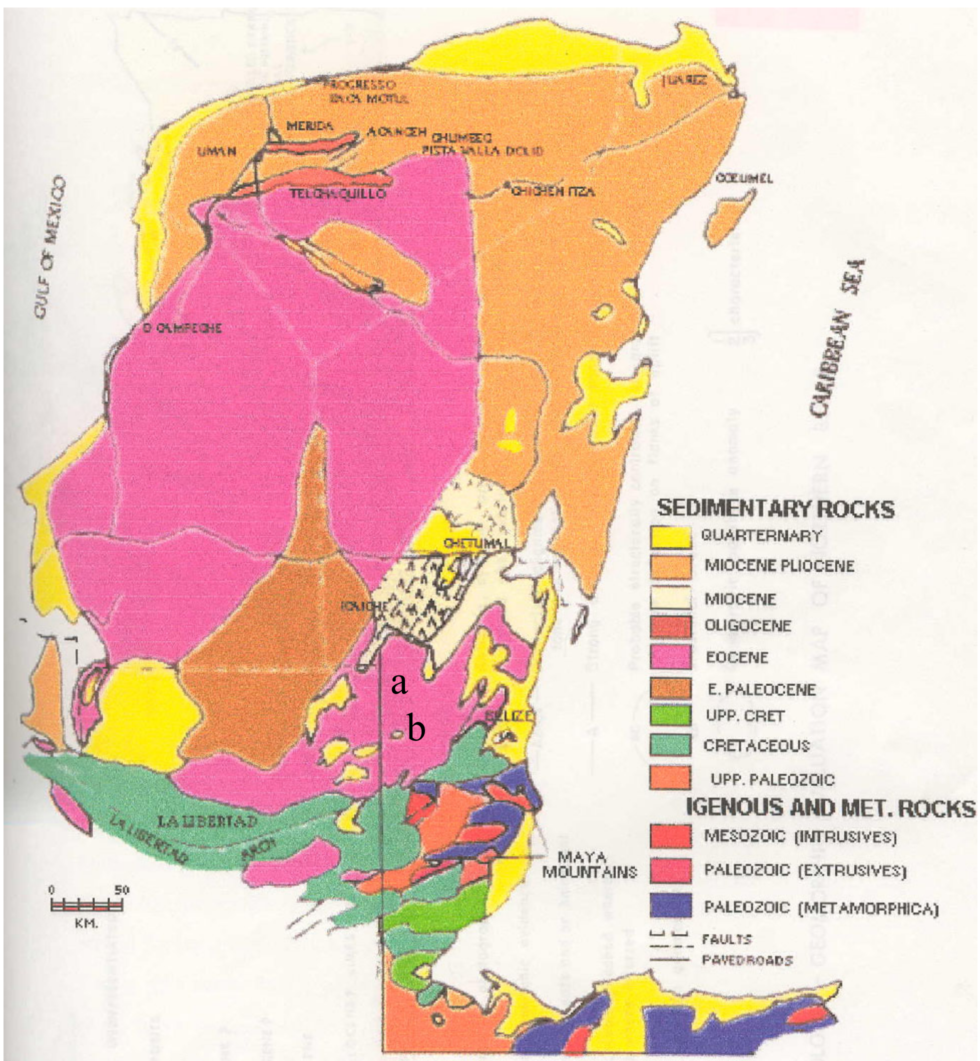

FIG. 1: Generalized surface geology of the Yucatan Peninsula including principal structural features (GeoPO, 1995). Ma'ax Na (a) and Chan Chich (b) sites are marked on this map.

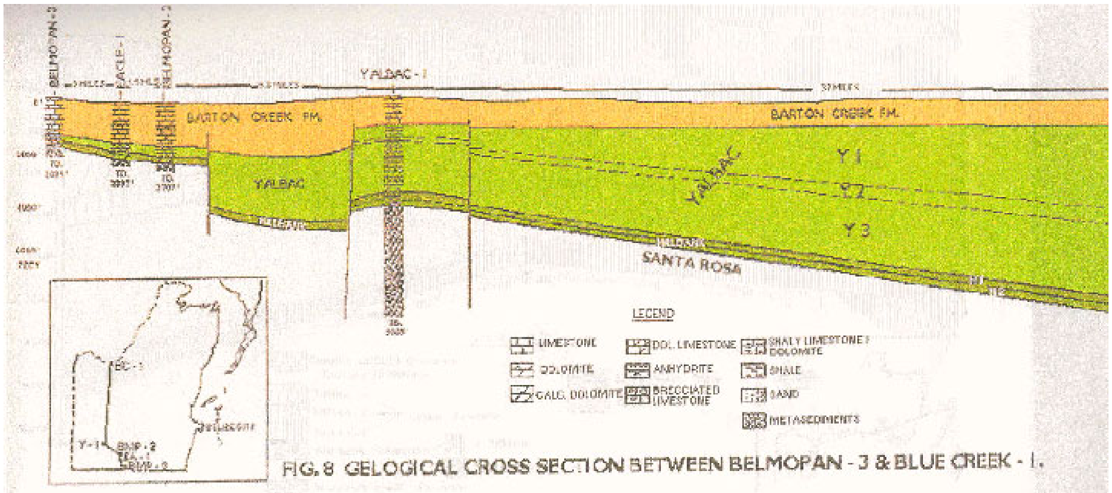

FIG. 2: Geological cross-section between Belmopan and Blue Creek (GeoPO, 1995).

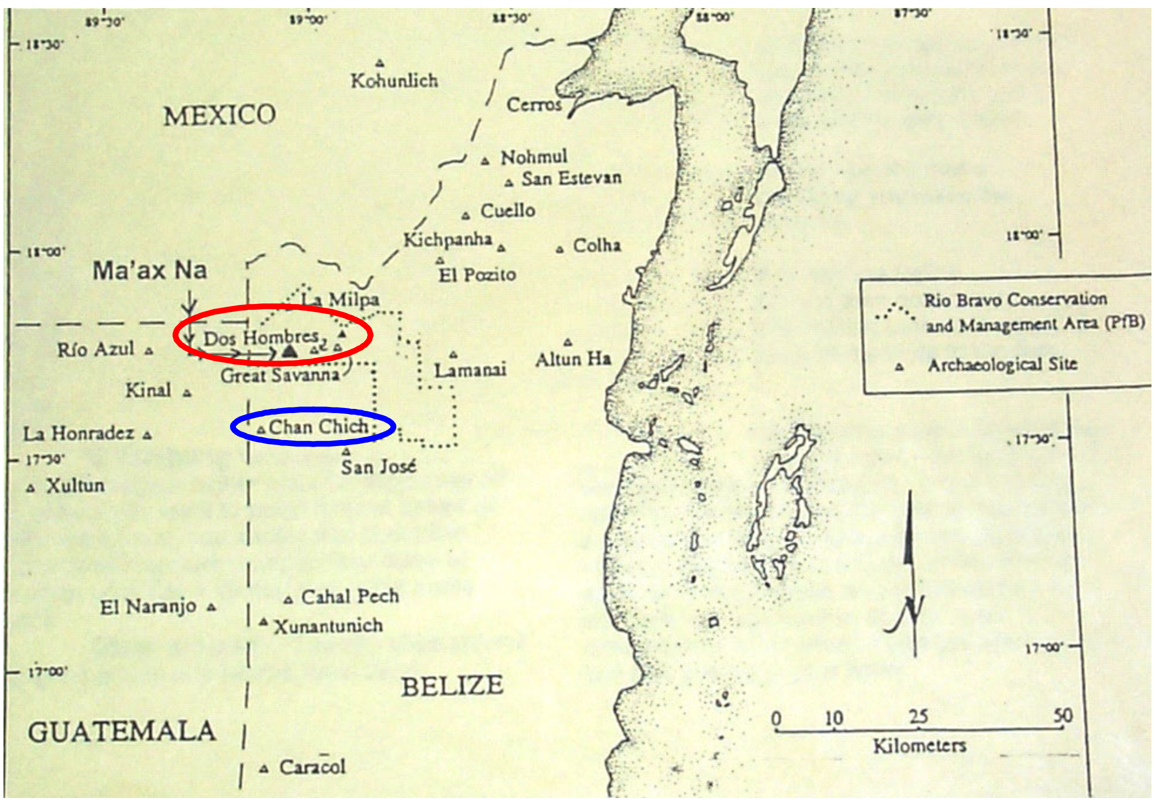

FIG. 3: Map of Belize, the Rio Bravo Conservation Area (with the Ma'ax Na site) and the Chan Chich site.

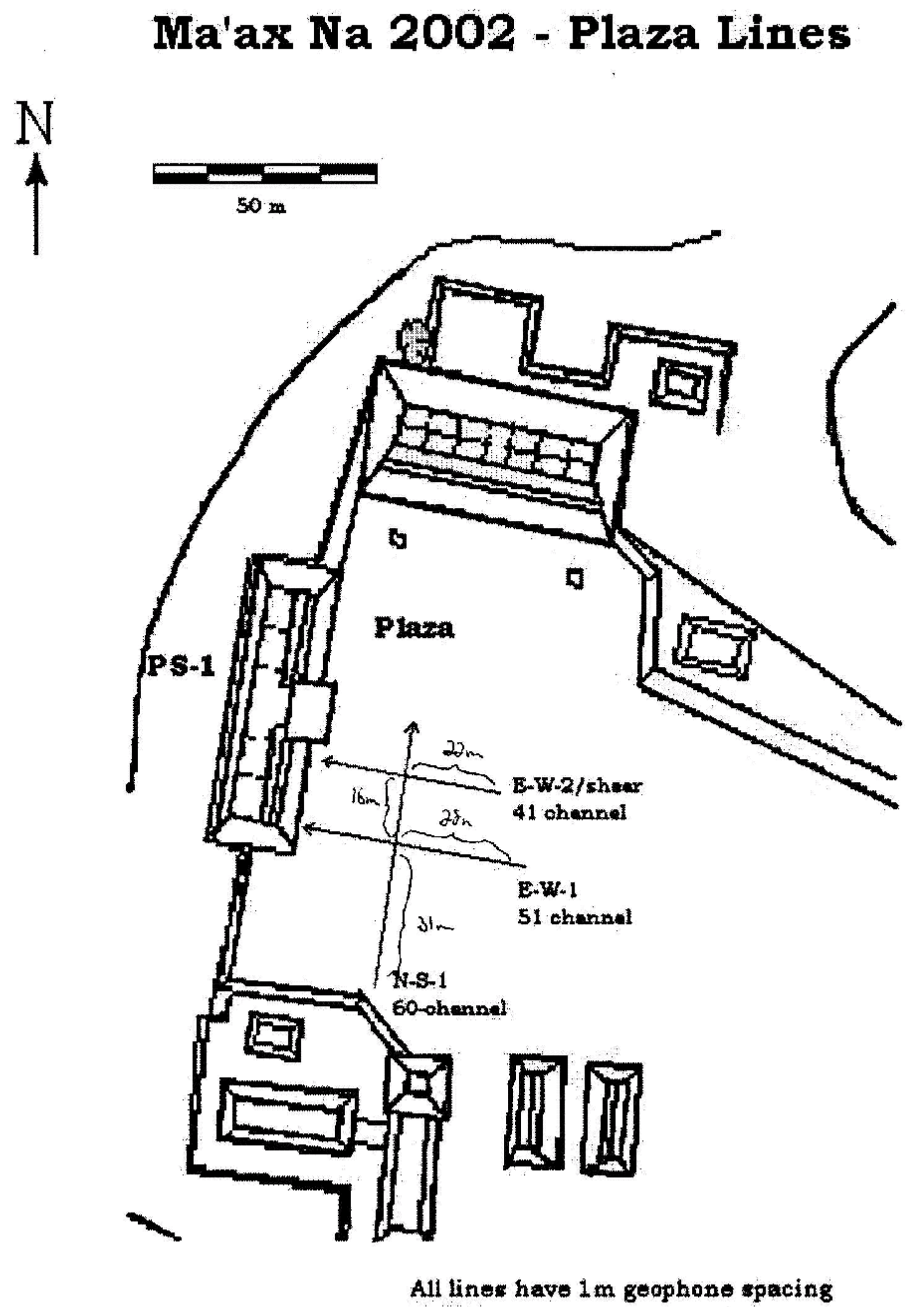

FIG. 4: Ma'ax Na Plaza lines. These lines represent Plaza project.

FIG. 5: Sensors & Software's Noggin® and Smart Cart® system at the Ma'ax Na site**.**

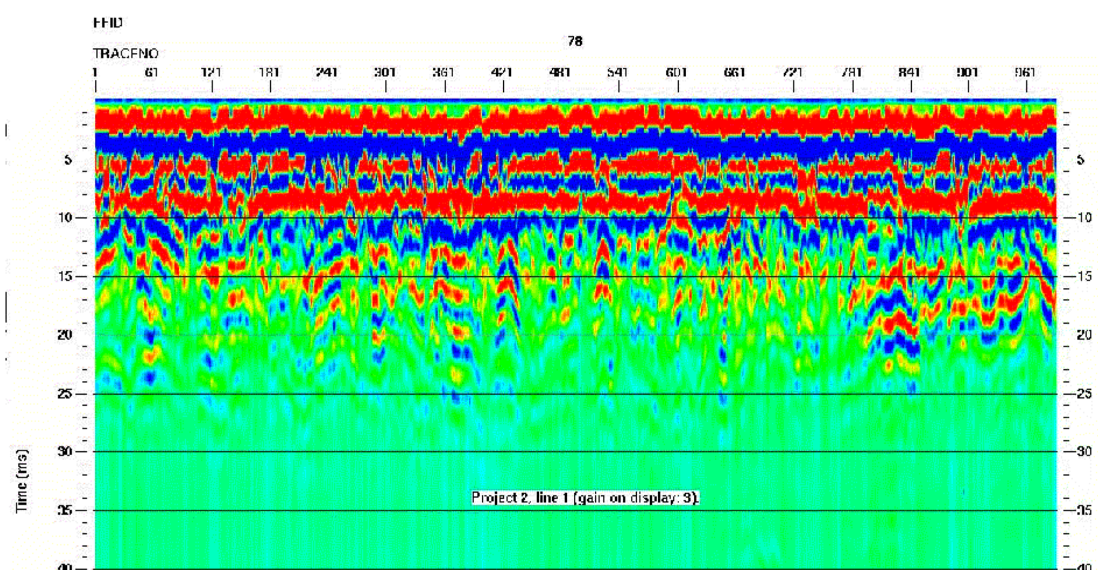

FIG. 6: Plaza project, EW line. This is a 49.45-m-long line acquired on the Plaza. Direction of the survey is SE-NW and traces were acquired every 5 cm. Data is bulk-shifted with 15 ns and gained with an AGC operator.

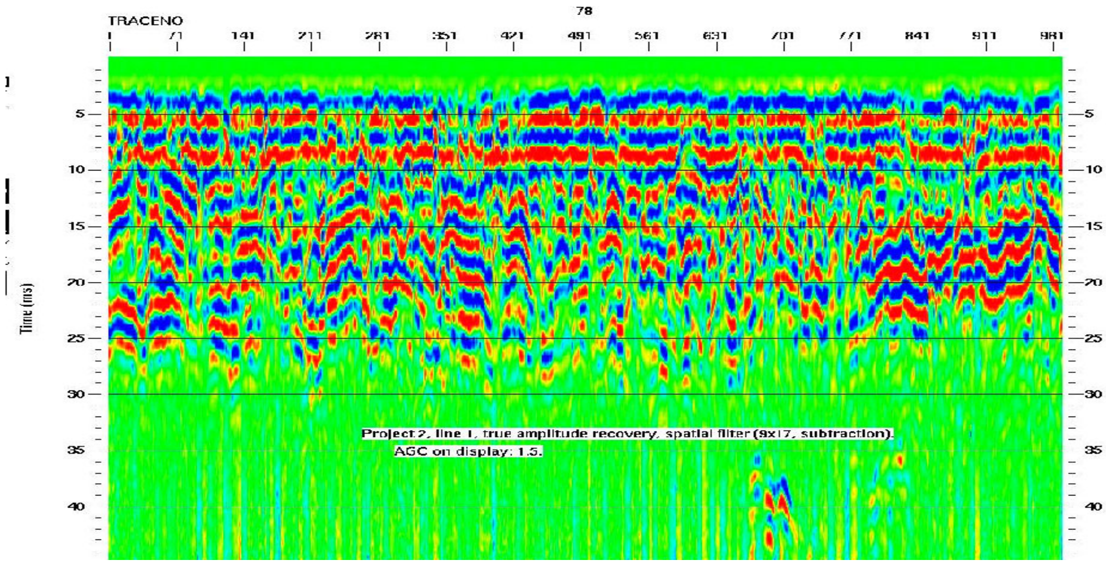

FIG. 7: Plaza project, EW line, processed section. The data is bulk-shifted with 15 ns and true amplitude recovery is applied. A 2D median filter (9x17), subtraction mode, is applied.

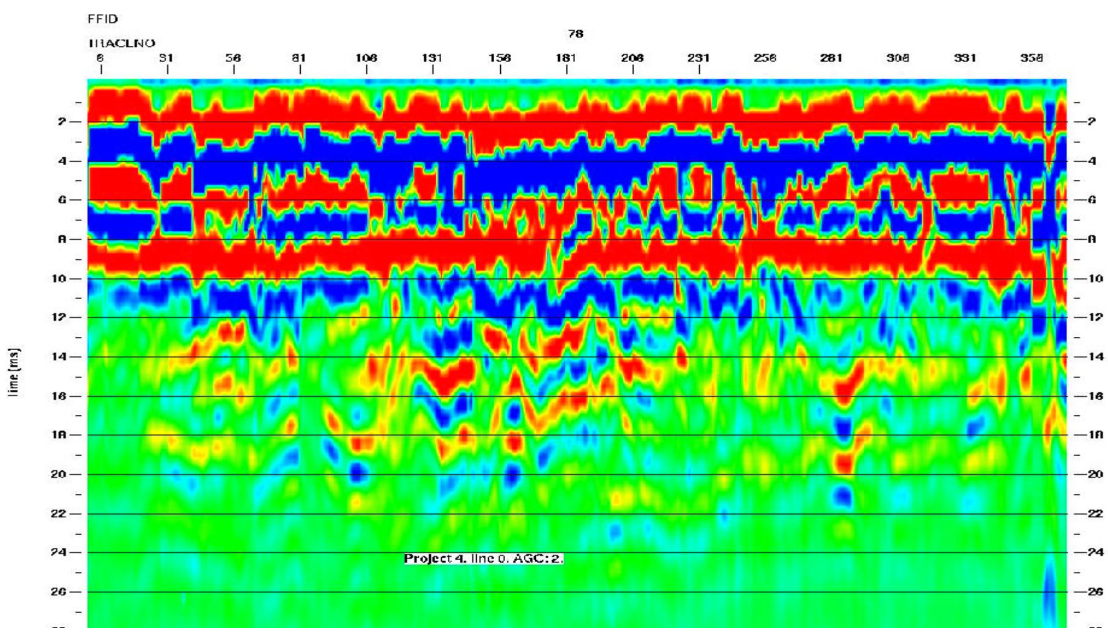

FIG. 8: Test project (project 4, line 0). This is an 18.35-m-long line acquired on the plaza. Data was bulk-shifted 15 ns.

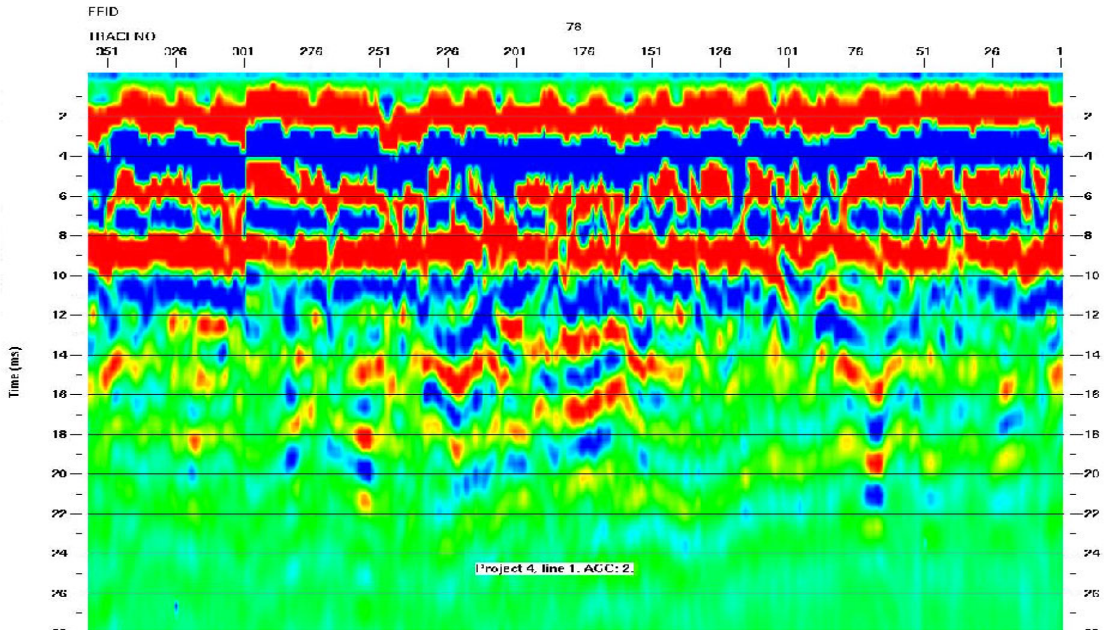

FIG. 9: Test project, line 1 (line 0 reversed). This is a 17.85-m-long line acquired on the plaza. Data was bulk-shifted 15 ns. We can notice the similarities between this line and line 0 (previous figure).

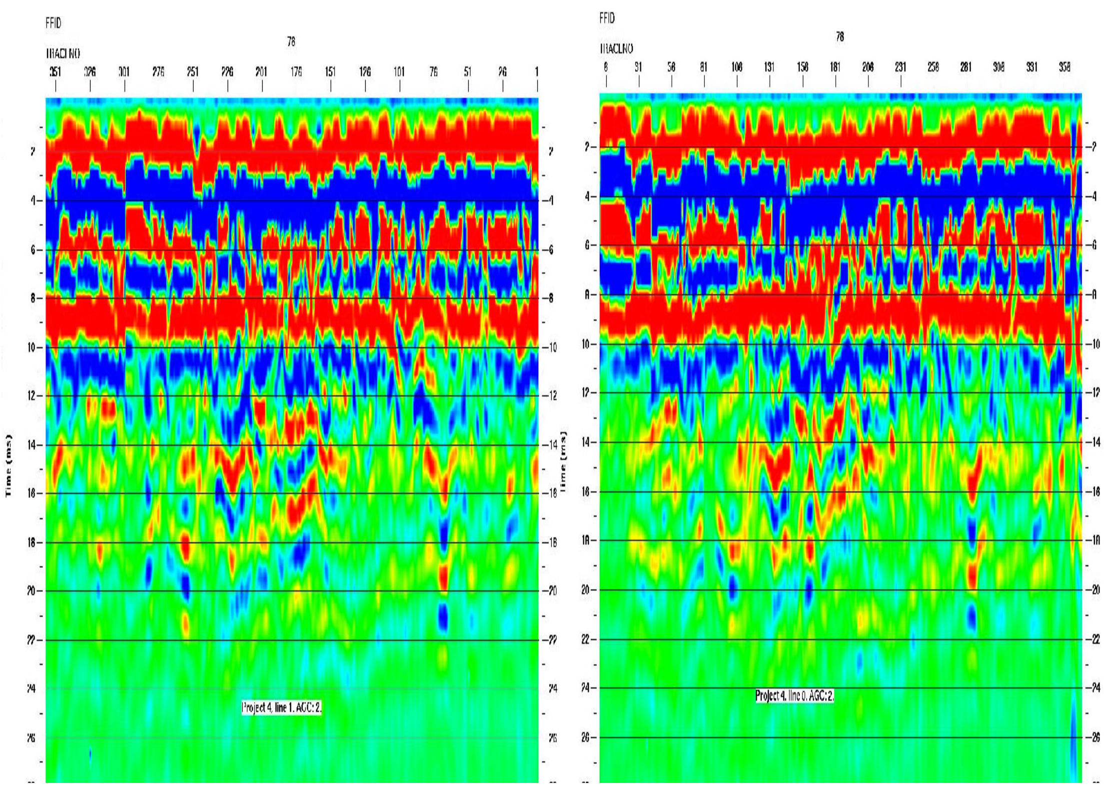

FIG. 10: Project 4, line 0 (left) and line 1 (right) are shown here to demonstrate the repeatability of the method. Although these are two different lines, we can notice the similarities of the plots.

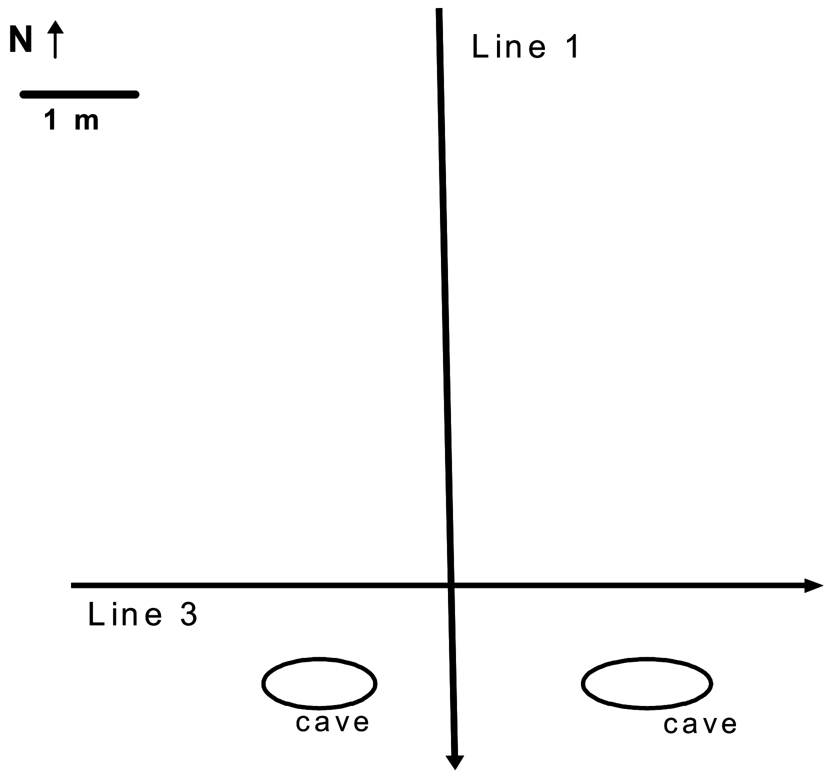

FIG. 11: Plan view of the Caves project with the possible location of the caves.

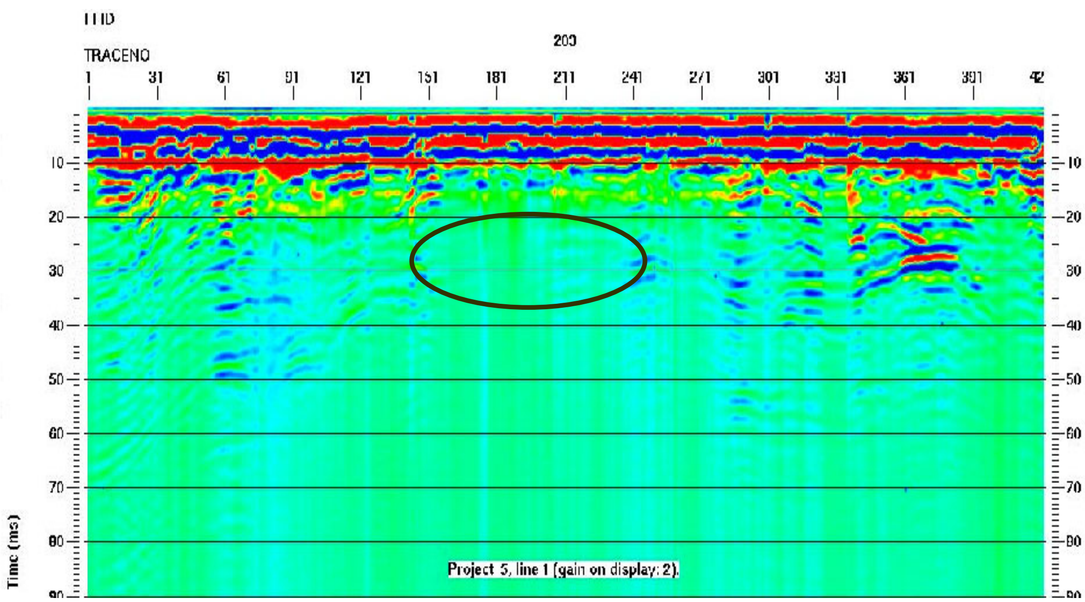

FIG. 12: Caves project, NS line. This line was acquired over the caves at Ma'ax Na site. Data was bulk-shifted 40 ns. The highlighted area indicates a possible location of the cave.

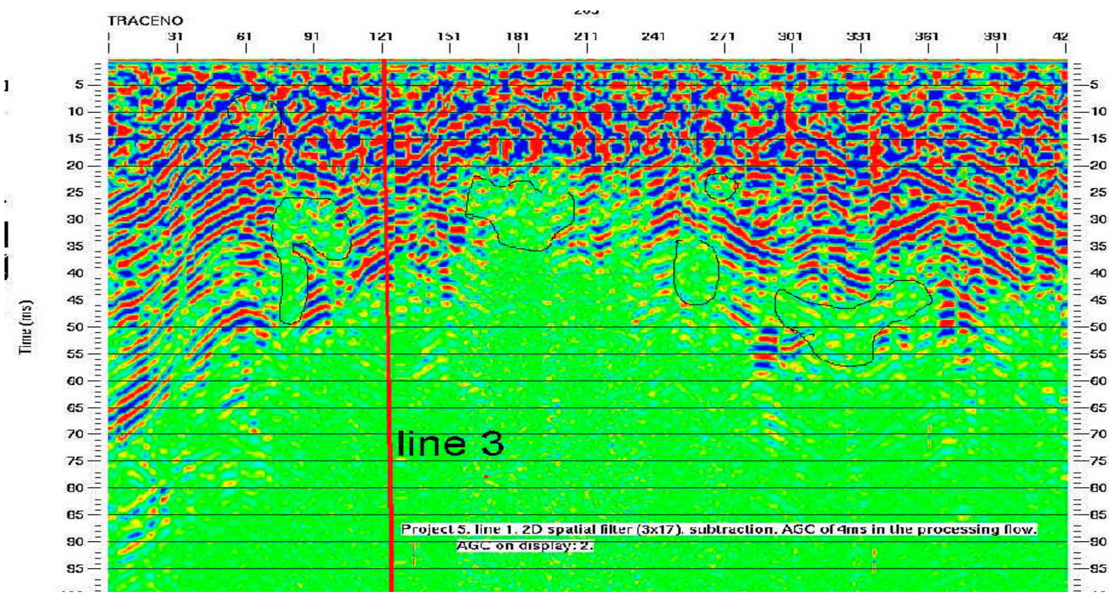

FIG. 13: Caves project, NS line (line 1) with median filter (subtraction mode) applied. We can identify subsurface features and interpret the caves. Interpreted structures are marked with the black border. A crossline (line 3) is also projected onto the section. The circled area represents a hole consistent with the field notes.

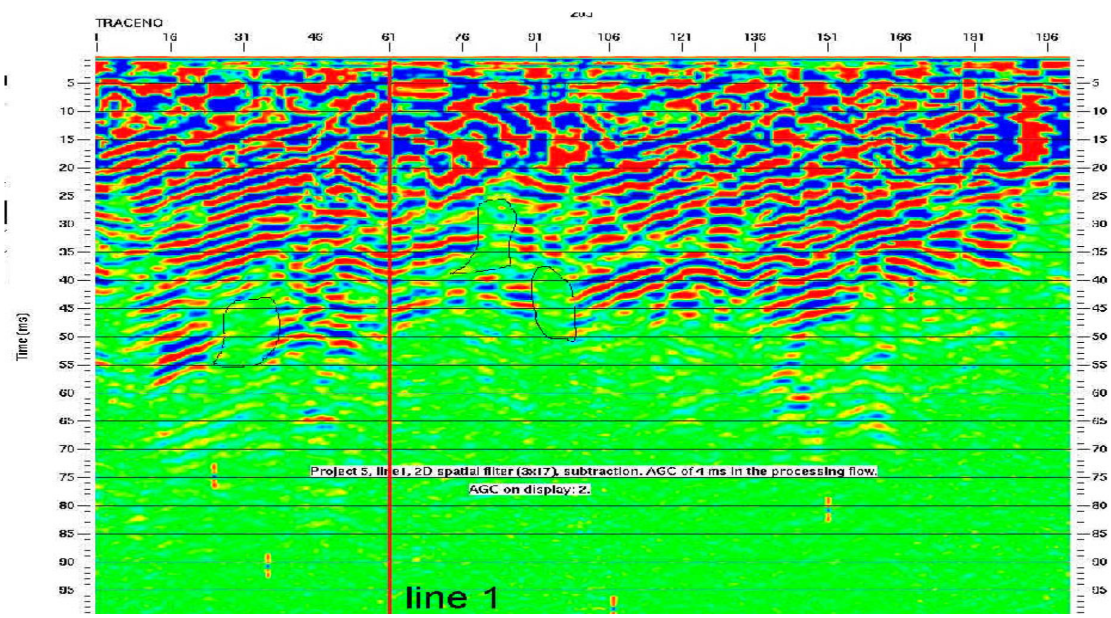

FIG. 14: Caves project, EW line with median filter (subtraction mode) applied. This is a crossline. On this line we can also identify the caves, circled in black. The top of the cave is at ~45 ns (~2 m depth), which is consistent to the field notes.