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Use of GPR for Imaging Subsurface Archaeological Remains in the Islamic City of Ayla, Aqaba, Jordan

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Abstract

The Islamic city of Ayla was founded in the eighth century. The city is located adjacent to the beach and extends for a few tens of meters north of the Gulf of Aqaba shoreline. The city was, once, a flourishing and commercial port, communicating with other ports around the Indian Ocean and with the Far East. The city had land roads that connect with Egypt, Iraq, Syria, and the Arabian Peninsula.

The excavated ruins and other features are related to an ancient Islamic city.

The ground penetrating radar survey was carried out using a Subsurface Interface Radar System- (SIRvoyer-20) with two different central frequency monostatic antennae 900 MHz and 400 MHz to target abundant subsurface buried archaeological material for forward excavations.

The interpretation of radar cross section (radargram) shows many buried features with different patterns, widths, and shallow depths between 0.20 m to 0.6 m. These anomalies are corresponding to the depth of the excavated walls in the study area.

GPR anomalies are discontinuous and being shifted and located at a high liquefaction susceptibility zone confirms that several earthquakes have rocked Aqaba and Gulf of Aqaba region.

Keywords: Islamic city of Ayla, Ground penetrating radar, Monostatic antenna, liquefaction, buried walls.

1. Introduction

The city of Aqaba is situated at the northern part of Gulf of Aqaba, about 320 km south of the capital of Jordan Amman (Figure 1a). Aqaba has been an important trading city throughout history, including the Roman, Nabatane, Byzantine, and Islamic times (from first century (BC) to present). Aqaba Sea routes lead to East and North Africa and the ports of southern Asia. Land routes have carried trade with Syria, North Africa, and the Hejaz.

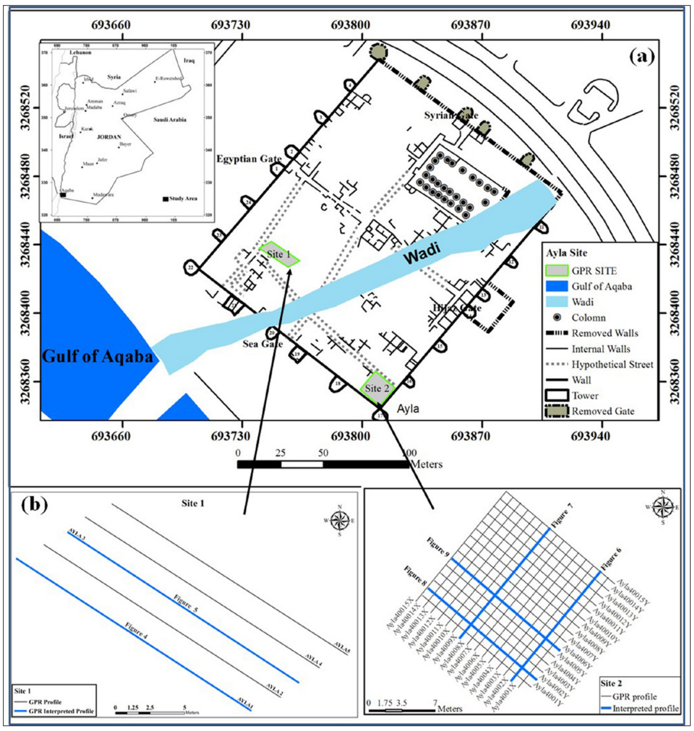

Figure 1. a) Location map of the study area showing the plan of excavations at the Islamic city of Ayla from 1986 to 1993 (Whitcomb 1994). **b)** Location map of the GPR profiles at the two sites.

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The discovery and delineation of the layout of the early Islamic city of Ayla is the result of excavations from 1986 through 1995 directed by Whitcomb (1990, 1991, 1994a, 1994b, 1994c, 1995, 1997, 2001) from University of Chicago. The excavations were carried out by the University of Chicago and the American Center of Oriental Research (ACOR), with the support of the United States Agency for International Development (USAID), in cooperation with the Department of Antiquities of Jordan.

GPR is an electronic device that emits Electromagnetic (EM) waves and determines the location of reflected energy. It has become a widespread instrument for usage in different fields, including geology, archaeology, the environment, engineering and construction, glaciology, and forensic science.

The GPR survey has been used to map buried remains or other construction features, the localization of tombs, burial mounds, shallow graves and the reconstruction of archaeological layers. The purpose of the surveys was to map the existence of uncovered subsurface archeological remains at a shallow depth, and, therefore, direct the archaeologists to the areas to be excavated.

2. Historical Background

The Islamic Ayla city was constructed by Caliph Othman Ben Afen around 650 AD. It was a flourishing city during the Umayyad period (650-750 AD) and the Abbasid period (750-970 AD) (Whitcamb, 1989a, 1989c, 1990, 1991) and also during the Fatimaied period (970-1116 AD) (Whitcamb, 1989b). The city was a very important port, and the artifacts found in the site indicated a commercial contact with ports in the Indian Ocean and the Far East; however, most of that contact was with the Arabian Peninsula, Egypt, Iraq, and with Syria using the road networks (Whitcamb, 1987). The city was established in a fortified 170 x 145 meters rectangle, with walls that are 4.5 meters high and 2.6 meters thick and is surrounded by twenty-four towers (Figure 1a). Excavations in 1987 at the site of the early Islamic Ayla (modern Aqaba, Jordan) revealed a city plan which included four gates (Whitcamb, 1987). The gates spread on all four sides as follows: the Damascus Gate (east), Door of the Sea (west), Door of the Hejaz (south), and Door of Egypt (north) (Figure 1a). In any Islamic city, the mosque is a very important building, and, here, it is located northeast of the city (Whitcamb 1994), (Figure 1a). Whitcomb (1993) theorised that the wadi running through the Islamic City of Ayla originated from earth's structural weakness. Such a fault was indicated on his site plan (Figure 1a). However, excavations by Rucker and Niemi (2005) of the Northeast corner tower of the walled city in the wadi and the interpretation of the 1918, 1945, and 1953 air photos indicated that the wadi was man-made. The city was destroyed in the late twelvth century by attacks of Bedouins, Crusaders, and also as a result of earthquakes. Whitcomb (1994) showed through a detailed mapping of the ancient architecture that this ancient city experienced subsidence due to several earthquakes.

The historical records indicate that numerous destructive earthquakes have occurred over the past 2000 years, and many of them are documented in Roman, Byzantine, and various Arabic sources (e.g. Guidoboni, 1994; Ambraseys, 2009). Several earthquakes are believed to have rocked Aqaba and the Gulf of Aqaba region in 1068, 1212, 1458, and 1588 A.D. (Ambraseys and Melville, 1989). The archaeological record verifys that a major damage to the Byzantine structures occurred in Aqaba in the 363 A.D. earthquake (Parker, 1999; Thomas et al., 2007). Also, a major damage occurred in the Islamic City of Ayla by the 1068 earthquake (Ghawanmeh, 1992; Whitcomb, 1994; Allison, 2013) which dstroyed the city of Aqaba (e.g. Guidoboni, 1994; Ambraseys, 2009). A comparison of the GPR images with the magnetic gradiometry maps were used by Conyers (2016) in order to provide information about buried buildings. GPR investigations are considered as an effective method to understand the ruins (Nawabi, 2016). The site was apparently never reoccupied after this earthquake. The geotechnical investigations carried out at the site showed sinking and tilting of the external walls, which was interpreted as slumping due to horizontal ground acceleration in an earthquake (Al-Hamoud and Tal, 1998). In the 1995 Nuweiba earthquake, many areas along the shoreline zone near Ayla ancient beared experiencing subsidence (Malkawi et al., 1999; Al-Tarazi 2000). The abundant groundwater and the shallow water table contributed to the rest and security of travelers and Hajj caravans from North Africa, Palestine, and Egypt, before continuing their journey through the desert. In other words, the shallow water table and shallow saturated sand demonstrated that Ayla lies in a high liquefaction susceptibility zone. (Mansoor et al., 2004; Abueladas, 2014). (Figure 2).

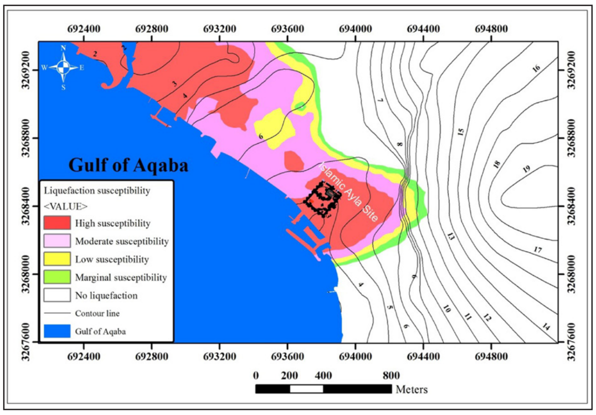

Figure 2. Map showing the ground water depth and the location of the liquefaction susceptibility zones (Abueladas, 2014).

3. GPR Concepts

The GPR technique, as a method of scientific investigation, has become an important technique that is neither destructive nor invasive, used for discovering, recovering, mapping, and understanding subsurface archeological data.

With this technique, a short pulse of high frequency (10 to 1,000 MHz) electromagnetic energy is transmitted into the ground from a shielded antenna pulled slowly across the ground at speeds varying from about 0.25– 4 m/h. The speed is dependent on the amount of detail desired and on the nature of the target.

The GPR signal is reflected, refracted, and attenuated depending on the distribution of the dielectric constant and electrical conductivity of the subsurface. These electrical properties are highly dependent on the water content of the subsurface, and the presence of a high porosity environment.

The radar signal velocities are related to the relative permittivity by:

$v = c/\sqrt{\mu_r \varepsilon_r}$ ....(1)

where is the ratio of the dielectric permittivity of the medium to the dielectric permittivity of free space, is the relative magnetic permeability of the medium, and $c=3\cdot10^8$ m/s is the velocity of the EM waves in free space. Because is close to unity for most rock materials, radar velocity is primarily controlled by.

The dielectric permittivity across an interface causes part of an impinging radar pulse to be reflected. The radar signal amplitude is decreased at a reflecting boundary depending on the contrast and the thickness of the layer. The amount of the reflected energy related to signal amplitude is given by the reflection coefficient (R) (Neal, 2004). The reflection coefficient is defined as:

$R= \{(\varepsilon_{r2})^{1/2} - (\varepsilon_{r1})^{1/2}\}/ \{(\varepsilon_{r2})^{1/2} + (\varepsilon_{r1})^{1/2}\}$

Where ε_{r1} and ε_{r2} are the relative dielectric permittivity of the adjacent layers 1 and 2, or:

$R= \{(v_2)^{1/2} - (v_1)^{1/2}\}/ \{(v_2)^{1/2} + (v_1)^{1/2}\}$

The attenuation of a radar wave and its depth of penetration depend on the electrical conductivity and the dielectric constant of the media through which the wave propagates can be reduced for the case of low-loss media $\sigma /\varepsilon_w <<1$ to a simple form $\alpha= (\sigma /2) \times (\mu/\varepsilon_r)^{0.5}$ Where α donates the attenuation constant, and σ combines both the direct current (D.C.) conductivity and dielectric losses. The depth of penetration depends on the used frequency (the lower the frequency, the deeper the penetration) and on the conductivity of the materials (the higher the conductivity, the higher the penetration).

The horizontal resolution relates to the capability to detect a reflector position in space or time, which is a function of the pulse width (Neal, 2004). The vertical resolution increases with the increase in the frequency (Knapp, 1990). The vertical resolution is also controlled by wavelength (λ) (Knapp, 1990) which is a function of velocity and frequency:

$\lambda = v/ f$

The optimum vertical resolution can be attained using one-quarter of the dominant wavelength (Sheriff, 1977).

The reflected energy is processed and displayed as a continuous strip chart recording of distance versus time. The depth of penetration of a GPR system is highly site-specific, and depends upon the soil and rock characteristics at the site, moisture content, and the frequency of the antenna (Battayneh et al., 2002).

The GPR data can be collected either by the fixed offset method in which the transmitter and the receiver antennas are separated by a fixed distance and moved across the area in regular steps, or by the common midpoint (CMP) mode in which the antennas are gradually separated from one another in constant steps. The CMP mode is often used to determine the velocity of the radar wave propagation through the subsurface.

The GPR methodology is similar to that of the shallow seismic reflection surveying in that these methods use the reflection of energy from underground features, but they differ largely in their site-specific applicability (Figure 3).

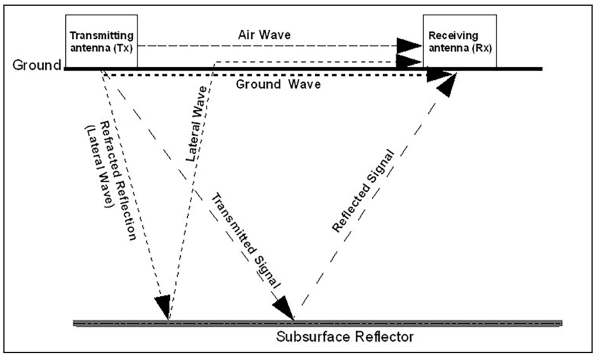

Figure 3. Ray paths between transmitting and receiving antennae (Neal, 2004). The diagram shows the ground surface along which the airwave and ground waves travel as well as the refracted lateral wave and the reflected wave. Modified after Fisher et al. (1996).

4. GPR Survey

4.1 Data aquisition

A continuous GPR survey was conducted using a Subsurface Interface Radar System- (SIRvoyer-20) manufactured by the Geophysical Survey System (GSSI) (Al-Ruzouq et al., 2018).

Two different central frequency antennae were used, namely the 900 MHz and 400 MHz antennae. The 400 MHz antenna is an excellent compromise between vertical resolution and depth penetration.

A total of 550 meters of GPR were collected along thirty-five profiles at two sites. The first survey site was located south-west of the Islamic city of Ayla, and the second was located at the south-east corner of the study area (Figure 1b).

4.2 Data processing

The GPR data were processed using the Geophysical Information System (GSSI) RADAN V software package.

Generally, attenuation reduces the radar signal with the increased travel time. Therefore, it is important to increase the weaker signals at greater receiver arrivals. Gains and color transformation are applied to increase the visibility of low amplitude features.

In the processing of the exhibited waveforms, two types of time domain filters, namely the finite impulse response (FIR) and infinite impulse response (IIR), were applied.

The horizontal and vertical high-pass filters have been used to remove the ringing system noise, and the horizontal and vertical low-pass filters have been applied to eliminate high-frequency noise from the GPR signal and to enhance the radar cross section. Data were stacked in a horizontal direction to get a clearer data dislpay. In the radargram, the vertical axis showed a two-way travel time (TWT) in nanoseconds (ns) (Ulriksen, 1982).

It is very important to calculate the subsurface radar wave velocity of the near-surface materials in order to convert the two-way travel time (TWT) of the reflected signal to the true depth of the reflector. The first way for estimating the GPR velocity is to measure TWT to a horizontal layer or buried object of an known depth (Annan, 2003; Topp et al., 1980; Fisher, 1992). However, the velocity was calibrated according to the known depth aligned with the top of the excavated wall in the study area.

The near-surface radar wave velocity estimates ranged from 0.10 to 0.12 m/ns at the Ayla site. An average velocity of 0.11 m/ns was adopted for general use at the site.

5. Results and Discusstion

Because the GPR anomalies of man-made origin are generally specified by their pattern and extension, rather than by their numeric values alone, so the results of the GPR data of the archaeological sites are generally shown graphically. When presented graphically, one can distinguish the cultural and natural patterns better, and imagine the physical phenomena causing the detected anomalies.

A reconnaissance survey was conducted by recording five continuous parallel profiles, up to 20 m long at site 1. The separation between the northwest-southeast adjacent profiles was 1 m (Figure 1b).

In the radargram of figure 4, two strong anomalies are visible really well due to the presence of a strong reflector at a depth of about 0.6 and 0.5 m. The first anomaly may correspond to the buried wall. The second strong anomaly appears as a diffraction hyperbolas shape with high amplitudes observed at a depth of 0.5 m, and is probably caused by a metal pipe (Figure 4).

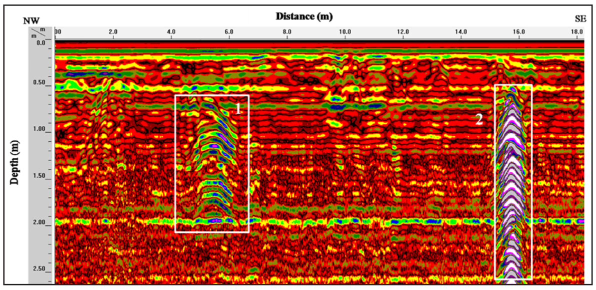

Figure 4. Part of the radar profile (400 MHz antennae) along Ayla 1. The first anomaly may represent a buried wall that is 0.6 m deep. The second anomaly is probably caused by a metal pipe that is 0.5 m deep.

GPR profile Ayla 3 runs parallel to profile Ayla 1 (Figure 1b). The radargram shows two anomalies at a depth of about 0.3 m (Figure 5). These reflectors are probably caused by two shallow walls.

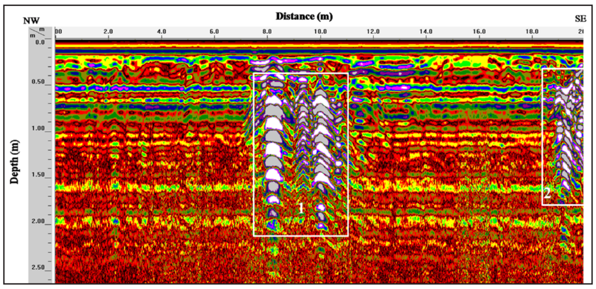

Figure 5. Radar profile (400 MHz antennae) along Ayla 3. The two main anomalies may represent 0.3 m deep buried walls.

Site 2 was a rectangle of 15 x 15 m, applied to the south-east of Islamic city of Ayla (Figure 1b). The uni-directional survey was conducted along fifteen profiles oriented approximately SW-NE, and fifteen profiles SE-NW oriented being 1 m apart, using the 400 and 900 MHz antennae.

In the radargram of figure 6, two strong anomalies are pictured at depths of about 0.5 and 0.3 m (Figure 6). These anomlaies perhaps refer to buried walls.

A hyperbolic event in the radargram at a depth of almost 1m as in figure 7 probably refer to a 0.3 m deep wall.

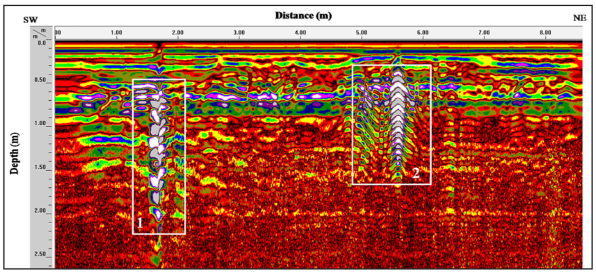

Figure 6. Part of the radar profile (400 MHz antennae) along Ayla4002x. The two main anomalies may represent 0.5 m and 0.3m deep buried walls.

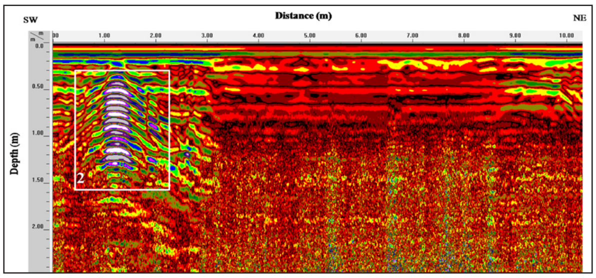

Figure 7. Radar profile (400 MHz antennae) along Ayla4009x. The hyperbolic- shaped anomaly may represent a 0.3 m deep buried wall.

GPR profile Ayla4002y runs perpendicular to Ayla4002x (Figure 1b). The two 0.3 and 0.5 m deep anomalies probably represent shallow buried walls (Figure 8).

Two different antenna frequencies were applied along this profile Ayla4006y (Figure 1b). In the radargram of figure 9a (400 MHz antennae), three anomalies are well visible due the presence of a strong reflector at about 0.2 m, 0.3 m and 0.5 m deep. The same anomaly can be seen at the 900 MHz profile (Figure 9b).

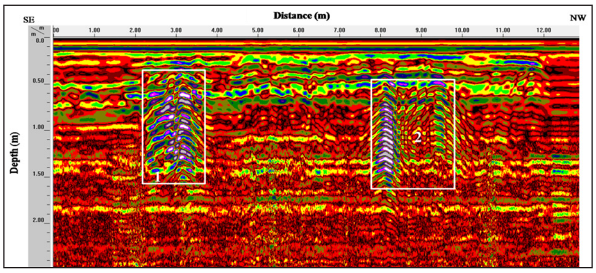

Figure 8. Part of the radar profile (400 MHz antennae) along Ayla4002y. The two 0.3 and 0.5 m deep anomalies probably represent shallow buried walls.

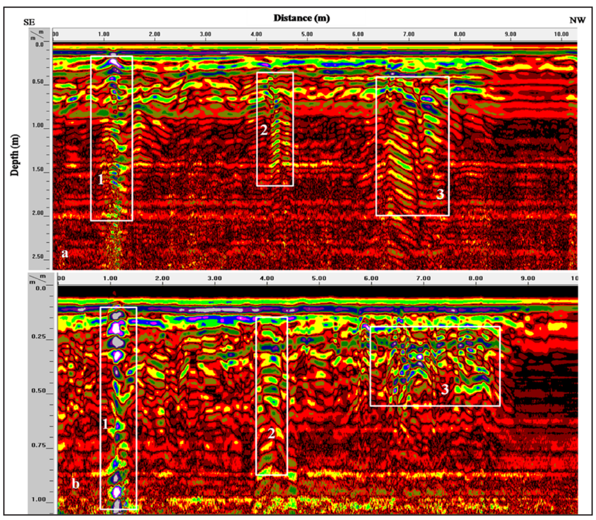

Figure 9. a) Part of the radar profile (400 MHz antennae) along Ayla 4006y. **b)** Part of the radar profile (900 MHz antennae) along Ayla 9006y. Both profiles show the same anomalies.

The GPR radargram profiles revealed many different subsurface anomalies across the study area located at different depths from 20 to 60 cm at both sites (Figure 10). Some of these anomalies are isololated and others are continuous. The anomaly map shows individual features at both sites. The anomalies appear similar to the GPR signature of the buried walls or scattered blocks at site 1 (Figure 10a), except for the second anomaly along profile Ayla1, which was probably caused by a metal pipe located at 50 cm (Figure 4).

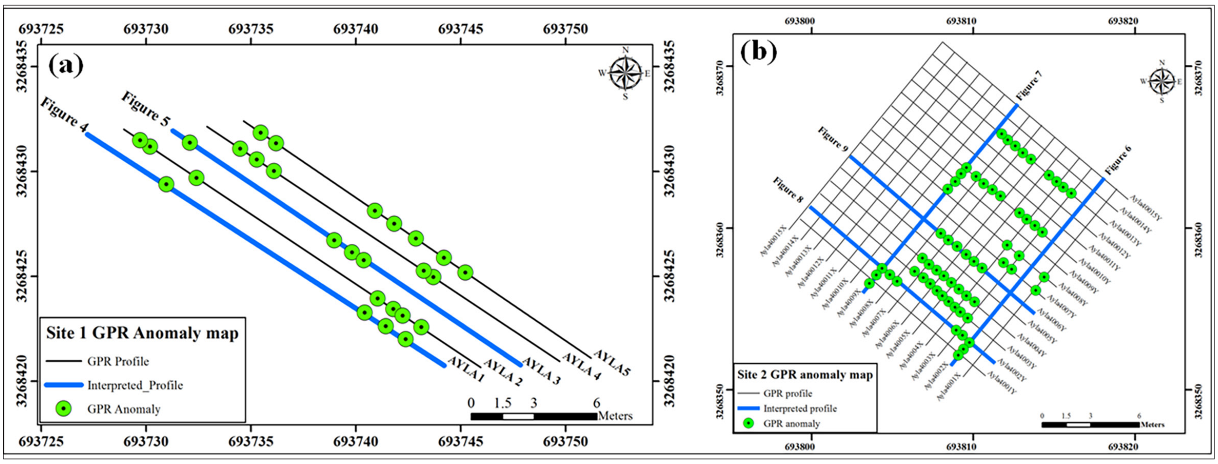

Figure 10. a) GPR anomaly location map, site 1. b) GPR anomaly location map, site 2.

Many anomalies were pictured at site 2, especially at the north-east and noth-west parts of this site. Continuous anomalies may represent buried walls (Figure 10b). The shape and direction of these anomalies are similar to the excavated walls which refer to the Egyptian, Hijaz, and Syria gates (Figure 1a). Other individual anomalies represented by walls had collapsed due to earthquakes.

6. Conclusions

Geophysical methods are intensively used for both the rescue and exploration of archaeology in some countries.

The main advantage of the GPR method is its capability of investigating a structure or a site with a non-destructive and a non-invasive technique, i.e., without digging, boring or causing changes to its original structure or shape especially in an urban area such as the Islamic Ayla site.

The GPR successfully produced images of the subsurface and the burried walls by using high and medium-frequency. It proved to be an excellent tool for the distinguishing and delineation of subsurface structures which are clearly expected to be of an archaeological interest.

The flat topography, the presence of sand and gravel, and the good electrical-property contrasts between a stonewall and sand at the study sites can help detect the anomalous zones at the study area.

Most of the archaeological anomalies are concentrated in the NE and SE parts of site 2.

The shallow hidden feature with depths between 10 cm to 60 cm mapped by GPR can interfere in the preservation of buried heritage and may provide basic information not only to increase the knowledge of the past, but also to aid in planning any future excavations.

The scattering anomalies at both sites may indicate damaged or missplaced wall sections due to several natural factors including earthquakes, or human activities such as wall demolition, removal, or reconstruction. The confirmation has been extemely difficult without excavations.

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