Gorokhovich,Y., Papadopoulos, N., Soupios, P. and Barsukov, P. 2014. Application of Geographic Information Systems, ground penetrating radar and transient electromagnetic methods for locating water supply structures at the ancient site of Aptera in Crete. *Boletín Geológico y Minero,* 125 (3): 273-284
ISSN: 0366-0176

Application of Geographic Information Systems, ground penetrating radar and transient electromagnetic methods for locating water supply structures at the ancient site of Aptera in Crete

Y. Gorokhovich[(1)], N. Papadopoulos[(2)], P. Soupios[(3)], P. Barsukov[(4)]

(1) Department of Earth, Environmental and Geospatial Sciences,
Lehman College, City University of New York, 250 Bedford Boulevard Park West, Bronx, NY 10468
yuri.gorokhovich@lehman.cuny.edu
(2) Laboratory of Geophysical-Remote Sensing & Archaeoenvironment,
Institute for Mediterranean Studies (IMS), Foundation for Research & Technology Hellas (FORTH),
Nikiforou Foka 130, 74 100 Rethymno, PO BOX 119, Rethymno, Crete, Greece
nikos@ims.forth.gr
(3) Department of Natural Resources & Environment,
Technological Educational Institute of Crete, 3 Romanou, 73133, Chalepa, Chania, Crete, GREECE
soupios@chania.teicrete.gr
(4) Geoelectromagnetic Research Centre IPE RAS,
Russian Academy of Sciences, Moscow, Russia
bars@igemi.troitsk.ru

ABSTRACT

The ancient town of Aptera is located in the western part of the island of Crete. The prominent size of the L-shaped cistern that is visible today suggests an intensive domestic use of water. The existing research on the method of water supply for the cistern is inconclusive. There is no indication of the existence of remnants of either rain harvesting structure or an aqueduct. Therefore it is wide open area for research and field investigations. The developed hypothesis suggests the collection of the surface runoff for filling the cistern.

Developed Geographic Information Systems (GIS) is a terrain-based hydrologic model which outlined a possible drainage area to the main L-shaped cistern in Aptera. When the delineated area was overlain on the contemporary map of Aptera it showed the coincidence between the lower drainage area boundary and the modern road leading to Aptera. The end of the modern road almost touches the corner of the cistern. This coincidence indicates a possibility of the existence of a water supply structure that could be used to fill the cistern with the surface runoff.

We applied two geophysical methods to identify the possible structure: Ground Penetrating Radar (GPR) and the Transient Electromagnetic Method (TEM). Preliminary results show a strong and complementary signal returns along the road from both methods, mapping different depth layers of the subsurface. The combined application of GIS and geophysical methods shows complimentary benefits for locating subsurface features when they are associated with the surface characteristics of the terrain.

Key words: ancient water supply, Aptera, geophysics, ground penetration radar, transient electromagnetic method.

Aplicación de los Sistemas de Información Geográfica, el georadar y los métodos electromagnéticos transitorios para localizar estructuras de suministro de agua en la antigua ciudad de Áptera en Creta

RESUMEN

La antigua ciudad de Áptera tiene una cisterna romana que proveía agua para uso doméstico. Su gran tamaño sugiere que se llenaba mediante un sistema de recolección de aguas pluviales o acueducto, pero los estudios disponibles sobre el método de llenado de la cisterna no son concluyentes. No hay indicios sobre la *existencia de restos de sistemas de recolección de aguas pluviales ni de acueductos. Por tanto, este tema es un área amplia de investigación y de trabajo de campo. La hipótesis que evaluamos en este artículo sugiere un sistema de recogida de agua de escorrentía para el llenado de la cisterna. La red de drenaje generada mediante un Sistema de Información Geográfica define una posible área de drenaje a la cisterna principal de Áptera. Cuando dicha área se superpone sobre el mapa actual de Áptera, el límite inferior del área de drenaje y la carretera actual hacia el yacimiento de Áptera coinciden. El final de la carretera casi toca la esquina de la cisterna. Esta coincidencia indica la posible existencia de una estructura de aprovisionamiento de agua que pudo haberse usado para llenar la cisterna con agua de escorrentía. Hemos aplicado dos métodos geofísicos para localizar dicha estructura: georadar (ground penetrating radar , GPR) y sondeo electromagnético transitorio (transient electromagnetic method, TEM). Los resultados preliminares de los dos métodos muestran fuertes señales de retorno a lo largo de la carretera. Sin embargo, debido a diferencias en profundidad, aún no está claro si los resultados están correlacionados. Son necesarios más sondeos con métodos geofísicos diferentes para clarificar los resultados obtenidos.*

Palabras clave: Antigua provisión del agua, Áptera, geofísico, georadar, sondeo electromagnético transitorio

VERSION ABREVIADA EN CASTELLANO

Introducción

Las ruinas de la antigua ciudad de Áptera es uno de los yacimientos arqueológicos más interesantes de Creta (figura 1). La estructura más impresionante del yacimiento es una cisterna en forma de L (figura 2) que aparentemente era el principal depósito de almacenamiento de agua dulce con un volumen total de 3050 m^3 (Niniou-Kindeli and Christodoulakos, 2004). Estudios recientes relacionados con el suministro de agua a Áptera han sido realizados por Gorokhovich et al (2012), Christodoulakos et al (2009), Gikas et al (2009) y Niniou-Kindeli and Christodoulakos (2004). Estos estudios explican posibles modos de rellenar con agua la cisterna en forma de L, pero todavía no existen hallazgos arqueológicos que corroboren ninguna de las teorías.

El último estudio de Gorokhovich et al (2012) consideraba la escorrentía superficial como una fuente de agua para el llenado de cisternas. El estudio usaba modelado hidrológico y análisis del terreno con Sistemas de Información Geográfica (SIG) para identificar un área potencial de drenaje y evaluar su capacidad para rellenar con agua cisternas con forma de L. Los resultados mostraban como era posible llenar cisternas con agua procedente de la escorrentía superficial del área de drenaje identificada.

Los resultados del modelado mostraron que el borde norte del área de drenaje era coincidente con la carretera actual a Áptera (figura 3). Esta observación condujo a la revisión de los métodos hidrológicos disponibles que pueden optimizar la recolección de la escorrentía superficial. Uno de los métodos para dicha optimización es una zanja drenante hecha perpendicular a la pendiente con el objeto de interceptar el flujo superficial. Ejemplos del uso de zanjas desde perspectivas tanto modernas como antiguas se pueden encontrar en Carluer and De Marsily (2004), Aby Zreig et al (2000), Kedar (1957) y Toulouse (1945). Por consiguiente nosotros sugerimos la existencia de una zanja drenante antigua para rellenar la cisterna con forma de L. Es muy probable que la zanja drenante proporcionara una base muy conveniente sobre la que construir la carretera actual y que por consiguiente la zanja se rellenara durante la construcción de dicha carretera.

Para encontrar una respuesta a la pregunta acerca de la existencia de una estructura subterránea bajo la carretera actual se sugieren el empleo de técnicas de prospección geofísica a lo largo de dicha carretera. La investigación que se propone incluye la toma de imágenes del subsuelo mediante el empleo de métodos geoelectromagnéticos: el georadar (GPR) y los sondeos electromagnéticos transitorios (TEM).

Métodos

Georadar (GPR)

Radar es el acrónimo de sistema de "Radio Detecting And Ranging" que utiliza la radiación electromagnética de alta frecuencia para cartografiar el subsuelo; y se basa en la transmisión de una radiación electromagnética de alta frecuencia al terreno y el registro de las señales reflejadas, similar al método de sísmica de reflexión. Para la exploración de Áptera se empleo el equipo Noggin Plus-Smart Cart (Sensors & Software) GPR con antenas de 250 MHz para obtener datos preliminares. La cartografía detallada del área de investigación (cada 5 cm a lo largo de los perfiles de georadar separados 50 cm) cubrió una superficie de 900 metros cuadrados alcanzando una profundidad máxima de 2.4 m bajo la superficie del terreno.

Sondeos electromagnéticos transitorios (TEM)

El TEM se ha utilizado ampliamente en estudios geoambientales y ha dado lugar a numerosas publicaciones científicas (Kanta et al. 2013; Soupios et al. 2010; Nabighian and Macnae 1991; Kaufman and Keller 1983). Un sistema TEM típico consiste en un dipolo transmisor (Tx) y receptor (Rx) (llamados bucles en TEM) con tamaños variables (2 x 2 m, 5 x 5 m, 10 x 10 m, 50 x 50 m, etc.) dependiendo de la profundidad de exploración. Un incremento en el bucle Tx permite aumentar el ratio señal/ruido (S/N) lo que resulta en un incremento de la profundidad de exploración (Kanta et al. 2013; Soupios et al. 2010; Barsukov et al. 2007). Una corriente que pasa por el bucle Tx genera un campo estacionario primario. El ratio de atenuación de este campo depende de la distribución de la resistividad en el subsuelo. En base a este principio, el voltaje medido en la bobina Rx proporciona información acerca de las estructuras geoeléctricas a varias profundidades (Barsukov et al. 2007). La adquisición de los sondeos TEM en Áptera se efectuó con el equipo TEM-FAST 48 (AEMR Company, Holanda).

Resultados

Campaña de georadar

La figura 4 muestra el área cubierta con el método GPR así como la dirección de la prospección (desde A hasta B). La figura 5 muestra rebanadas horizontales para diferentes profundidades, extraídas de los datos GPR tridimensionales. Se confeccionaron mapas geofísicos a color y en escala de grises (figuras 5 y 6) utilizando colores rojizos en los mapas a color y colores negros en los mapas de escalas de grises para representar valores de intensidad altos. Por otra parte, los colores azulados en los mapas a color y los colores claros (blanco) en los mapas con escalas de grises representan anomalías de baja intensidad. Se utilizo el programa Surfer (Golden and Software v.11) para rectificar los mapas geofísicos y para sobreponer sobre ellos el plano topográfico del lugar.

Método electromagnético transitorio

Las primeras campañas TEM se realizaron en marzo de 2013 utilizando una configuración en bucle cuadrado simple con dimensiones de 10 x 5 m (figura 7) y realizando 39 sondeos a lo largo de la carretera, alcanzando una profundidad de 20 m. Los resultados del procesado de las series temporales TEM obtenidas del bucle de 10 x 5 m mostró que todas las curvas (para todos los tiempos transitorios) están bien correlacionadas (figura 8). Los resultados también mostraron que las respuestas a los tiempos límite (esto es, t > 20µs) eran "respuestas metálicas" con E~1/t (Figura 9). Como no pudieron ser separadas las respuestas "terreno" y "metálica" (principalmente de vallas metálicas a lo largo de la carretera), resulta difícil invertir los datos y estimar el modelo resistivo 1D final. De este modo se concluyó que los datos TEM-FAST eran ruido y el bucle 5 x 10 m funcionó fudamentalmente como un detector de metales. Aún más, estudios TEM previos en la vecindad de Áptera mostraron que la roca subyacente tiene fuertes propiedades SPM (Soupios et al. 2010; Nagata 1961; Neel 1950). Para rectificar estas dificultades, se modificó el método TEM y se aplicó un bucle Tx-Rx más pequeño en una campaña de prospección TEM diferencial en junio de 2013.

El análisis de datos de la campaña anterior también mostró que aproximadamente el 10% de la respuesta electromagnética (señal) se debía al SPM de la roca y aproximadamente un 90% era debido a vallas metálicas a lo largo de la carretera y posibles rasgos subterráneos. Como el SPM es proporcional al tamaño del bucle (Barsukov et al. 2007), se cambió el tamaño del bucle a 2 x 2 m y también se tomaron medidas lejos de las vallas (figuras 10a,b), siguiendo la dirección a lo largo de la carretera. De este modo, sustrayendo la señal para diferentes elevaciones E(h=0.14m)-E(h=1.30m) se esperó obtener medidas SPM directamente de los objetivos subterráneos desconocidos. El nuevo método estaba basado en un bucle 2 x 2 m para obtener medidas a dos alturas diferentes desde el terreno (1.30 m y 0.14 m, ver figuras 10a y 10b. Para cada altura se tomaron 72 sondeos a lo largo de la carretera y se combinaron para la interpretación final. En esta nueva configuración, el bucle a 1.30 m sobre el terreno se utilizó para el filtrado de anomalías producidas por objetos cercanos a la superficie.

Basados en los modelos finales (figura 10), se determinó por lo menos una anomalía SPM (ver el rectángulo relleno de azul entre las líneas discontinuas). Ya que esta anomalía es por lo menos de 5 a 10 veces mayor que los errores de prospección y los datos se tomaron con una confianza alta, es posible asociarlo con un objetivo subterráneo localizado entre los intervalos de profundidad comprendidos entre1.5 y 2 m (parte superior) y de 3 a 5 m (parte inferior).

Discusión

Este estudio ha demostrado como un modelo hidrológico basado en análisis del terreno mediante SIG puede ayudar a identificar sitios potenciales de investigación arqueológica. Después de identificar el lugar, se utili-

zaron dos métodos geofísicos diferentes, GPR y TEM, para descubrir objetivos subterráneos potenciales que podrían ser vestigios de una estructura hipotética de suministro de agua, presumiblemente una zanja drenante. Ambos métodos produjeron anomalías a diferentes niveles; por lo que la comparación de los resultados no es directa. Sin embargo, la combinación de modelos TEM y GPR (figura 12) muestra que al menos dentro de la parte superficial de la carretera, hay cierta coincidencia en las señales de respuesta.

Introduction

The site of Aptera is one of the most interesting archaeological sites in Crete, located in its northwestern coastal area (Figure 1). Its history dates back to late Minoan period and it was intermittently occupied by Greek, Roman and Turkish settlers. The most impressive structure of the site is the L-shaped cistern (Figure 2) that was apparently the main storage of fresh water, with total volume of 3 050 m^3 (Niniou-Kindeli and Christodoulakos, 2004). Most recent studies related to Aptera's water supply were done by Gorokhovich *et al.,* (2012), Christodoulakos *et a.,l* (2009), Gikas *et al.,* (2009) and Niniou-Kindeli and Christodoulakos (2004). These studies explain possible ways of filling the L-shaped cistern with water ranging from rain harvesting structures to collection of the surface runoff. However, there are no archaeological findings to support any of these theories.

The latest study by Gorokhovich *et al.,* (2012) considered a surface runoff as a main source of water to fill cisterns during the rainy season. The study used simple terrain-based hydrologic modelling with Geographic Information Systems (GIS) to identify a potential drainage area and evaluate its capacity to fill the L-shaped cistern with water. The model used the location of the cistern at high elevation as a potential drainage area outlet. From this point the drainage area was automatically delineated and measured (Figure 3). The results (with the assumption that contem-

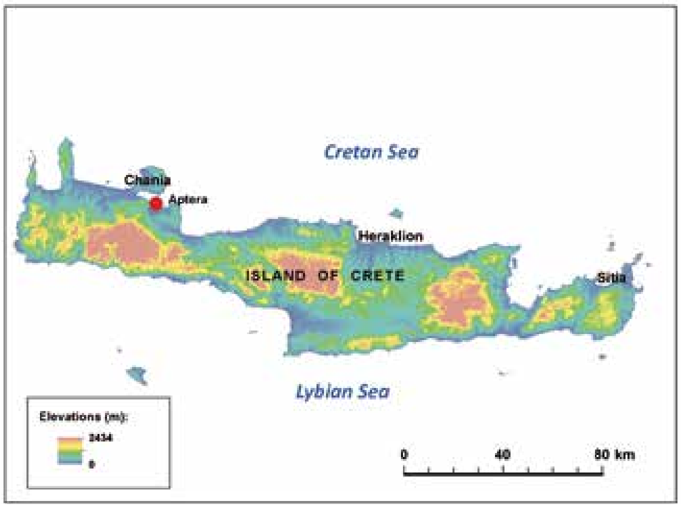

Figure 1. The location of Aptera in Crete.
Figura 1. *Localización de Áptera en Creta.*

Figure 2. *The long side of the L-shaped cistern in Aptera.*
Figura 2. *El lado más largo de la cisterna con forma de L en Áptera.*

porary rainfall data are close or equivalent to the similar conditions in ancient times) showed that cisterns could possibly be filled by water from the surface runoff. This result is based on solely on a GIS model and modern maps and does not bear any material evidence.

After reviewing modelling results we found that the northern boundary of the drainage area coincided with the modern road to Aptera (Figure 3). This observation led to a review of the available hydrologic methods that are able to optimize surface runoff harvesting. One of the methods to optimize surface runoff harvesting is to create a cut-off (or interception or barrier) ditch across the slope. The ditch intercepts surface flow and passes it along the channel to a potential water collecting structure, for example a cistern. This method is being used in various rural communities around the world; it is also widely used in mountainous areas to reduce water infiltration in landslide prone areas.

Thorough analysis of ditch uses in modern agricultural communities in France and their influence on hydrology is presented by Carluer and De Marsily (2004). Interesting experimental work was done by Aby Zreig *et al.,* (2000) who demonstrated the efficiency of sand filled ditches to intercept surface runoff in dry agricultural lands of Northern Jordan. Regarding ancient water supplies, a ditch leading to the cistern was discovered in Shivtah (Subeita) city in the Negev (Kedar, 1957). The same study mentions several well-preserved agricultural ditches that could be used even now.

The most interesting and noteworthy issue regarding Aptera is a discovery made in the Gran Quivira National Monument in New Mexico (Toulouse, 1945). In this article the author described "… the ditch which runs along the top of the ridge on which the ruins lie. This ditch is connected with a "tank" some 200 yards east of the ruins and runs westward to another "tank"

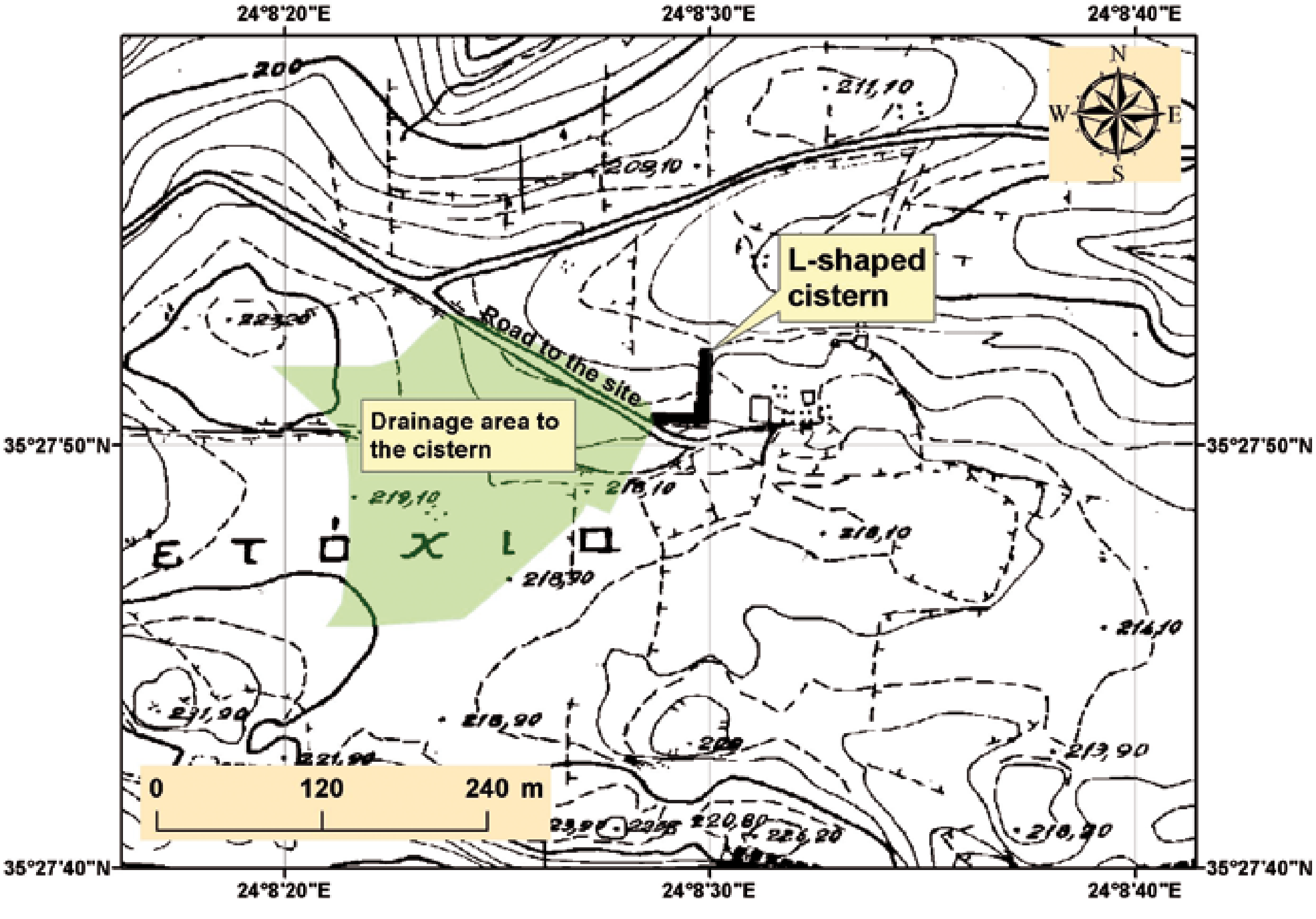

Figure 3. Superimposed results of the terrain-based hydrologic model (drainage area in green) on the topographic map. The road to the site coincides with the modelled northern boundary of the drainage area.

Figura 3. *Superposición del resultado del modelo hidrológico basado en el terreno (área de drenaje en verde) sobre el mapa topográfico. La carretera al lugar coincide con el límite norte del área de drenaje modelada.*

some thirty feet from the eastern boundary of the village." This setting can be applied to the Aptera site that also has several cisterns below the main L-shaped one. The length of the northern boundary of the modelled drainage area that coincides with modern road is almost 200 m.

Therefore we suggest a possibility for the existence of the ancient cut-off ditch as a means to intercept surface flow and pass it to the L-shaped cistern. It is also possible that the cut-off ditch provided a convenient base for the modern road construction. We can also hypothesize that after the last habitation and possible earthquake that put an end to the city, the ditch was abandoned, never cleaned and filled up with sediments. Because the ditch structure provided an already leveled surface, it is possible that the modern road was built on the top of it and covered the original surface.

To find an answer to the question about the existence of the subsurface structure under the modern road we used a geophysical survey as a standard tool to map buried objects without physical invasion or destruction of the surface material. The geophysical campaign included subsurface imaging using electromagnetic methods such as Ground Penetrating Radar (GPR) and a Transient Electromagnetic Method (TEM) along 200 m stretch of the road leading to Aptera that coincided with lower drainage area boundary. Integrated analysis of obtained subsurface data should reveal any remnants of the ditch-like structure under the road and will allow testing the presented hypothesis.

Area of study

Aptera is located in Crete near the coastline of Souda Bay (Figure 1). It is situated on a hill with elevation 231 m and was a convenient place for the monitoring of incoming ships and road traffic. The total area of the site is about 80 ha. According to the description of the Institute for Mediterranean Studies (Digital Crete, 2013), "Aptera (or Aptara, Apteria, Apteraia, Apteron) was one of the most important cities on the northern coast of western Crete." With its two ancient harbours, Kisamos and Minoa, located correspondingly near the modern villages of Kalyves and Kalami, Aptera was a busy commercial centre. The ancient city and its surroundings have not yet been systematically investigated. The large number of financial inscriptions and numerous coins demonstrate the city's commercial importance from the Late Classical to the Roman periods.

According to Digital Crete (2013) "the city may have been definitively destroyed during the Saracen conquest of Crete in AD 823. Under Nicephoros Phokas, Aptera was neither rebuilt nor re-inhabited, and the city's territory was divided into large estates. In 1118, Emperor John Comnene Kaloiannis ceded the territory of ancient Aptera to the monastery of Patmos; it has remained the monastery's property ever since. The settlement of Palaikastro that developed outside the city's fortification wall to the east in the Venetian period was destroyed by Khair-Eddin Barbarossa in 1538. Sultan Selim II caused further destruction in 1571. In the Ottoman period, Reuf Pasha used building material from the ancient fortifications of Aptera to build the nearby Izedin fort. The area remained uninhabited until the end of the 1866 revolution."

Methods

Ground Penetrating Radar (GPR)

Ground Penetrating Radar (GPR) has gained an increasing attention since the 1960s within the archaeological, geological and geotechnical geophysical community. The GPR system is composed of a signal generator, a transmitting and receiving antenna, as well as hardware to record and store the collected measurements. The transmitter antenna generates a small duration electromagnetic pulse at a frequency that is determined by the characteristics of the antenna. This pulse is transmitted into the ground and diffused in the subsurface materials depending on their electrical properties. Part of the pulse energy is reflected on the surface separating materials with different properties and is recorded by receiver while the remaining pulse energy is diffused at deeper levels.

The time between the transmitting and the receiving pulse depends on the velocity of the pulse. The time and velocity of electromagnetic wave propagation can help to determine the depth of the reflector. The conductivity and dielectric constant (relative permittivity) of geologic materials are the main parameters that affect the pulse propagation. The maximum penetration depth of the GPR depends on the absorption of electromagnetic waves. The absorption increases with frequency; therefore, a smaller frequency can be used for detecting deeper targets. On the other hand, an increase in frequency decreases the GPR resolution.

The literature refers to numerous applications of GPR, spanning different domains. These include the mapping of permafrost thickness (Annan and Davis, 1976), the detection of fractures in rocks (e.g. Olsson *et al.,* 1983), geological (e.g. Leggo, 1982) and geotechnical applications (e.g. Davis and Annan, 1989), contribution in forensic geophysics (e.g. Schultz. 2012), extensive mapping of buried archaeological structures (e.g. Leckebusch, 2003). The GPR data acquisition in Aptera was completed with Noggin Plus by Sensors & Software using 250 MHz. A total area of 900 square metres was covered with densely spaced parallel transects separated by 50 cm. The sampling interval along each profile was set to 5 cm. The specific field GPR layout allows the mapping of possible buried features up to a maximum depth of 2.4 m below the ground surface.

Transient Electromagnetic Method - TEM

TEM has been widely used in geoenvironmental studies and described in several textbooks and published research articles (Kanta *et al.*, 2013; Soupios *et al.,* 2010; Nabighian and Macnae 1991; Kaufman and Keller 1983). The method belongs to the so-called class of controlled source electromagnetic (CSEM) methods. A typical CSEM system consists of a transmitter (Tx) and a receiver (Rx) dipole (called "loops" in TEM) with varying sizes (2 x 2 m, 5 x 5 m, 10 x 10 m, 50 x 50 m, etc.) depending on the exploration depth. Specifically, an increase in Tx loop increases the signal to noise ratio (S/N), resulting in an increase in exploration depth (Kanta *et al.,* 2013; Soupios *et al,.* 2010; Barsukov *et al.,* 2007). A current passing through the Tx loop generates a primary, stationary field. The decay rate of this field depends on the distribution of the resistivity in the subsurface. Based on this principle, the measured voltage on Rx coil provides information about geoelectrical structures at several depths (Barsukov *et al.,* 2007). The acquisition of the TEM soundings in Aptera was done with the TEM-FAST 48 equipment (AEMR Company, Netherlands).

Figure 4. Area of the GPR survey. The direction of survey was from A to B.
Figura 4. *Área de la campaña GPR. La dirección de investigación fue desde A hasta B.*

Results

Ground Penetrating Radar Survey

The GPR sections were geo-referenced to local a X, Y coordinate system. The first peak was determined in order to define the initial meaningful signal from each line. This determination was based on the intensity percentage of the first reflected wave (5-30%). Based on the selected first peak line equalization was used to bring the first reflections of each line to a common starting time. Then data were filtered by AGC, Dewow and DC shift filters to enhance the reflected signal. Trace-to-trace averaging filter helped to clear the background noise and smooth the data. Finally, horizontal depth slices at different depth levels were created by the original vertical sections after estimating the velocity for the electromagnetic waves (0.1m/ns) according to the hyperbola matching method. In this way, the 3D volume of the subsurface will break down to individual slices/maps of specific width with increasing depth. Synthesis of the processed sections was accomplished with the GPR SLICE software (Goodman, *et al.,* 1995).

Figure 4 shows the area and direction of GPR survey (from A to B) whilst Figure 5 shows horizontal depth slices extracted from the 3-D GPR data. Hot colours (reddish colours) in the colour maps represent high intensity values attributed to strong subsurface reflectors. Bluish colours represent low intensity anomalies. The Surfer of Golden Software was used to rectify the geophysical maps and overlay them onto the topographic plan of the site.

The GPR survey was quite successful since it produced a number of linear features that can be clearly distinguished as high intensity reflectors. The GPR signals indicate a number of linear separated anomalies which are aligned in the south east – north west direction. They have a quite superficial appearance since they are registered within the depth range 20 to 60 cm below the ground of the road leading to the entrance of the archaeological site. It is also clear that these anomalies follow the same orientation. The attribute, linearity and the orientation of these anomalies could possibly justify the existence of a subsurface ditch to collect the water. The discontinuous nature of these linear anomalies could reflect that the ditch has been partially destroyed in some

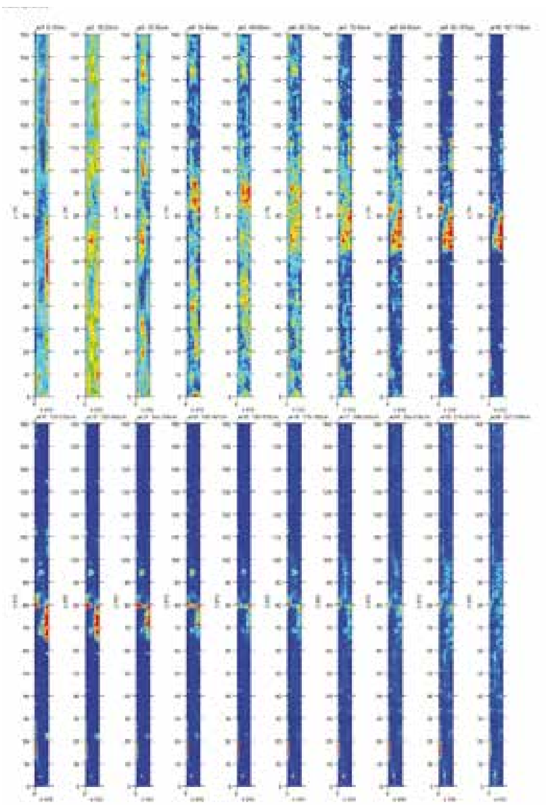

Figure 5. Horizontal slices at increasing depths extracted from the 3-D GPR data. The beginning of the survey (0 m) corresponds to letter A in Figure 3. The end of the survey (160 m) corresponds to letter B in Figure 3.
Figura 5. *Rebanadas horizontales a profundidades crecientes de los datos GPR 3-D. El comienzo de la prospección (0 m) corresponde a la letra A en la figura 3. El final de la prospección (160 m) corresponde a la letra B en la figura 3.*

places. Figure 5 shows an integrated image of the most prominent geophysical anomalies discovered by GPR arising from the contribution of each different depth slice to the compilation of this diagrammatic interpretation. The confidence level of the particular anomalies (potential targets) depends on the intensity of GPR signal.

Transient Electromagnetic Method

The first TEM surveys were conducted in March 2013 using a single square loop configuration with dimensions 10 x 5 m (Figure 7) and collecting 39 soundings along the road down to a depth of 20 m. The data were noisy with high Super ParaMagnetic effect

Figure 6. An integrated diagrammatic interpretation of the GPR geophysical anomalies that are registered within all the different GPR slices.
Figura 6. *Esquema interpretativo de las anomalías geofísicas GPR que se han registrado dentro de todas las rebanadas GPR.*

Figure 7. Preparation of the 10 x 5 m single loop for the TEM survey in the Aptera site.
Figura 7. *Preparación del bucle sencillo de 10 x 5 m para la investigación TEM en el yacimiento de Áptera.*

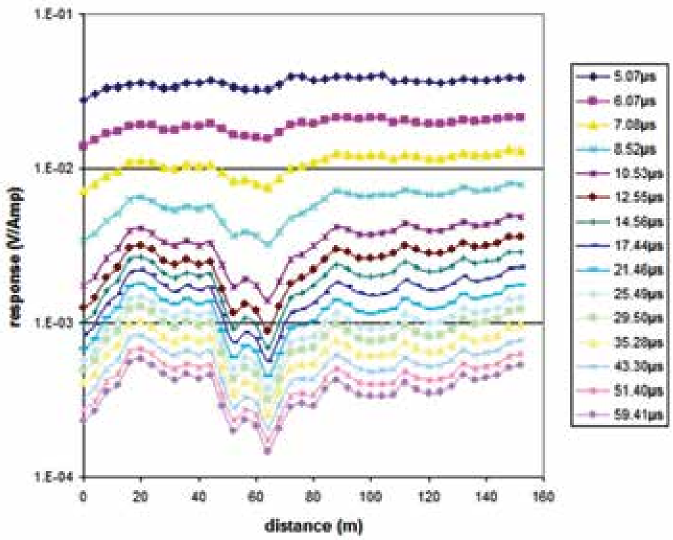

Figure 8. TEM curves for all transient times.
Figura 8. *Curvas TEM para todos los tiempos transitorios.*

(SPM) that could be caused by magnetic metal objects (e.g. fences, pipes), rocks with high concentration of magnetite, fired clay bricks, ceramics, etc. The TEM-RES software package was used for processing the apparent variations in resistivity to 1D profile to solve the inverse problem in time domain electromagnetic soundings.

The results from processing the TEM time series data collected with 10 x 5 m loop showed that all curves (for all transient times) are well correlated (Figure 8). Results also showed that late time (i.e. t > 20μs) responses are "metallic responses" with E~1/t (Figure 9). Because the "ground" and "metallic" responses (mainly from metallic fences along the road) could not be separated, it was difficult to invert the data and estimate the final 1D resistivity model. Therefore we concluded that the TEM-FAST data were noisy and the loop 5 x 10 m worked mainly as a metal-detector. Moreover, previous TEM studies in the vicinity of the Aptera showed that the bedrock has strong SPM properties (Soupios *et al.,* 2010; Nagata 1961; Neel 1950). To rectify these shortcomings we modified the TEM method and applied a smaller Tx-Rx loop in the differential TEM survey in June, 2013.

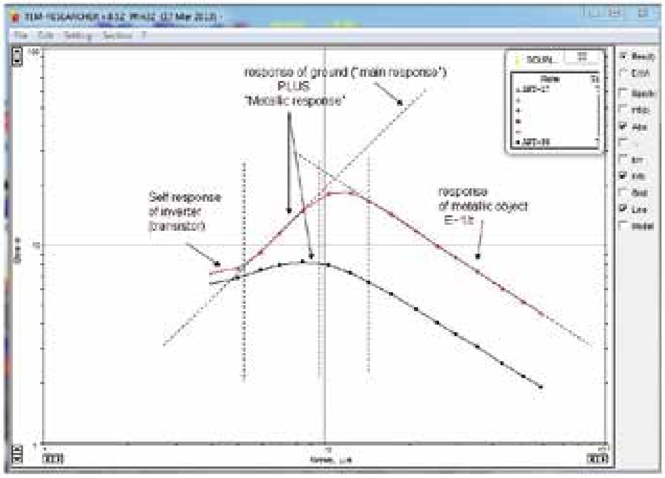

Figure 9. Resistivity curves for the 19th and 39th soundings.
Figura 9. *Curvas de resistividad para los sondeos 19 y 39.*

Data analysis from a previous survey also showed that about 10% of electromagnetic response (signal) was due to rock SPM and about 90% due to metal fences along the road and possible subsurface features. Since SPM is proportional to the loop size (Barsukov *et al.*, 2007), we changed the size of the loop to 2 x 2 m and also took measurements away from the fences (Fig. 10a,b), following the direction along the middle of the road. Thus, by subtracting the signal from different elevations E(h=0.14m)-E(h=1.30m) we expected to obtain SPM measurements directly from the unknown subsurface targets. The new method was based on the 2 x 2 m loop that was used to acquire measurements at two different heights from the ground (1.30 m and 0.14 m, see Figure 10a and 10b). 75 and 69 soundings were taken along the road for the high (1.3m) and the low (0.14m) loop, respectively and then the TEM measurements were combined for the final interpretation. In this new configuration the loop at 1.30 m above the ground was used for filtering anomalies produced by near surface objects.

The responses from different elevations for each measurement along the road were calculated for different time intervals (Figure 11). The data processed for all time gates but finally, t=14.56μs and t=29.60μs were used for the final interpretation since these time gates present the best signal coherency. Data show that the low (0.14 m) loop response is masked by surface heterogeneities. The high (1.30 m) loop response was the optimum and very stable providing reliable results till a depth of 5 m. Based on the final models (Figure 11), at least one SPM anomaly was determined (see blue filled rectangle between dashed lines). Since this anomaly is at least 5-10 times more than the survey errors and data were collected with high confidence, it can be possibly associated with the subsurface target located between 1.5 – 2 m (top) and 3 – 5 m (bottom) depth intervals.

From the geological point of view, we should mention that the study area is composed of carbonate rocks which formed the bedrock of the broader area. This rock is rich in SPM particles and produces a strong SPM effect which was verified by Soupios *et al.*, (2010)

Figure 10. (a) 2 x 2 m single loop 1.30 m above the ground; (b) the same loop, 0.14 m above the ground.
Figura 10. *(a) Bucle sencillo 2 x 2 m y 1.30 m sobre el terreno; (b) el mismo bucle pero 0.14 m sobre el terreno.*

(collecting TEM soundings using a 25x25m loop and/or 100x100m loop). The quaternary rocks (modern sediments) do not have these particles and do not produce SPM anomalies. Based on the TEM measurements and interpretation we can assume that a low level of SPM effect depicts a pit with modern rock inside.

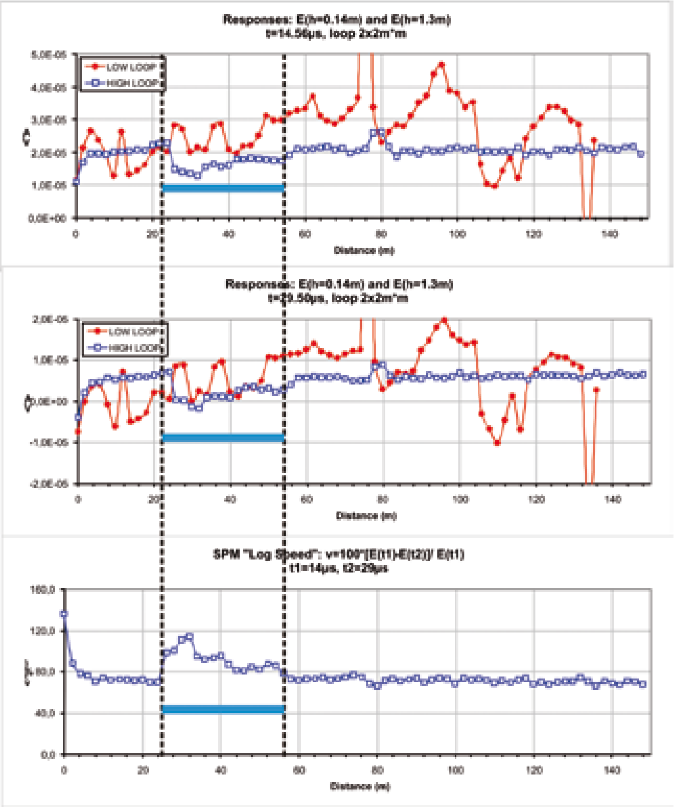

Figure 11. Responses from the different elevations (E(h=0.14 m)-E(h=1.30 m)) and obtained SPM anomaly.
Figura 11. *Respuestas desde las diferentes elevaciones (E(h=0.14 m)-E(h=1.30 m)) y anomalía SPM obtenida.*

Discussion and conclusions

This study demonstrates how a GIS terrain-based hydrologic model can help in identifying potential investigation sites for archaeological research. After the site had been identified, two different geophysical methods, GPR and TEM were used to discover a potential subsurface target that might be the remains of the hypothetical water supply structure, presumably a cut-off ditch. Both methods produced anomalies at different levels; therefore the comparison of the results is not straightforward. However, the combination of TEM and GPR models (Figure 12) shows that at least within the shallow part of the road there is some agreement in signal responses.

To increase the confidence in the obtained results it would be necessary to conduct different geophysical surveys (e.g. magnetic mapping, seismic refraction tomography or electrical resistivity) and integrate with the results of this study. In addition, factors such as rock properties and seasonality (e.g. wet *vs* dry season) add uncertainty to the interpretation of the final results. Hopefully, this study will stimulate enough interest to collect several samples and identify rock properties in the lab.

The GPR survey produced a number of linear separated anomalies which are aligned in the south east – north west direction. They have a quite superficial appearance since they are registered within the depth range 20 to 60 cm below the surface of the road leading to the entrance of the archaeological site. It is clear that these anomalies follow the same orientation. The attribute, linearity and the orientation of these anomalies could possibly justify the existence of a subsurface structure to collect water. The discontinuous nature of these linear anomalies may reflect the fact that the structure has been partially

Figure 12. Combined TEM and GPR results
Figura 12. *Resultados combinados de TEM y GPR.*

destroyed. A TEM survey revealed at least one anomaly coincidence with a GPR distinguished anomaly (Figure 12). The absence of other anomaly coincidences can be possibly explained by differences in responses/sensitivities of measuring techniques to geologic structure. The addition of another geophysical method (e.g. magnetic and/or seismic) would add more clarity and confidence to the obtained results.

Acknowledgements

The geophysical survey at Aptera (Chania) was carried out in the periods of 9-10 June 2012, March 2013 and 8-9 June 2013 under the collaboration of the Foundation for Research and Technology, Hellas (F.O.R.T.H.) and the Technological Institute of Crete with the Lehman College, City University of New York. Special acknowledgements to the 25th Ephoria of Prehistoric and Classical Antiquities in Chania for providing the permit to conduct the survey in Aptera archaeological site. The authors are grateful to Manolis Michalis and Xristos Panagiotidis, collaborators at TEI of Crete, for the great help during the GPR and TDEM data acquisition. The work was also supported by the project POLITEIA of Action KRIPIS of the General Secretary for Research and Technology under the framework of the operational programme "Competitiveness and Entrepreneurship – NSRF 2017-2013".

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Recibido: junio 2013
Revisado: febrero 2014
Aceptado: marzo 2014
Publicado: septiembre 2014