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ISSN 0016-8033 (print)
ISSN 1942-2156 (online)

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Case History

Exploration for a cave by magnetic and electrical resistivity surveys: Ayvacık Sinkhole example, Bozdağ, İzmir (western Turkey)

Çağlayan Balkaya¹, Gökhan Göktürkler², Zülfikar Erhan², and Yunus Levent Ekinci³

ABSTRACT

Geophysical survey techniques have been successfully applied to near-surface cave detection in karstic terrains. We used magnetic and electrical resistivity surveys to delineate the karstic structure of the Ayvacık Sinkhole, which may be considered to be a vertical cave. The magnetic-total-field-anomaly map helped reveal the metamorphic and sedimentary units in the study area. The total-horizontal-gradient map, which was based on a calculated pseudogravity anomaly, successfully identified the contact between the limestone unit and the cave system. Using these results, we positioned and carried out a vertical electrical sounding (VES) survey with a Schlumberger array along a line that consisted of 11 stations. The VES data were then processed using a 1D global optimization technique, which used a genetic algorithm and a 2D linearized least-squares algorithm. The results were generally in good agreement with each other, and together they pointed out three geologic layers: (1) an overburden layer (>316 Ωm), (2) an approximately 25-m-thick alluvial fill (100–316 Ωm), and (3) a limestone unit (316–3162 Ωm); and also suggested the existence of a high-resistive anomaly (>15000 Ωm), possibly a karstic cave, located at the depth of approximately 40 m. Also, the results suggested that the buried limestone unit had an undulating karstic topography including a probable pinnacle structure. A synthetic modeling study was carried out, and it validated the reliability of the results. Finally, our findings indicated that the geophysical survey techniques used here were successful in detecting a cave located deep enough to make human exploration difficult.

INTRODUCTION

A cave is here defined as a natural subsurface space that can be created by a variety of agents, including tectonism, pressure, atmospheric influences, erosion by water, chemical processes, and the activities of microorganisms (Wikipedia, 2012). Caves are mainly classified into four groups: limestone (solution), lava, sea, and ice (glacier) caves. Of these, limestone caves occur in karstic areas all over the world. These caves are formed in carbonate and sulfate rocks (e.g., limestone, dolomite, marble, and gypsum) as a result of the action of groundwater and rainwater moving slowly through them (Davies and Morgan, 1987). According to The Ministry of Culture and Tourism of The Republic of Turkey, approximately 40% of Turkey’s land surface is underlain by rocks that are suitable for karstification. Also, it is estimated that the caves in the country number more than 20,000. A total of 1250 caves have so far been investigated by the General Directorate of Mineral Research and Exploration (800) and various speleological societies (450). Because the popularity of cave tourism increases day by day, 13 of them have been opened to tourists. Among these, the Damlataş, Dim (Antalya), İnşuyu (Burdur), and Karaca (Gümüşhane) caves are best-known in the country.

The determination of the location, geometry, and dimensions of a cave is of great importance for civil engineering applications, including pile driving, tunneling, and the construction of dams and foundations, etc. (Armadillo et al., 1998). Exploration of a cave

Manuscript received by the Editor 2 August 2011; revised manuscript received 21 November 2011; published online 30 April 2012.

¹Süleyman Demirel University, Department of Geophysical Engineering, West Campus, Isparta, Turkey. E-mail: caglayanbalkaya@sdu.edu.tr.
²Dokuz Eylül University, Department of Geophysical Engineering, Tınaztepe Campus, Buca/Izmir, Turkey. E-mail: gokhan.gokturkler@deu.edu.tr; zulfikar.erhan@deu.edu.tr.
³Çanakkale Onsekiz Mart University, Department of Geophysical Engineering, Terziolu Campus, Çanakkale, Turkey. E-mail: ylekinci@comu.edu.tr.
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can be carried out by direct methods (i.e., mechanical soundings or drilling) or nondestructive geophysical survey techniques. The geophysical survey techniques are more effective and thus preferable to the other techniques, considering their lower cost and fast data acquisition (e.g., Leucci and De Giorgi, 2005; Monteiro Santos and Afonso, 2005). These techniques are based on the contrast of the physical properties, such as electrical resistivity, density, and magnetic susceptibility, between a cave and the surrounding host rock (El-Qady et al., 2005; Mochales et al., 2008).

The detection of a subsurface cave in a karstic terrain using a variety of geophysical survey techniques is one of the common and straightforward problems (e.g., van Schoor, 2002; Leucci et al., 2004; Monteiro Santos and Afonso, 2005) of engineering, environmental, and exploration geophysics, because the caves may be filled with air, water, clay, or mud depending on the local distribution of fractures and depressions. According to The National Research Council (NRC, 2002), geophysical methods for cave detection are classified into three groups based on their general applicability, even though there are many exceptions to these generalities. Electrical resistivity, electromagnetic ground-penetrating radar (GPR), and microgravity are primary methods, whereas seismic reflection and refraction are secondary methods. Induced polarization, airborne sensing, and magnetic methods are tertiary methods, defined as having limited or no general applicability to cave detection.

In the past few decades, researchers have widely used the primary methods in a karstic terrain: electrical resistivity tomography (ERT) (Smith, 1986; van Schoor, 2002; Zhou et al., 2002; Park et al., 2009; Fehdi et al., 2011), GPR (Chamberlain et al., 2000; Al-fares et al., 2002; Batayneh et al., 2002), and microgravity (Butler, 1984; Styles et al., 2005). The self-potential (SP) method, which does not have general applicability to caves, has been also used for their detection (Vichabian and Morgan, 2002). In addition, there are surveys for caves that used integrated geophysical approaches, such as ERT and GPR (Leucci et al., 2004; El-Qady et al., 2005; Leucci and De Giorgi, 2005; Şeren et al., 2008; Lazzari et al., 2010); ERT and microgravity (McGrath et al., 2002); ERT and seismic refraction tomography (Cardarelli et al., 2010); ERT and magnetic (Gibson et al., 2004); GPR and microgravity (Beres et al., 2001; Leucci and De Giorgi, 2010); GPR, microgravity, and magnetic (Mochales et al., 2008); gravimetry and ERT (Kaufmann et al., 2011); vertical electrical sounding (VES) and magnetic (Erhan et al., 2010); VES, ERT, and radioactivity methods (i.e., gamma ray) (Gautam et al., 2000). It is obvious that ERT is the most commonly used of the methods mentioned above, but the researchers using ERT have generally investigated only near-surface cave structures (less than 10 m deep) in a karstic terrain.

This study aimed to identify the karstic structure of a vertical cave by using geophysical methods, including VES and magnetic methods in the vicinity of the Ayvacık Sinkhole located between the districts of Ödemiş and Salihli (Figure 1). A detailed map of the study area superimposed over the topographic map is shown in Figure 2a. The
The study area is generally covered by metamorphic and sedimentary rocks, including schist and limestone, respectively. To display the subtle details in the magnetic map, a pseudogravity transformation was applied to the magnetic data set. Calculation of the pseudogravity anomalies followed by mapping of their steepest horizontal gradients may aid the interpretation of magnetic data by reflecting abrupt lateral changes in magnetization (Cordell and Grauch, 1985). The resulting anomaly map, showing the contrast in horizontal gradients between the cave system and the host sedimentary rock, was sufficient to produce a geophysical target and to limit the investigation area for the VES measurements. The apparent resistivity data obtained by using a Schlumberger electrode array were processed with 1D and 2D inversion techniques. The 1D VES data were processed with a global optimization technique based on a genetic algorithm (GA) (e.g., Başokur et al., 2007; Jha et al., 2008). Such an algorithm has some advantages compared with gradient-based (i.e., derivative-based) local optimization schemes (e.g., the linearized least-squares algorithm). For instance, GA yields solutions not dependent on an initial model, and it is also successful in avoiding becoming trapped in local minima. Concurrently, a 2D interpretation of the same data set was achieved by a linearized least-squares algorithm that yielded an image of the subsurface, including lateral resistivity changes.

**TECTONIC SETTING**

The study area is located in the west Anatolian extensional province characterized by major east–west and secondary northeast–southwest-trending grabens, including the Gediz (GDG), Küçük Menderes (KMG), and Büyük Menderes grabens (BMG), as shown in Figure 1 (Şengör et al., 1985; Seyitoğlu and Scott, 1992; Köçyiğit et al., 1999; Bozkurt, 2001). The horsts (i.e., Bozdağlar and Aydın Mountains) between these grabens are the other characteristic structures in the region, and they and the grabens compose the Menderes Massif (Bozkurt and Sözbilir, 2004). As seen from Figure 1, the Bozdağlar horst, which is a part of this horst-graben system of western Anatolia, is bounded by the GDG in the north and the KMG in the south. Gneisses, metamorphic rocks of the Menderes Massif, form the basement and are covered by limestone and metamorphic schist in the study area. The limestone has been recrystallized as a result of the repeated metamorphic processes, and karstification occurred at the end of geologic periods in the Miocene (Koçman, 1989).

**AYVACIK SINKHOLE**

Based on their morphologies, caves are generally classified into two types: horizontal and vertical. The first group consists of some nearly horizontal passages and the second one consists of shafts connected by short passages. The horizontal systems present easier caving and exploring opportunities than do the vertical systems that present difficult access and methodological constraints (Ballesteros et al., 2011). The Ayvacık Sinkhole is located between the Subatani and Ayvacık Plateaus of the Ödemiş district. The sinkhole is composed mainly of a vertical shaft rather than horizontal passages. Long-term erosion by water may cause development of such vertical cave systems in limestone. The cave entrance is approximately 2 × 2 m. According to the Archaeological Settlements of Turkey (TAY Project, 1998), surface water runoff (e.g., rainwater or snowmelt) seeps down into this active cave in the winter. The cave growth is initially vertical, but it expands horizontally below a depth of 120 m. The cave ends in a siphon at the depth of ~228 m. The total horizontal extent of the cave is 1822 m, according to well-known French speleologist Wolozan and his crew’s caving in 1992. The cave was also explored by Boğaziçi University Cave Exploration Society (BUMAK) in 1988 and Dokuz Eylül University Cave Exploration Society (DEUMAK) in 1997–1999, and present day investigations are carried out by DEUMAK (TAY Project, 1998).

**DATA ACQUISITION OF THE MAGNETIC AND ELECTRICAL RESISTIVITY SURVEYS**

Metamorphic and sedimentary rocks have low magnetic susceptibility values in general, but schists are characterized by a higher average susceptibility than that of limestone (Telford et al., 1990). Thus, a total field magnetic survey was performed to select the locations of the VES stations by determining the contact between the limestone and metamorphic unit (covered with alluvium). A total of 387 points were measured along six profiles (Figure 2b) using an ENVI-MAG proton magnetometer with a sensitivity of 0.1 nT. The World Geodetic System 1984 (WGS 84) was used for the positional datum. The sample interval along each profile was 5 m. The sensor height was 1.5 m from the surface. Readings recorded at a base station were used for diurnal variation corrections to remove the effects of the possible abrupt changes of the earth’s magnetic field from the data.

Based on the results of the magnetic survey, we set the locations of 11 VES measurements along a line running approximately south–north, as shown in Figure 2b. The VES measurements in the study area were collected by using the Schlumberger array, which is commonly used in VES studies, with a half-spacing ranging from 5 to 150 m. The stations and the orientation of the current electrodes were approximately along the line A (223 m long).

**ELECTRICAL RESISTIVITY INVERSION**

1D resistivity inversion

A GA is initialized by a randomly generated population (i.e., a set of solutions). Then, the fitness (i.e., the value of an objective function) of each individual (i.e., a solution) is evaluated. Obviously, the GA tries to maximize the fitness value; therefore the fitness must be taken as the inverse of the objective function that would be used in a minimization problem. The next step is the production of a new population, using the original one as the starting point. This is achieved by GA operators, which are selection, crossover, and mutation. To form a new population, two parents (i.e., two solutions from the original population) are selected by considering their fitness. They are crossed over with a crossover probability to generate two new offspring (i.e., new solutions). The new individuals are mutated with a mutation probability. The mutation helps the algorithm to avoid being trapped in local minima. The new generation is used for the next run of the steps above. The algorithm stops after reaching a specified, finite number of generations. The individual with the best fitness value is considered to be the solution of the problem (Obitko, 1998; Luke, 2009; Lee and Mohamed, 2002). In this study, a real-valued GA is used for parameter estimation. Elist selection and convex crossover methods are used for the generation of each new population. A population size of 100 individuals with a crossover probability of 0.7 and mutation probability of 0.1 was used in producing 100 generations. The following objective function, which corresponds to error energy, was considered during the parameter estimation
where $N$ is the number of observations, $\tilde{\rho}_o^i$ and $\tilde{\rho}_c^i$ are logarithms of the observed- and the calculated-apparent-resistivity data, respectively, and $i$ denotes each observation. The rms value is the square root of equation 1. The GA starts an inversion process with a randomly generated initial model within the predefined lower and upper bounds for the parameters (Tables 1 and 2). The inversion

Table 1. General parameter ranges for the GA and corresponding geologic units.

<table>
<thead>
<tr>
<th>Geologic units</th>
<th>Resistivity (Ωm)</th>
<th>Thickness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overburden layer</td>
<td>100–900</td>
<td>0.1–8</td>
</tr>
<tr>
<td>Alluvial fill</td>
<td>30–1000</td>
<td>3–40</td>
</tr>
<tr>
<td>Limestone</td>
<td>500–5000</td>
<td>3–30</td>
</tr>
<tr>
<td>Possible karstic cave</td>
<td>5000–30,000</td>
<td>—</td>
</tr>
</tbody>
</table>

Table 2. Parameter ranges used in GA.

<table>
<thead>
<tr>
<th>VES</th>
<th>Number of parameter</th>
<th>$\rho_1$ (Ωm)</th>
<th>$\rho_2$ (Ωm)</th>
<th>$\rho_3$ (Ωm)</th>
<th>$\rho_4$ (Ωm)</th>
<th>$\rho_5$ (Ωm)</th>
<th>$t_1$ (m)</th>
<th>$t_2$ (m)</th>
<th>$t_3$ (m)</th>
<th>$t_4$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>7</td>
<td>100–500</td>
<td>30–300</td>
<td>100–1000</td>
<td>500–5000</td>
<td>—</td>
<td>0.1–5</td>
<td>3–20</td>
<td>8–40</td>
<td>—</td>
</tr>
<tr>
<td>A2</td>
<td>7</td>
<td>100–700</td>
<td>30–500</td>
<td>100–1000</td>
<td>500–5000</td>
<td>—</td>
<td>0.1–5</td>
<td>3–20</td>
<td>8–40</td>
<td>—</td>
</tr>
<tr>
<td>A3</td>
<td>7</td>
<td>300–700</td>
<td>30–500</td>
<td>100–1000</td>
<td>500–5000</td>
<td>—</td>
<td>0.1–5</td>
<td>3–20</td>
<td>8–40</td>
<td>—</td>
</tr>
<tr>
<td>A4</td>
<td>7</td>
<td>500–1500</td>
<td>30–500</td>
<td>100–1000</td>
<td>500–5000</td>
<td>—</td>
<td>0.1–5</td>
<td>3–20</td>
<td>8–40</td>
<td>—</td>
</tr>
<tr>
<td>A5</td>
<td>7</td>
<td>100–600</td>
<td>30–500</td>
<td>100–1000</td>
<td>500–5000</td>
<td>—</td>
<td>0.1–8</td>
<td>3–20</td>
<td>8–40</td>
<td>—</td>
</tr>
<tr>
<td>A6</td>
<td>9</td>
<td>100–500</td>
<td>30–300</td>
<td>100–1000</td>
<td>10–500</td>
<td>500–5000</td>
<td>0.1–5</td>
<td>1–10</td>
<td>3–20</td>
<td>8–40</td>
</tr>
<tr>
<td>A7</td>
<td>7</td>
<td>100–500</td>
<td>30–300</td>
<td>100–1000</td>
<td>500–5000</td>
<td>—</td>
<td>0.1–5</td>
<td>3–20</td>
<td>8–40</td>
<td>—</td>
</tr>
<tr>
<td>A8</td>
<td>9</td>
<td>100–300</td>
<td>100–500</td>
<td>50–300</td>
<td>500–5000</td>
<td>5000–30,000</td>
<td>0.1–5</td>
<td>0.1–5</td>
<td>8–30</td>
<td>3–30</td>
</tr>
<tr>
<td>A9</td>
<td>7</td>
<td>200–400</td>
<td>50–300</td>
<td>500–5000</td>
<td>5000–30,000</td>
<td>—</td>
<td>0.1–6</td>
<td>8–30</td>
<td>3–30</td>
<td>—</td>
</tr>
<tr>
<td>A10</td>
<td>9</td>
<td>400–900</td>
<td>100–500</td>
<td>30–400</td>
<td>500–5000</td>
<td>5000–30,000</td>
<td>0.1–5</td>
<td>1–10</td>
<td>8–30</td>
<td>3–30</td>
</tr>
<tr>
<td>A11</td>
<td>7</td>
<td>400–900</td>
<td>30–500</td>
<td>500–5000</td>
<td>5000–30,000</td>
<td>—</td>
<td>0.1–5</td>
<td>8–30</td>
<td>3–30</td>
<td>—</td>
</tr>
</tbody>
</table>

Table 3. The best three solutions by GA for VES stations A1, A4, A7, and A11 at the end of 20 iterations. Best-fitting model parameters appear in bold face type.

<table>
<thead>
<tr>
<th>VES</th>
<th>Iteration</th>
<th>$\rho_1$ (Ωm)</th>
<th>$\rho_2$ (Ωm)</th>
<th>$\rho_3$ (Ωm)</th>
<th>$\rho_4$ (Ωm)</th>
<th>$t_1$ (m)</th>
<th>$t_2$ (m)</th>
<th>$t_3$ (m)</th>
<th>$t_4$ (m)</th>
<th>rms</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>4</td>
<td>250</td>
<td>135</td>
<td>260</td>
<td>2690</td>
<td>3.6</td>
<td>12.1</td>
<td>26.88</td>
<td>0.022</td>
<td></td>
</tr>
<tr>
<td></td>
<td>17</td>
<td>240</td>
<td>125</td>
<td>235</td>
<td>2015</td>
<td>4.2</td>
<td>9.7</td>
<td>23.8</td>
<td>0.021</td>
<td></td>
</tr>
<tr>
<td></td>
<td>19</td>
<td>245</td>
<td>130</td>
<td>285</td>
<td>3760</td>
<td>3.8</td>
<td>11.6</td>
<td>32.25</td>
<td>0.021</td>
<td></td>
</tr>
<tr>
<td>A4</td>
<td>11</td>
<td>775</td>
<td>165</td>
<td>280</td>
<td>3310</td>
<td>3.5</td>
<td>15.8</td>
<td>20.5</td>
<td>0.047</td>
<td></td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>860</td>
<td>175</td>
<td>145</td>
<td>4510</td>
<td>3.2</td>
<td>15.5</td>
<td>12.0</td>
<td>0.038</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>810</td>
<td>155</td>
<td>290</td>
<td>2730</td>
<td>3.5</td>
<td>15.8</td>
<td>17.9</td>
<td>0.049</td>
<td></td>
</tr>
<tr>
<td>A7</td>
<td>15</td>
<td>165</td>
<td>125</td>
<td>260</td>
<td>3310</td>
<td>1.5</td>
<td>10.2</td>
<td>29.9</td>
<td>0.033</td>
<td></td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>277</td>
<td>120</td>
<td>275</td>
<td>3980</td>
<td>1.2</td>
<td>10.6</td>
<td>32.4</td>
<td>0.034</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>140</td>
<td>115</td>
<td>325</td>
<td>3405</td>
<td>3.6</td>
<td>9.4</td>
<td>34.2</td>
<td>0.039</td>
<td></td>
</tr>
<tr>
<td>A11</td>
<td>9</td>
<td>745</td>
<td>180</td>
<td>3270</td>
<td>15,970</td>
<td>3.1</td>
<td>23.2</td>
<td>9.9</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>750</td>
<td>180</td>
<td>3270</td>
<td>18,370</td>
<td>3.0</td>
<td>23.1</td>
<td>13.0</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td></td>
<td>19</td>
<td>745</td>
<td>180</td>
<td>3340</td>
<td>19,780</td>
<td>3.1</td>
<td>23.2</td>
<td>10.2</td>
<td>0.04</td>
<td></td>
</tr>
</tbody>
</table>
of each VES data set is repeated 20 times, using a different starting model each time. Among the resulting parameter sets, the one with the minimum objective-function value is taken as the best-fitting model, i.e., the solution (Table 3).

2D resistivity inversion

Commonly, a resistivity cross section obtained from the 1D VES data is used to display VES results. It successfully identifies the layers with respect to the depth, but it may not produce satisfactory results in terms of lateral continuity and resolution. So, we applied a 2D inversion algorithm that uses a code developed by Uchida and Murakami (1990) to include vertical and horizontal variations in the solutions. The 2D algorithm uses a linearized least-squares inversion with a smoothness constraint based on a statistical criterion, namely the Akaike Bayesian information criterion (ABIC), to obtain a 2D resistivity distribution in the subsurface. Calculated resistivity data are obtained by a finite-element method in the forward modeling, and the algorithm iteratively updates the resistivity of each block by minimizing the misfit between the observed and calculated data. The algorithm has been widely used by researchers in various field studies, including geothermal exploration (e.g., El-Qady et al., 2000; Ushijima et al., 2000; Özurlan et al., 2006; Suparno et al., 2010), archaeological prospecting (e.g., El-Qady et al., 1999; Candansayar and Başokur, 2001), detection of cavities (e.g., Ulugergerli and Akça, 2006), and delineation of shallow resistivity structure (e.g., Balkaya et al., 2009).

RESULTS AND DISCUSSION

Magnetic survey

The total-field-magnetic-anomaly map is shown in Figure 3a. After calculating the residual-total-field anomaly by removing a planar horizontal trend from the data, a 5-m upward continuation process was performed to reduce possible noise and the effects of very near-surface sources. Figure 3b shows the upward-continued-anomaly map. It is obvious that the shortest wavelengths are largely removed whereas the basic anomalies still remain, although in a smoother form. As is known, metamorphic rocks often have low remanent magnetization (Blakely, 1995). The Königsberger ratio (the ratio of the two intensities, i.e., intensity of remanent magnetization/intensity of induced magnetization) for metamorphic rocks is less than one (Burger et al., 2006; Reynolds, 1997) and when this ratio is small (<1), remanent magnetization can be negligible in comparison to the induced magnetization (Lowrie, 2007). Because metamorphic units are dominant in the study area, it was assumed that the Königsberger ratio was less than one. This assumption validates and facilitates the use of some linear operations, such as reduction-to-pole (RTP) and pseudogravity transformations.

Figure 3. (a) Total-field-magnetic-anomaly map and (b) upward continued (5 m) anomaly map.

Figure 4. (a) RTP-anomaly map and (b) pseudogravity anomaly map.
An RTP transformation, which centers the magnetic anomalies over their respective sources by removing the skewness caused by the earth’s magnetic field, was applied to upward continued data by assigning 55° and 4° for the earth’s magnetic inclination and declination angles, respectively. Because the metamorphic rocks are expected to have much higher magnetic susceptibility than do sedimentary rocks, the relatively higher magnetic anomaly features are assumed to be related to the metamorphic rocks. They are clearly seen only in the north–northeast parts of the RTP image map (Figure 4a). Thus, the existence of a limestone-cave system in this part of the study area cannot be predicated solely on the basis of the RTP magnetic map.

Image enhancement techniques have the ability to display the subtle details in potential field data. The computation of directional derivatives is the most commonly used technique for contact and edge mapping. Because shallow bodies produce gravity anomalies with maximum horizontal gradients located nearly over their edges, transforming magnetic anomalies into ridges of maximum pseudogravity gradients may locate the edges of causative magnetic bodies (Blakely and Simpson, 1986). Additionally, gravity anomalies are in some ways more instructive and easier to interpret and quantify than are magnetic anomalies. Thus, a pseudogravity transformation, which converts a magnetic anomaly to an equivalent gravity anomaly, may be useful in interpreting magnetic anomalies (Blakely, 1995). Upward-continued-magnetic data were transformed into pseudogravity data using the same inclination and declination values used for the RTP calculation, and the resultant anomaly map

Figure 5. Total-horizontal-gradient of pseudogravity anomaly map.

Figure 6. Apparent resistivity data obtained from the VES measurement along the line A together with location map of the VES stations and cave entrance.
is displayed in Figure 4b. This enhanced image ensured the location of the anomalies with high magnitudes (in the north–northeast part of the map) as a result of the metamorphic basement. A map (Figure 5) of the total-horizontal-gradient of the pseudogravity was produced using some simple finite-difference relationships (Blakely, 1995). The elongated set of maximums encircled with a red ellipse shows an abrupt amplitude change in pseudodensity, which may be interpreted to indicate the contact between the limestone unit and the cave system. Taking into account the location of the cave entrance marked by a red square, we may infer that the cave system exists along the eastern edge of the set of total-horizontal-gradient maximums. The VES survey was located and carried out based on this result. Six VES stations were selected to coincide with the maximums shown in Figure 5.

**Electrical resistivity survey**

Apparent resistivity data (A1–11) obtained from the study area are shown in Figure 6. The data are mainly characterized by four- and five-layer VES curves. The apparent resistivities indicate a gradual increase from A1 to A11 and they almost reach 1000 Ωm at an electrode...
The apparent resistivity curves were divided into four groups (A1–A3, A4 and A5, A6 and A7, and A8–A11) (Figure 7). The grouping was done on the basis of similarities in their curves. Such a grouping of the VES curves was very useful for the determination of the general parameter ranges required by the GA (i.e., Table 1). Figure 8 shows the interpretation of some of the observed data, including the VES stations A1, A4, A7, and A11, respectively, based on 1D GA inversion. Table 3 shows the best three solutions for each of the four locations obtained by the GA at the end of 20 iterations. These data display four-layer, HA-type curves ($\rho_1 > \rho_2 < \rho_3 < \rho_4$). The top, relatively high-resistivity overburden layer (165–860 $\Omega$ m) may be caused by dry soil at and near the surface. The second and third layers, with resistivities between 125 and 260 $\Omega$ m in the models, correspond to alluvial fill in the study area. The lowermost layer at A1, A4, and A7 has relatively higher resistivities (between 2015 and 4510 $\Omega$ m) originating from the limestone. The fourth layer at A11 with the highest resistivity (15,970 $\Omega$ m) may indicate a possible air-filled cave.

Figure 9 displays a geoelectrical resistivity cross section constructed from 1D GA interpretations of the VES data displayed in Figure 6. These column sections include the solution at each VES point. A large search space for parameters (i.e., resistivity and thickness) was used for finding the solutions (see Table 2). The models were obtained with rms errors in the range of 0.021–0.044. The interpreted results mainly reveal the presence of the three geologic layers mentioned above, whereas only a few locations exhibit the presence of a possible cave characterized by the highest resistivity (>15,000 $\Omega$ m). These anomalous locations are at the northern end of the section along the line A (the lowermost layers of the VES stations A8–A11) and in the vicinity of the cave entrance. The overburden layer exhibits resistivities in the range of 165–860 $\Omega$ m, and the thickness of this layer varies from 1.5 to 5.6 m. The second layer (alluvial fill) is dominated by lower resistivity values (90–330 $\Omega$ m) and displays an average thickness around 30 m (between approximately 20–40 m). As also shown in Figure 9, the thickness of the alluvial fill gradually...
decreases toward the northern end of line A. The lowermost, relatively high-resistivity layers (1975–4510 Ωm) at VES stations A1–A7 and the third layer (2515–3270 Ωm) at VES stations A8–A11 represent the sedimentary limestone layer separated from the upper alluvial fill by an undulating boundary. The highest resistivities along the section are seen between VES stations A8–A11 and at elevations below 957 m. This may indicate the presence of a possible air-filled cave in the study area. Because this type of geoelectrical section, obtained by 1D inversion of VES data, inherently lacks resolution in the lateral direction, we employed 2D inversion to acquire better resolution in the lateral and vertical directions.

The same VES data set was processed using a 2D inversion algorithm described by Uchida and Murakami (1990). The model mesh consisted of 22 × 30 cells. A homogeneous initial model consisting of an average of the observed apparent resistivities (350 Ωm) was used to initiate the 2D inversion process. The algorithm is very stable because it can handle very different initial models, i.e., starting with resistivities 10 times greater and 10 times smaller than the average value (see Öztürk et al., 2006; Balkaya et al., 2009). The observed-apparent-resistivity pseudosection acquired along line A and the calculated-apparent-resistivity pseudosection demonstrate apparent resistivities in the range of approximately 110 to 1000 Ωm (Figure 10a and 10b, respectively). The solution is shown in Figure 11a and it is in good agreement with the pseudosections displayed in the previous figure. The rms error is 0.044 at the end of six iterations, as indicated on the figure. To improve the appearance of the model in Figure 11a, the solution was regridded to a finer grid spacing in Figure 11b. The contours of the resistivity values (for arbitrary choices of log [Ωm]) of the layers were also superimposed on Figure 11b. The overburden layer is represented by relatively

Figure 12. Comparison between the resistivity distributions obtained from 2D inversion and that from the 1D layered model from the GA algorithm.

Figure 13. Observed- (empty blue circles) and calculated-apparent-resistivity data of VES stations A1–A11, obtained by 1D (green continuous line) and 2D inversion (red continuous line), together with location map.
high-resistivity values (greater than the 316 Ωm that corresponds to \(2.5 \log[Ωm]\)) indicating dry soil near the surface. Beneath this, there is a layer of alluvial fill characterized by relatively lower resistivity values (100–316 Ωm). The thickness of this layer varies between approximately 14 and 37 m, and it is deeper beneath VES stations A2 and A3, and A6 and A7, respectively. The bottom layer (limestone unit) with resistivity values ranging from 316 to 3162 Ωm (i.e., from 2.5 to 3.5 \(\log[Ωm]\), respectively) is considered to be bedrock (Figure 11b). As can be seen in the section, the limestone unit is separated from the upper alluvial fill by an undulating boundary that may indicate a pinnacled surface of buried limestone, having steep cliffs (see Figure 2 in Abu-Shariah, 2009). A high-resistivity anomaly is observed under VES stations A8–A11 (>3162 Ωm), approximately at horizontal distances between 0 and 60 m, and it is interpreted to be a possible air-filled cave within the limestone unit. As seen from Figure 12, there is a reasonable agreement between the resistivity distribution in Figure 11b and the one in Figure 9. A comparison between the theoretical apparent resistivity curves obtained from 1D and 2D inversion and the observed-apparent-resistivity data for all VES stations are shown in Figure 13. Clearly, the results are quite consistent with one another.

**SYNTHETIC MODELING**

We also carried out a forward calculation using a synthetic model that was constructed based on the results from 1D and 2D inversion of the VES data to assess the reliability of our inversion results discussed above. Figure 14a shows the synthetic model together with assigned resistivity values for the overburden layer (400 Ωm), alluvial fill (160 Ωm), limestone unit (3980 Ωm), and the expected air-filled cave (15,850 Ωm). The expected high-resistivity, air-filled-cave anomaly, 60 m wide, is located at the bottom left side of the synthetic model beneath VES stations A8–A11. The model mesh consisted of 22 × 30 cells as with the field data. Then, this synthetic data set was 2D inverted. The solution and interpreted section of the model are shown in Figure 14b and 14c, respectively. The inverted model was obtained at the end of four iterations with an rms error of 0.0093. The interfaces in the synthetic model are overlain on the section in Figure 14c. As clearly seen from this figure, the main features of the synthetic model and the expected air-filled cave anomaly, extending from 0 to 60 m in the lateral direction, stand out in the results. Comparing the solution for the synthetic model with the one obtained from the field data reveals the vertical smearing effect of the inversion at the interface between the alluvial fill and limestone unit. This smearing is attributable to the high-resistivity contrast (a factor of approximately 25) between the units. Thus, this synthetic test provided very useful support to our interpretations.

**CONCLUSIONS**

The results presented in this paper illustrate that the methods — electrical resistivity and magnetic — and the evaluation techniques described here worked well for investigating and mapping a deep cave in a karstic area. The magnetic method and the use of linear transformations yielded a good estimation of the location of the contact between the limestone and metamorphic unit and helped position the VES stations. An electrical resistivity survey showed a possible cave beneath the VES stations A8–A11 at a depth of approximately 40 m and a limestone surface that may display pinnacles and/or steep cliffs. A 1D inversion of the VES data by the GA yielded results that were comparable with those obtained from a 2D linearized inversion. The synthetic modeling study was a useful way to examine the credibility of interpretations obtained by them. Thus, we believe that the presented methods and evaluation techniques could be successfully applied to additional work in this and other settings, and perhaps to related geophysical problems.

**ACKNOWLEDGMENTS**

The authors thank the Department of Geophysical Engineering, Dokuz Eylül University, for support during the field work. We also thank M. Fatih Büyüktopçu (DEUMAK and Department of Civil Engineering, Dokuz Eylül University) for informing us of the


