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# Selected Radar Images of Man-made Underground Galleries

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ABSTRACT Ground-penetrating radar (GPR), as a high-resolution geophysical prospecting method, has proved to be a very useful tool in archaeological site investigations, especially in the detection and identification of tunnels and galleries. This work shows seven selected profiles collected at four different archaeological sites in Spain and Mexico, with a wide variety of targets, not only in terms of their size (from 1 × 1 m to 3 × 4 m) but also in their depth (from 0.5 to 7 m). In all, 14 galleries and/or tunnels were detected. The approach to these studies was organized in two ways: firstly the presence of a known subsoil was used to compare the response of different antennae looking for these kinds of targets; secondly, GPR was used to find unknown historical galleries before any excavation took place. The equipment used in these studies were the SIR-8, with 120 and 500 MHz monostatic antennae, and PulseEkko IV, with 100 MHz bistatic antennae. Copyright © 2002 John Wiley & Sons, Ltd.

*Key words:* remote sensing; ground-penetrating radar; radar; archaeology

## Introduction

The suitability of ground-penetrating radar (GPR) in the location of galleries or tunnels beneath the ground is attributable to the high electromagnetic contrast between them and the material which surrounds them. From the point of view of GPR, a cavity (natural or anthropogenic) is seen as an air volume situated in the natural soil or rock. Hence, this electromagnetic contrast will be between the air parameters and the soil or rock parameters, which is clear if the signal does not attenuate in its two-way travel of transmitter–reflector–receiver. Fortunately, in many cases they are shallow reflectors, at least for archaeological investigations, and this facilitates their detection with GPR.

One of the most important characteristics of a gallery is its vaulted ceiling, which appears in radar profiles as a clear hyperbola. The appearance of this reflection hyperbola depends on many factors: depth and size of the gallery, number of traces detecting it, antenna or antennae used, etc. One more characteristic that aids identification of these reflectors is the usual presence of reflections from their floor.

Antennae with a 100–500 MHz centre frequency are best suited for archaeological gallery detection. 500-MHz antennae have limited ground penetration, but they give a very high-resolution map of the subsoil in the first 2–3 m. Below this depth, lower frequency antennae work better, but those with a centre frequency below 100 MHz have insufficient resolution to locate smaller galleries.

First references of the use of pulse radar for geophysical prospection are from the 1970s, with mining and geology applications (Unterberger, 1974; Annan and Davis, 1976; Rubin and Fowler,

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1977). A common aim of these works was to find out the best penetration conditions in subsoil. In the 1980s, GPR started to be used for shallow investigations, where attenuation phenomena are less, using 500 MHz to 1 GHz antennae, which give an appropriate resolution (Ulriksen, 1982; Glover, 1987). During this period it is possible to find the first applications of GPR in archaeology (Hara and Sakayama, 1984; Imai *et al*., 1987). In the 1990s, new antennae with lower (10, 20 and 50 MHz) and higher (2.5–3 GHz) centre frequency were used for the GPR and this allows its use in many new applications: glaciology, pavement inspection, mine detection, construction, etc. Also, in recent years, many examples can be found in the literature where GPR surveys were used successfully at different archaeological sites (Kong *et al*., 1992; Goodman, 1994; Conyers *et al*., 1996; Lorenzo and Hernández, 1997; Tohge *et al*., 1998). Some of these surveys were made inside historics buildings, such as Pérez *et al*. (1998) in the Cathedral of Valencia (Spain), Lorenzo *et al*. (1998) in La Alhambra of Grenade (Spain), Vaish and Sharma (2000) in Taj Mahal (India) or Colla and Maierhofer (2000) in St Nicolo Cathedral in Noto (Italy).

## Case histories

Four case histories are summarized to show how GPR can be used to obtain detailed information of archaeological galleries and tunnels. Three of these cases are located in Spain: La Alhambra (Grenade), Santa Helena Castle (Grenade) and Alcalá University Campus (Madrid); the last case is located in Cuicuilco Remains in Mexico D.F. Seven profiles are selected, most of them from La Alhambra, where a known subsoil was used to study the response from 120 and 500 MHz antennae looking for galleries of different sizes and at different depths. This situation is the same in Cuicuilco Remains, where a known 7 m deep natural tunnel at the interface between the basalt and the soil was detected with a pair of 100 MHz antennae operating in bistatic mode. In the two other cases, there were historical references to the presence of a gallery/tunnel on both sites. In Alcalá, an old Arab water conduit was detected at a depth of 3.5–4 m with a 120 MHz antenna. In the vicinity of Santa Helena Castle, a hyperbolic reflection appears at 40 ns two-way travel (twt) time in the profile obtained with the 500 MHz antenna; the excavation revealed the presence of a small and very sloping tunnel at a depth of 3.5 m.

### *La Alhambra (Grenade, Spain)*

Figure 1 shows the basement of the Ambassadors Hall (Salón de Embajadores) in Comares Tower of La Alhambra. The presence of three vaulted galleries, $2 \times 3$ m in size and at a depth of 2 m and the profiles of 15 m can be seen, obtained with a 500 MHz antenna, two-way travel time range of 40 ns (Figure 1, centre), and a 120 MHz antenna, range of 80 ns twt time (Figure 1). In the profile obtained with the 500 MHz antenna, it is possible to recognize the presence of three very clear hyperbolae centred at 3, 7 and 11 m at a 30 ns twt time associated with the reflection of the pulse at the ceiling of the galleries; this gives a signal velocity of 15 cm ns$^{-1}$. Between 1–2 and 13–14 m a distortion appears, related to two marble slabs on the floor of the hall. The profile of the 120 MHz antenna doubles the time range. lts low resolution impede neither the detection of the reflections from the ceilings of the galleries nor the reflections from their floors. The time distance between them, 20–22 ns, indicates a 3–5 m maximum height to the galleries.

Figure 2 shows another (transverse) section of the basement of the Comares Tower and the profile attained with the 500 MHz antenna over it. The profile is 19 m long and 40 ns twt time range. The room of the first 2 m is a transverse view of the central gallery shown in Figure 1. There is another gallery situated between 3 and 4 m, which is 1 m wide, 2.5 m high and at a depth of 2 m; the time range selected does not allow the detection of reflections from its floor. The reflections from the very shallow 5 m long room situated between 5 and 10 m are partially hidden because of the presence of a marble slab situated at 7–8 m. It is easy to recognize two large hyperbolae associated with the ceiling and floor of the 4 m wide, 3 m high and 0.5 deep room situated between 12 and 16 m. The last gallery detected (at a depth of 17–18 m) has similar dimensions to the small one found at 3–4 m but its depth is

 

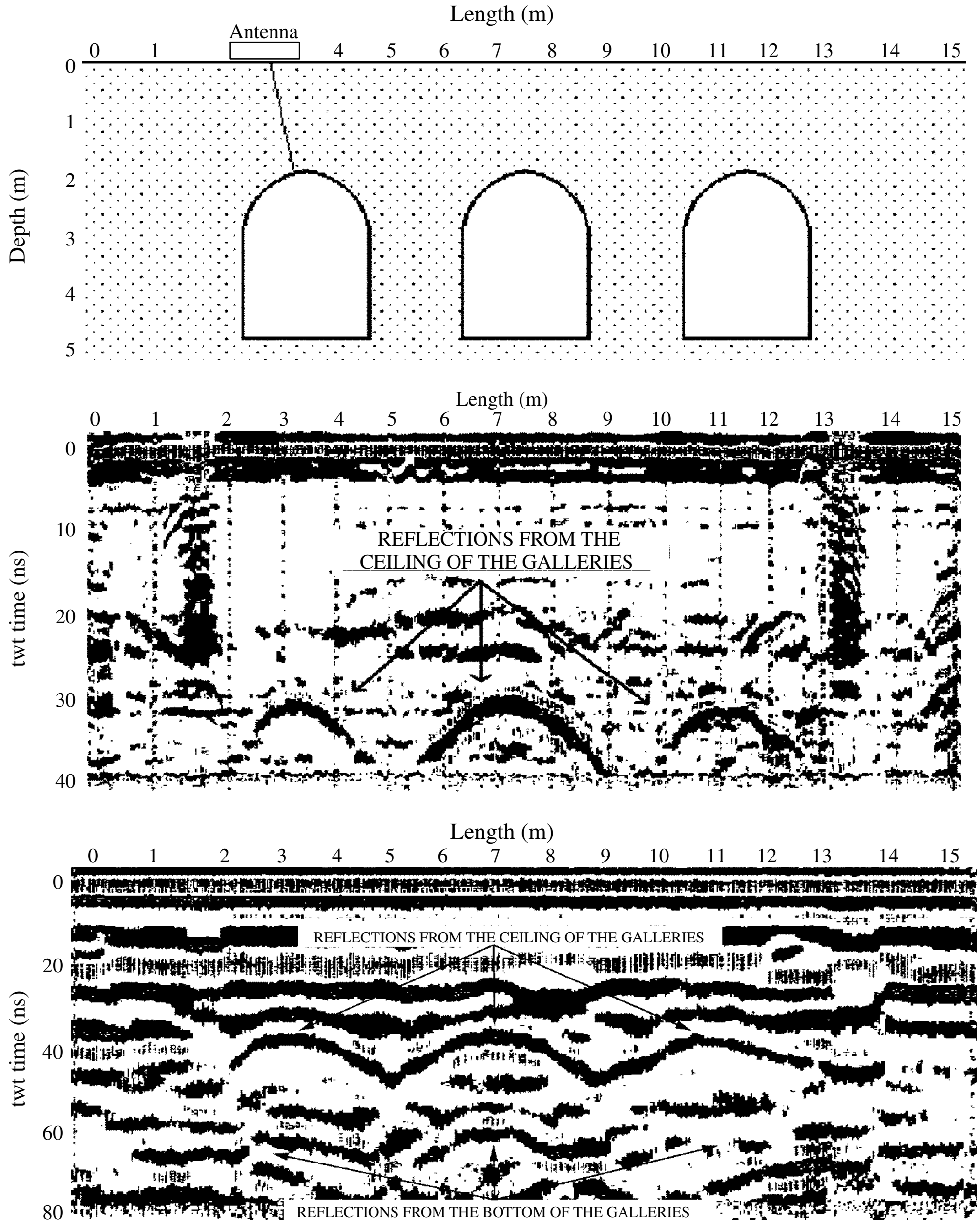


Figure 1. Subsoil beneath Salón de Embajadores, with reflections from three galleries at a depth of 2 m detected with a 500 MHz antenna (centre) and ceiling and floor of these galleries detected with a 120 MHz antenna (bottom).

less, about 1 m. It is also possible to recognize the reflection from its floor at 30 ns twt time. A distortion appears between the last two galleries owing to the presence of a new marble slab.

Finally, Figure 3 contains the last section studied in Comares Tower, with a length of 11 m, where three very shallow vaulted rooms are present. The rooms are 1.5 m wide, 3 m high and less than 0.5 m deep; the distance between them is 0.5 m. The lower part of Figure 3 is the wiggle format radargram over this section, obtained with the 500 MHz antenna. The hyperbolae from the ceilings are easy to recognize, and the reflection from the floor of the central room is stronger than

 

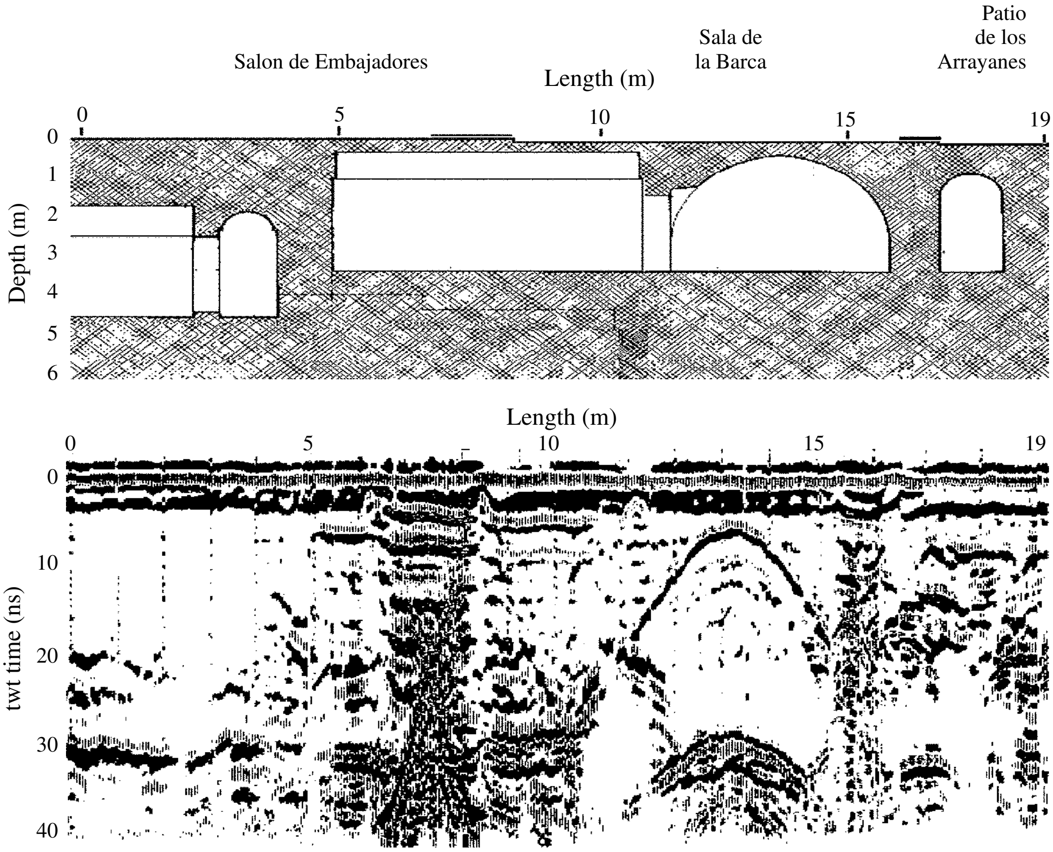


Figure 2. Subsoil beneath Comares Tower of La Alhambra and radargram attained with a 500 MHz antenna detecting five different size galleries and rooms at different depths (bottom).

the reflection from the other two floors. Also, at a range of 20 ns, it is possible to appreciate the effect of the complicated geometry of all the reflectors combined; the profile has not been processed.

## *Santa Helena Castle (Grenade, Spain)*

Santa Helena is a Moorish castle situated near to the city of Granade, on the top of a hill overlooking La Alhambra. The aim of the GPR study at this site was to investigate the shallow subsoil close to the structure of the Castle, where a large crack had appeared. This crack would be in relation to the presence of a man-made tunnel to which there were historic references. This tunnel could start anywhere in the castle and end at any point on the slope of the hill. References stated that its purpose was an exit for water, rubbish, etc., and was used occasionally as an emergency exit from the castle. Tunnel depth and size were unknown. Figure 4 contains a representative radargram of the results obtained in this study.

The profile, carried out using a 500 MHz antenna with a two-way travel time range of 60 ns, is 8 m long and it runs parallel to a wall of the building. A hyperbolic reflection appears at a time range of 40 ns at 3 m on the radargram, very close to the wall crack; the estimated velocity was 15 cm $ns^{-1}$, which gives this tunnel a depth of 3 m. The hyperbola geometry and the impossibility of making a clear separation between ceiling and floor reflections suggest that it is a small tunnel. An excavation was done at 3 m of the profile, with the detection of a very sloping tunnel at a depth of 3.5 m. Owing to its slope and small size it is impossible to stand up in the tunnel. The tunnel is partially collapsed.

 

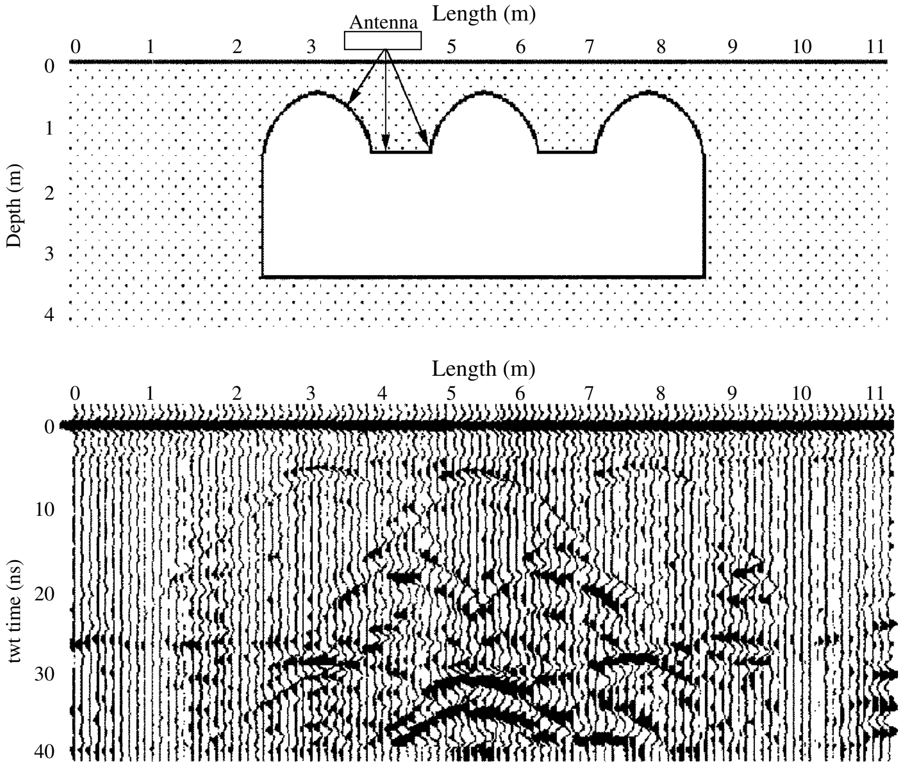


Figure 3. Detection of three very shallow galleries with a 500 MHz antenna. It is possible to recognize the reflections associated with their floors.

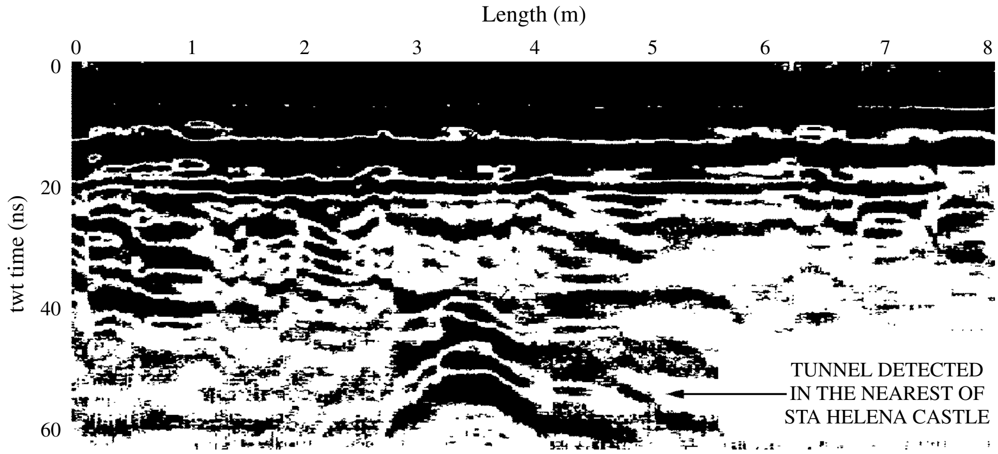


Figure 4. Detection of a small man-made tunnel in the vicinity of Santa Helena Castle in Grenade (Spain). Its estimated depth is 3 m.

## *Alcalá University Campus (Madrid, Spain)*

Figure 5 shows the radargram obtained in the vicinity of the University Campus of Alcalá, detecting an old subsoil water conduit from the Arab age. The presence of these galleries is known all around the city of Alcalá, but not all of them are mapped.

The study was done with a 120 MHz monostatic antenna in a zone where another

 

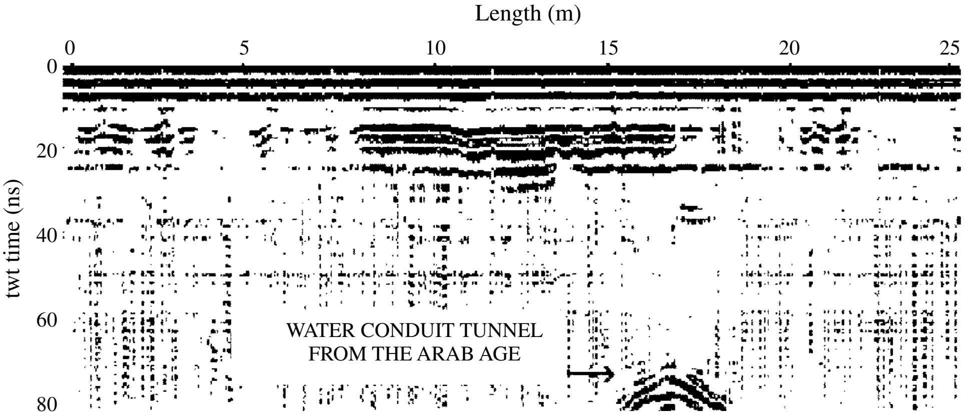


Figure 5. Reflection resulting from an Arab age tunnel detected at a depth of 3.5–4 m. The profile was attained with a 120 MHz monostatic antenna.

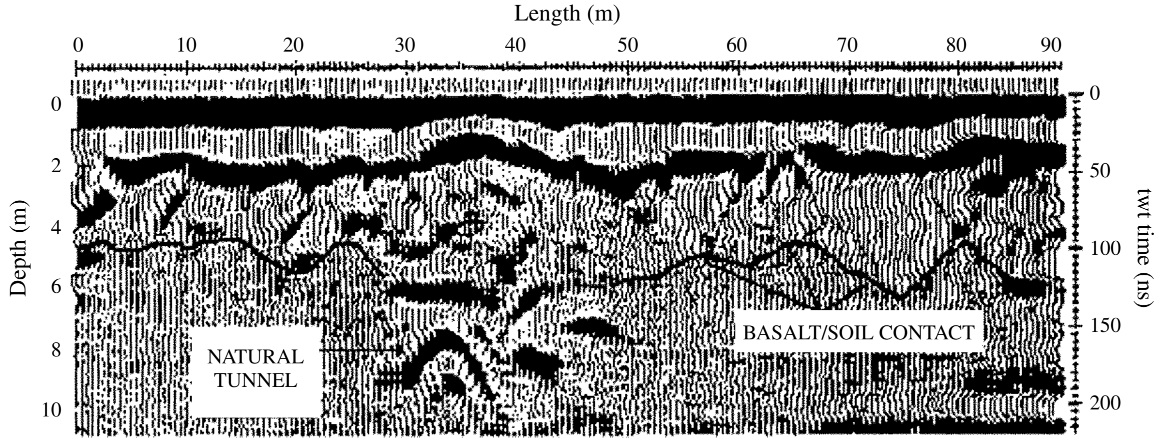


Figure 6. Detection of a natural tunnel in Cuicuilco (Mexico D.F.) at a depth of 6–7 m at the basalt–soil interface using a pair of 100 MHz antennae operating in bistatic mode.

geophysical investigation had found some of these conduits. The radargram of Figure 5 is 15 m long and 80 ns twt time range, being one of the best of the data obtained. A clear isolated reflection hyperbola appears at a time range of 70 ns, which corresponds with an approximate depth of 3.5–4 m. The known galleries explored on Alcalá are not large (no more than 1 × 2 m). This means that we are close to the resolution limits of this antenna, so the use of higher frequency antennae would be more appropriate. In our opinion, the detected gallery is more than 1 × 2 m. The profiles attained with 500 MHz show no reflectors, owing to the depth of the conduit and the higher attenuation of its signal.

## *Cuicuilco remains (Mexico D.F., Mexico)*

The last case study selected was undertaken in the remains of Cuicuilco, a very popular archaeological site near to Mexico City. The area of Cuicuilco was buried by a volcanic eruption, being partially excavated in the first half of this century; the excavation made evident the presence of a natural tunnel under the basalt layer. This tunnel is accessible from an excavated trench and its size is very variable, with some parts 4 m high and 3 m wide. This site was used to make some tests with GPR to try to detect it; Figure 6 is representative of the response of radar search.

This radargram was attained with a pair of 100 MHz antennae operating in bistatic mode;

 

the separation between the antennae was 1 m, the same distance selected for each trace collected. The profile is 90 m long and the time range is 200 ns, which allows information to be obtained from the first 10 m of subsoil. The hyperbolic reflection that appears between 30 and 40 m indicates the presence of the tunnel, together with other reflections that could result from cracks in the basalt. Also visible is the contact between the basalt and the soil along the profile, with the presence of many basalt cracks all over it (not only near the tunnel, but also at 2, 10, 20, 52, 65 and 85 m).

## Conclusions

The present work shows four site investigations aimed to demonstrate the possibilities of ground-penetrating radar in the detection of archaeological galleries and tunnels. The contrast between the electromagnetic parameters of the void and the soil or rock surrounding makes their detection easy, revealing hyperbolic reflections in radargrams. One more advantage of the use of GPR for these investigations is that an archaeological site is usually shallow, which facilitates the use of mid-frequency antennae (100–500 MHz) with an improvement in the resolution attained. In some good conditions it is possible to recognize reflections from the floor of these targets, giving an idea of their dimensions.

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