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# GROUND PENETRATING RADAR AS NONINVASIVE METHOD USED IN SOIL SCIENCE AND ARCHAEOLOGY

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## Abstract

Ground penetrating radar (GPR) is a non-invasive geophysical method that has been used primarily in geophysical exploration and civil engineering, to investigate the shallow subsurface of the earth, to identify the structural integrity of buildings, tunnels, roads, bridges or airport runways, and to detect pipes and cables. From the 1970s, the range of applications has been expanding, and now includes subsurface soil horizons identification, estimation of the thickness and characteristics of soil organic materials, assessment of water table depth, measuring soil water content, borehole inspection, archaeological sites and forensic investigations.

GPR has significantly improved the efficiency of the exploratory work in soil and archaeological survey due to its capability to provide an image of the subsurface and accurate depth estimates for many common subsurface objects or soil horizons. It can also provide information concerning the nature of buried objects.

There is a considerable amount of literature written on the uses of GPR in environmental and engineering applications. This paper presents a general review on this method applied in soil and archaeological investigations and also the capabilities and limitations of GPR applications in these domains.



*Keywords:* GPR, soil science, archaeology.

## 1. INTRODUCTION

Ground penetrating radar (GPR), also known as "ground-probing radar", "sub-surface radar", "surface-penetrating radar" (SPR) or "impulse radar", is a radar system designed for shallow (0–30 m) subsurface investigations, which transmits short electromagnetic pulses usually in a 10 MHz to 1.2 GHz frequency range. The term "surface-penetrating" describes most accurately the application of the method to the majority of situations including buildings, bridges, etc. as well as probing through the ground (Daniels, 2004). However, the term "ground penetrating radar" has become universally accepted and will be used in this paper.

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In *soil science* GPR has been applied since the late 1970s. It has been used to estimate thickness and characteristics of soil organic materials (Collins et al., 1986), depth of the water table (Doolittle et al., 2006), soil moisture content (Huisman et al., 2001, 2002, 2003; Galagedara et al., 2005), hard pan depth (Raper et al., 1990), permafrost (Doolittle et al., 1990), detecting illuvial lamellae in sandy soils (Tomer et al., 1996; Boll et al., 1996), assessing Bt horizon character in sandy soils (Mokma et al., 1990), spatial variability of depth to Bh horizon (Burgoa et al., 1991), mapping the depth to the texture contrast horizon of duplex soils (Simeoni et al., 2009) and to estimate the depth to buried palaeosols (Chapman et al., 2009). GPR has been also successfully used to update soil survey information and classify soils (Doolittle, 1987; Schellentrager et al., 1988, 1991; Collins, 1992), to improve soil-landscape models by systematic sampling (Doolittle et al., 1988) and for high resolution mapping of soil (Davis et al., 1989).

GPR is also commonly used in *archaeological* investigations since the mid-1970s. GPR was used to look for radar reflections from buried walls and a variety of other historic structures (Bevan and Kenyon, 1975; Bevan, 1977; Vickers and Dolphin, 1975); to locate voids, inconsistencies and buried metal work in a wide variety of structures: mediaeval cathedrals, castles, Egyptian pyramids and even the Ark (Filder, 2004); to investigate burial mounds (Goodman et al., 2009); to confirm the location of ancient structures (Gracia et al., 2000); for prospecting Roman buildings and sites (Eder-Hinterleitner et al., 2001; Neubauer, 1999; Piro et al., 2001; Seren et al., 2001; Goodman et al., 2002, 2004, 2009); monitoring of monuments as ancient fountains, historical bridges, historical buildings, statues (Solla et al., 2011; Sambuelli et al., 2009), identification of walled rooms, crypts, tombs, hidden frescoes and so on (Pieraccini et al., 2006; Grasso et al., 2011). Another issue of interest is the field of preventive archaeology - that is, the preventive prospecting of areas where something is going to be built (a road, a building, an underground station, etc.). This mitigates the risk of destroying archaeological sites and also diminishes the economic risk that the works will be stopped by a Cultural Heritage Institution (Persico, 2014).

Despite international recognition of the applicability of GPR in several domains, in Romania this method was rarely used, especially in archaeology (Ratoiu et al., 2010; Lazăr C. et al., 2011; Asăndulesei, 2012; Asăndulesei et al., 2012; Nicu, 2013) but an increased use may be observed in other areas such as hydrogeology (Nicu, 2011), geomorphology (Lesenciuc and Nicu, 2011), or limnology (Mihu-Pintilie, 2014).

The aim of this paper is to give a general review of the scientific literature devoted to GPR technology and applications in soil and archaeological research and also to highlight the capabilities and limitations of GPR method in these domains.

## 2. BASIC PRINCIPLES OF OPERATION

A typical GPR system is based on the impulse radar technique and consists of a radar unit with transmitting and receiving antennas. The control unit consists of a screen, microprocessor, and mass storage medium. A microcomputer is used to control the measurement processes, store data, and serve as a user interface. The radar waves (from about 10 MHz to 1.5 GHz) are transmitted, received, and recorded as the antenna is moved along the soil surface. Reflections are obtained from interfaces between layers and objects of contrasting electrical and magnetic properties, whose depth can be estimated from the time taken for the reflected wave to return. When the pulse hits the object, part of its energy is reflected back to the receiving antenna. The reflected electromagnetic pulse is converted by the receiving antenna to an electrical pulse. The electrical pulse is then recorded by the receiver (fig. 1). The technique is closely analogous to seismic reflection but, because of the high frequencies (short wavelengths) used, it is more suitable for shallow probing (Clark, 2004).

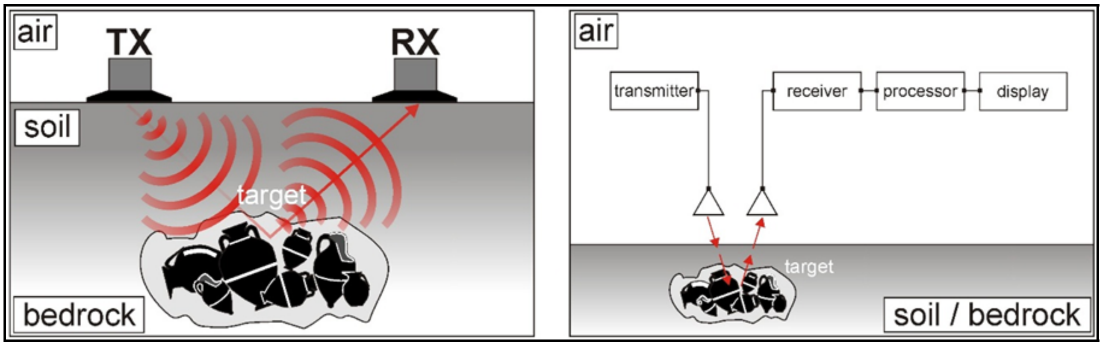


**Figure 1.** GPR – principle of operation (Tx - transmitting antenna; Rx - receiving antenna, and the data flow diagram (Mihu-Pintilie, 2014, adapted from Nicu, 2013).

The resolution and penetration depth of GPR are determined by the antenna frequency and the electrical properties of earthen materials (Olhoeft, 1998; Daniels, 2004).

In general, the needed band of frequencies depends on the particular application. Customarily, lower frequencies penetrate the opaque structures better than higher frequencies but provide an image of inferior quality of the targets. This drives us to use low frequencies (below 200 MHz) if the required investigation depth goes beyond 5–7 m or more (e.g., in some geological applications), radio frequencies (200–700 MHz) for applications where the targeted depth is of the order of 3 m (e.g., in most archaeological prospecting), higher radio frequencies (700–3000 MHz) for applications where the maximum required depth of investigation is of the order of 1 m and sometimes even higher microwave frequencies if the maximum investigated depth can be limited to the order of 50 cm (e.g., determination of the water content in the shallower layers of the soil). This classification indicates an average distribution, and many exceptions might be found (Persico, 2014). In general, the maximum penetration depth depends on the current case history and can be estimated in the field, on the basis of the data.

GPR produces vertical cross-sectional images of the shallow subsurface, based on propagation, reflection and scattering of high-frequency electromagnetic waves within it. The resulting image is similar in style to seismic reflection profiles (Davis and Annan, 1989; Gawthorpe et al., 1993; Mellet, 1995).

Modern GPR systems are also equipped with a GPS in order to geo-reference the probed areas, and are highly portable, allowing data collection at walking speed.

Principal manufacturers of GPR include Geophysical Survey Systems Inc. (GSSI, U.S.A.), MALÅ (Sweden), and Software & Sensors (Canada).

## 3. GPR AND SOIL SURVEYS

Compared with other geophysical techniques, GPR provides the highest resolution of subsurface features. However, GPR is not appropriate for use on all soils (Doolittle, 1987). The performance of GPR in soil survey is dependent upon the electrical conductivity of soils. Soils having high electrical conductivity rapidly attenuate the radar energy, restrict penetration depths, and severely limit the effectiveness of GPR. There are a number of factors that may increase dissipation of radar energy passing through soils including water content, soluble salts, carbonate minerals, and gypsum (Campbell, 1990; Olhoeft, 1998; Daniels, 2004).

Because of their high adsorptive capacity for water and exchangeable cations, the penetration depth of GPR is inversely related to clay content. Using a 100 MHz antenna, Olhoeft (1986) observed a penetration depth of about 30 m in clay-free sands. However, the addition of only 5% (by weight) smectitic clays reduced the penetration depth by a factor of 20. Doolittle and Collins (1998) noted that depending on antenna frequency and the specific conductance of the soil solution, penetration depths range from 5 to 30m in dry, sandy (>70% sand and <15% clay) soils, but average only 50 cm in wet, clayey (>35% clay) soils.

Related to the soil water content, it was found that at frequencies above 500 MHz, the absorption of energy by water is the principal mechanism for radar energy loss in soils and even under very dry conditions, the amount of bound water is sufficient to affect radar energy loss (Daniels, 2004).

In saline soils, depending on moisture contents, penetration depths typically range from a few to a maximum of 25 cm (Daniels, 2004; Ben-Dor et al., 2009), therefore GPR is considered an inappropriate tool in these conditions.

Electrical conductivity and energy loss rise also with the increasing cation exchange capacity (CEC) of the clay fraction. Cations adsorbed to the clay particles provide an alternative pathway for electrical conduction and, therefore, contribute to electromagnetic energy losses. Soils with clay fractions dominated by high-CEC clays (e.g., smectite and vermiculite) are more attenuating to GPR than soils with an equivalent percentage of low-CEC clays (e.g., kaolinite, gibbsite, and halloysite) (Saarenketo, 1998).

The most commonly used antennas for soil investigations have center frequencies between 100 and 500 MHz. Higher-frequency (400–500 MHz) antennas often provide more satisfactory results in relatively dry, electrically resistive soils. In highly attenuating soils, where the depth of penetration is very limited, these higher-frequency antennas often provide comparable depths and greater resolution than lower-frequency antennas. Antennas with frequencies of 900MHz–1.5GHz have been used for some shallow investigations in sandy soils. For organic soils, where greater depths of penetration are often needed, lower-frequency (70–200MHz) antennas are commonly used (Doolittle and Butnor, 2009).

### 3.1. Determining the depth to soil horizons

GPR was first used in U.S.A. to identify and determine depths to diagnostic subsurface horizons used to classify and map soils (Benson and Glaccum, 1979; Johnson et al., 1979; Collins, 2008). Where these horizons have abrupt upper boundaries that contrast with overlying horizons in physical (texture, bulk density, moisture) and chemical (organic carbon, calcium carbonate, sesquioxides) properties, they often produce strong reflections.

Johnson et al. (1979) working in sandy soils with well-expressed horizons, observed that radar interpreted depths of selected horizon boundaries were within ± 2.5–5.0 cm of the measured depths. Asmussen et al. (1986) observed an average difference of 19.2 cm between the radar interpreted and measured depths to argillic (Bt) horizons, which ranged in depth from about 20 to 450 cm. Rebertus et al. (1989) observed that the difference between the interpreted and measured depths to a discontinuity, which ranged in depth from 0 to about 230 cm, was less than 15 cm in 94% of the observations. Collins et al. (1989) determined an average difference of 6 cm between the interpreted and measured depths to bedrock, which ranged in depth from about 80 to 240 cm. Simeoni et al. (2009) reported an accuracy of ±10 cm between the interpreted and measured depths to B horizon, which ranged in depth from about 25 to 100 cm. For organic soils, Rosa et al. (2008) reported a mean maximum difference of 32 cm between measured and GPR interpreted depths of

peat, which ranged in thickness from 0 to 8 m. Differences were attributed to surface and subsurface irregularities, and spatial variations in peat moisture contents and bulk densities (Rosa et al., 2008).

### 3.2. Determining textural differences and contrasting horizons

The GPR has been used to detect textural differences and it works best in soils with low clay content and low electrical conductivity. It needs calibration as the dielectric constant is a function of water and salt content, and the presence of clay minerals. Horizons with abrupt boundaries caused by sudden changes in texture, bulk density, moisture, organic carbon or calcium carbonate produce strong reflections and GPR imagery (Doolittle and Collins, 1995). Provided soil conditions are suitable, GPR is used to determine the depth to contrasting master (B, C, and R) subsurface horizons. Other soil horizons and layers (e.g., buried genetic horizons, dense root-restricting layers, frozen soil layers, illuvial accumulations of organic matter, and cemented or indurated horizons) have also been identified with GPR. Ground penetrating radar does not image subtle changes in soil properties (e.g., color, mottles, structure, porosity, and slight changes in texture), transitional horizons (e.g., AB, AC, BC), or vertical divisions in master horizons (Doolittle and Butnor, 2009).

Contrast between soil horizons is often associated with differences in moisture contents, physical (texture and bulk density) and/or chemical (organic carbon, calcium carbonate, and sesquioxides) properties. Simeoni et al. (2009) developed a procedure for mapping the depth to the texture contrast horizon of duplex soils using GPR, GPS and kriging.

### 3.3. Determining the depth to soil/bedrock interface

The soil/bedrock interface often provides an abrupt and well expressed, easily identifiable reflector on radar records, therefore GPR can be an effective tool for evaluating bedrock depths. Often, this interface provides smooth, continuous, and high-amplitude reflections. However, the soil/bedrock interface is not always easy to identify on radar records. Coarse fragments in the overlying soil, irregular bedrock surfaces, fracturing, and the presence of saprolite make the identification of the soil/bedrock interface more ambiguous on some radar records (Doolittle and Butnor, 2009).

### 3.4. Determining the thickness, distribution and volume of peat deposits

Ground penetrating radar has been used to inventory and map peatlands and to classify organic soils. GPR is an effective way to measure the thickness and volume of organic deposits (Ulriksen, 1980; Turenne et al., 2006; Proulx-Mclnnis et al., 2013), to map and inventory histosols (Collins et al., 1986; Turenne et al., 2006), or to distinguish layers having differences in degree of humification and volumetric water content (Lapen et al., 1996).

Peatlands often display considerable anisotropy in composition, moisture content, and bulk density (Warner et al., 1990), and such differences have allowed separation of organic layers that differ in degree of humification, bulk density, and dielectric permittivity (Tolonen et al., 1982; Chernetsov et al., 1988; Comas et al., 2005; Lowry et al., 2009). The successful identification of interfaces resulting from differences in water content and degree of humification, however, has not been universal (Wastiaux et al., 2000; Sass et al., 2010).

## 4. GPR AND ARCHAEOLOGY

The first application of GPR in archaeology started soon after the first commercial equipment became available in the 1970s. The science to study, measure and quantify archaeological structures remotely has been designated as the field of Archaeometry. Remotely detecting

archaeological structures is very important because excavation of a site can inadvertently destroy essential archaeological evidence which can then never be recovered (Goodman et al., 2009).

In general, the smallest detectable size of archaeological materials is dependent on the frequency of the transmitting antenna. Typical frequencies for archaeological investigation range from about 200 to 800 MHz; however, even a low-frequency antenna on the order of 20 MHz might be used to discover structures buried below 15m and 4 GHz antenna might be used to measure shallow features a few centimeters thick for instance on ancient mosaic floors (Utsi, 2006).

Radar produces better images of convex or low-relief features which are freer of confusing lateral reflections and is most effective over preferably dry, uniform deposits, for maximum penetration. The performance and limitations of the GPR method in archaeological research depends mainly on the electrical conductivity of soils, an issue which has been presented previously in this paper.

### 4.1. Detecting buried historical buildings and structures

One of the earliest documented uses of GPR for archaeological prospection occurred in the mid-1970s when Bevan and Kenyon (1975) used GPR to look for radar reflections from buried walls and a variety of other historic structures. Vaughn (1986) used GPR to discover a 16$^{th}$ century Basque whaling station; Imai et al. (1987) applied GPR to discover pit house floors buried in volcanic soils with great precision and DeVore (1990) used GPR for investigations at the Fort Laramie National Historic Site.

GPR technology is also capable of providing information on fractures, previous reconstructions, material integrity and a variety of the characteristics of building materials (Goodman and Piro, 2013). For this reason GPR has found a multitude of applications in studying the integrity of historical buildings (Barone et al., 2010; Cosentino et al., 2011; Kadioglu and Kadioglu, 2010; Perez-Gracia et al., 2009; Sambuelli et al., 2011).

Several important buildings were studied in Puerto Rico to discover subsurface structures as well as to indicate areas of deterioration. In addition to finding lost crypts, a GPR survey was also designed to assist in the determination of areas that are undergoing accelerated alteration from weathering. The survey was also able to identify and verify if water infiltration had affected the integrity of portions of unglazed floor tiles which have been damaged by water seepage. Some of the walls at the site have been surveyed with high frequency antennas (1.5 GHz) in order to determine the support structures. In one subsurface image where renovations are known to have been done, a front prayer room shows internal wall repairs or large stone headers near the sides of one of the stain glass windows (Goodman and Piro, 2013). The same authors investigated the applicability of GPR for assessing the structural integrity on ancient bridges, in Galicia, Spain. The main goal was to evaluate the fill material homogeneity, detect hidden features such as internal holes or cracks, and define its internal construction characteristics.

GPR technology has been applied with great success to map many archaeological structures that could be verified in excavations. Ancient burial pits, rock walls, pit house floors, to name only some variety of archaeological features, were very suitable for GPR detection (Kvamme, 2001; Conyers, 2004; Dalan et al., 2011). Mapping Roman sites have proved to be one of the most straightforward applications that highlight the remote sensing capabilities of GPR (Goodman and Piro, 2013). Subsurface foundations and walls from destroyed Roman buildings usually have strong reflection contrasts that can be easily detected and mapped by GPR (Nishimura and Goodman, 2000; Conyers et al., 2002; Gaffney et al., 2004; Piro et al., 2003; Goodman et al., 2004; Seren et al., 2007; Campana and Piro, 2009).

In Romania, there are a few applications of GPR in archaeological research. This method was used for investigations on the Roman mosaic pavement from Constanţa (Ratoiu et al., 2010), or for identification of several structures from Mariuta - La Movila necropolis (Călăraşi county) such as a prehistoric pit belonging to the Kodjadermen-Gumelnita-Karanovo VI culture, a grave from the IVth century A.D., and a modem burrowing pit (Lazăr et al., 2011)

Nicu (2013) used the GPR method to identify archaeological sites located in underwater sediments. A number of four possible dwellings were found along twelve GPR profiles on the Sârca lake using a 250 MHz antenna (fig. 2).

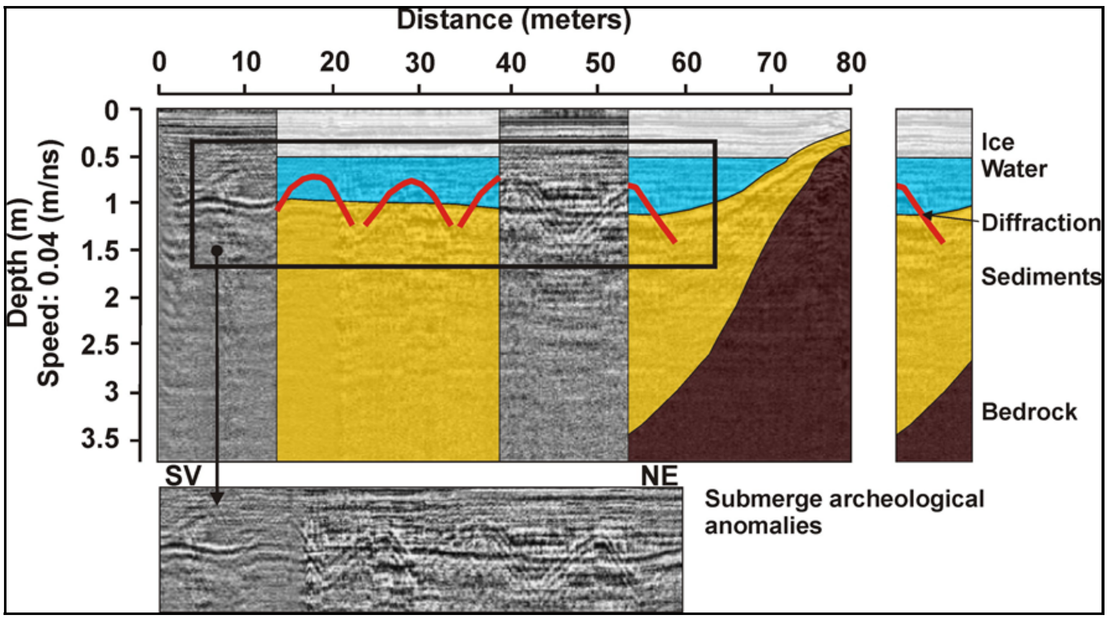


**Figure 2.** GPR profile (Mihu-Pintilie, 2014, adapted from Nicu, 2013).

GPR has also been used for estimation of sediment accumulation rate in a natural lake (Cuejdel) from Stânişoarei mountains (Mihu-Pintilie, 2014). He used a 100 MHz antenna which permitted the identification the velocities of the electromagnetic waves propagation through different density-specific environments: ice, water, lake sediments and buried/flooded soils. His research confirms that GPR is a useful tool in identifying underwater archaeological sites at depths of up to 10-15 m (fig. 3).

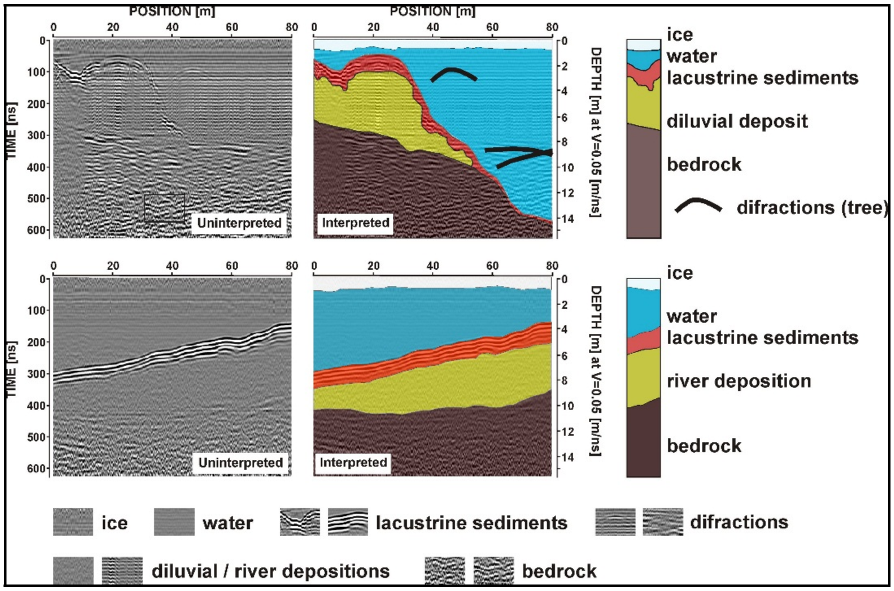


**Figure 3.** GPR prospections - Cuejdel lake (Mihu-Pintilie, 2014).

Bolohan and Asăndulesei, 2013 used two prospection techniques (magnetometric mapping and GPR technology) at Siliştea-Pe Cetăţuie (Neamţ county) archaeological site to search the inhabited area for inner structures and other remains. A correspondence was found between the anomalies detected by the magnetometer and those identified by the GPR, to the degree that the position, shape and depth of specific details could be extracted (fig. 4).

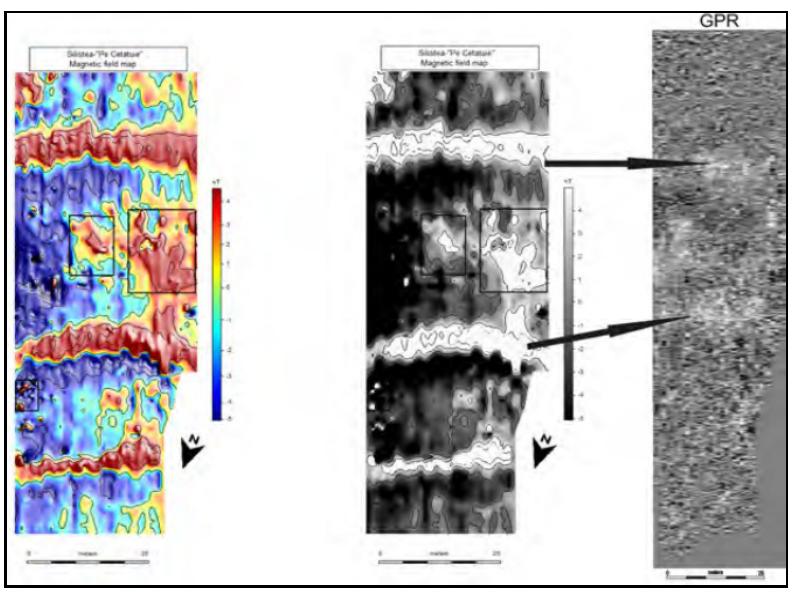


**Figure 4.** Geomagnetic and GPR prospections at Siliştea-Pe Cetăţuie (Bolohan and Asăndulesei, 2013).

### 4.4. Applications of GPR in cemeteries

GPR is commonly used in archaeological and forensic investigations, including the determination of the exact location of graves. In surveying grave sites, where there is some initial knowledge that the graves are running, for example, in a north–south direction, investigators will normally orient the line taking in an east–west direction. This will yield the best possible chance of traversing the graves. If a profile spacing of say 1m were applied, there is a possibility of missing a grave if one were to profile parallel to the long axis, because the grave may be less than 1m wide. Taking data perpendicular to the longer axis of the grave, or for that matter any archaeological structure, will aid detection. Recording of profiles in orthogonal directions will insure that a grave will have been traversed and increase the probability of detection if the line density is at least half the smallest horizontal dimension of the buried targets (Goodman et al., 2009). Conyers (2006) and Jones (2008) have also provided guidelines concerning transect spacing and profile orientation.

One of the first applications of GPR in cemeteries for the discovery of unmarked graves was initiated by Bevan and Kenyon in 1975. They used this method for locating historic graves and found that burials with substantial coffins were easiest to detect, while those containing only reburied bones were not detectable.

In the last decades, the use of GPR has become a popular geophysical option for grave detection and the results of these researches have been reported widely in the archaeological, forensic sciences, and geophysical literature (Vaughn, 1986; Bevan, 1991; King et al., 1993; Nobes, 1999; Buck, 2003; Conyers, 2006; Schultz, 2007; Jones, 2008; Doolittle and Bellantoni, 2010).

The importance of locating unmarked graves illustrates the need for the improvement of various geophysical survey methodologies, as well as testing the limitations of different instruments in specific contexts (Dionne et al., 2010).

The GPR method is based primarily on detecting contrasts in relative permittivity - an EM property that measures a material's capacity to store electrical energy (Cassidy, 2009) and which is strongly dependent on water content and changes in relative magnetic permeability which are negligible in most cases. Potentially detectable targets include: (1) the burial pit (i.e., contrast between background and backfill materials), (2) the burial container (i.e., contrast between container and backfill material), and (3) the skeletal remains (i.e., contrast between bone and backfill material) (Damiata et al., 2013). A burial pit can be detected in different ways. For example, it may be detected due to differences in moisture content, homogeneity, or compaction between background and backfill materials. In some cases, it may be identified through truncation of the natural stratigraphy (Bevan, 1991; Mellett, 1992; King et al., 1993; Conyers, 2006), by subtle slumping of the ground surface (Conyers, 2006; Doolittle and Bellantoni, 2010) or via "pull-ups" or "pull-downs" indicating lateral changes in velocity (Unterberger, 1992). In other instances, the pit may not provide a measurable contrast - either initially lacking or attenuated with time - whereas the burial container (Mellett, 1992; Unterberger, 1992; Dionne et al., 2010), if present, or the skeletal remains may still be detectable (Mellett, 1992).

According to Conyers (2006b), a cemetery grave may be detected with GPR by imaging four features that include (1) the undisturbed soil below and surrounding the grave, (2) the displaced backfill used to fill the vertical grave shaft, (3) the interment that includes the coffin, human remains, and associated grave, and (4) any surface sediment or soil that has accumulated over the interment. If the wooden coffin has collapsed, thereby eliminating the void space, however, what is left of the decayed coffin wood and human remains may not provide enough of a physical or chemical contrast to be detected with GPR. If the grave shaft has been dug through soil comprised of distinctly different horizontal strata, however, the grave shaft may be detected due to different

physical and chemical changes in the backfill or as a disruption of the natural and undisturbed stratigraphy surrounding the grave (Bevan, 1991; King et al., 1993; Conyers, 2006b).

## 6. CONCLUSIONS

For many years the GPR was used without understanding its essential capabilities and limitations. Many researchers realize that GPR cannot see through the ground with perfect clarity after many applications to their sites. Sometimes the test trenches, where geological and archaeological material profiles were recorded showed little corroboration on the recorded GPR profiles (Goodman and Piro, 2013). However, despite some limitations, the future of GPR on soil science and archaeology looks very promising. After a first generation of analogue GPR systems and the second which started when the first digital systems became available in the mid-1980s, the third generation of 3D GPR systems are now available with multiple antennas, faster processors and larger data storage capabilities. This opens a new range of applications in which soil properties, historical structures and other buried objects can be analyzed in a 3D format. Although the technology is widely popular, the users need to consider that it is a highly specialized area that requires a good understanding of the complexity of this geophysical method if it is to be applied successfully.

Because the number of papers reporting the use of GPR on this domain has greatly increased in the last decades, a comprehensive review of the current state of the applications of GPR along with the fundamental theory is hard to achieve. However, we hope this paper will provide sufficient detail to allow the practitioners in the area of GPR to use it as a research reference.

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