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Ground penetrating radar and palaeontology: The detection of sirenian fossil bones under a sunflower field in Tuscany (Italy)

Méthodes du géoradar et paléontologie : détection d'un squelette de sirénien sous un champ de tournesols en Toscane (Italie)

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ABSTRACT

The application of Ground Penetrating Radar (GPR) in vertebrate palaeontology is very rare. We describe the discovery of an Early Pliocene sirenian skeleton detected by GPR in a locality near Grosseto (Tuscany, Italy). The specimen represents one of the most complete skeletons of *Metaxytherium subapenninum* (Mammalia: Sirenia) ever found in the Mediterranean area. Using a monostatic antenna of 200 MHz, this non-invasive technique allowed us to detect most of the bones of the skeleton (skull, mandible, vertebrae and ribs) revealed in a distinct zone reflecting the electromagnetic waves. Other bones were found in correspondence with some smaller reflective zones of high back-scattered energy. Each bone was located in a grid system to compare its position with the spatial distribution of reflective zones. We are confident that the positive outcomes experienced in this work will encourage the use of GPR for future field research in vertebrate palaeontology.

RÉSUMÉ

Le géoradar est rarement appliqué à la recherche de vertébrés. Dans la présente étude, cette méthode a permis la découverte d'un squelette de sirénien dans le Pliocène inférieur de la région de Grosseto (Toscane, Italie). Le spécimen représente l'un des squelettes les plus complets de *Metaxytherium subapenninum* (Mammalia : Sirenia) découvert dans la région méditerranéenne. Cette méthode non destructrice est un bon outil pour la découverte des ossements de vertébrés. En utilisant une antenne monostatique de 200 MHz, cette technique a permis de détecter la plupart des os du squelette (crâne, mandibule, vertèbres, côtes). Les ossements ont été mis en évidence par une zone spécifique constituée de réflecteurs électromagnétiques. D'autres os ont été trouvés en correspondance avec des zones plus faiblement réfléchissantes. Chaque os a été localisé dans un système de quadrillage, afin de comparer son positionnement spatial dans les zones réfléchissantes.

1. Introduction

Fossil vertebrates are often concentrated in unusual fossiliferous layers exposed in relatively narrow areas. The field research for these fossils is often conducted randomly

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and the process can entail considerable time and funds. Fossils covered by sediments often required intensive excavation to evaluate their effective extent and to recover them. Moreover, fossiliferous sites can be located in areas affected by anthropogenic activities, such as quarries, cultivated fields, and building construction sites. In these cases, the time required to find fossils can be even more onerous and the palaeontological field research might hinder or completely stop the anthropogenic activities. Unfortunately, whenever field research cannot be conducted, the fossils are often partially or totally destroyed by the ongoing activities. In this context, we propose that the Ground Penetrating Radar (GPR, or Georadar) technique may be successfully used to detect fossil vertebrate remains, optimizing the palaeontological fieldwork, reducing excavation times and providing a benefit for local planning. The GPR technique has been applied in civil engineering, geological, environmental, forensic and archaeological contexts (Jol, 2009). However, its use in vertebrate palaeontology is very rare; in fact, there are few examples relating to this scientific research. The first known GPR palaeontology field tests were conducted by Bernhardt et al. (1988) and Borselli et al. (1988). In both cases, GPR was applied in different geological contexts: Bernhardt et al. (1988) considered both the fluviallacustrine clays of Rotonda (Potenza, Italy) where some terrestrial vertebrates were discovered, and some of the "Pietra Leccese" rock blocks in which some vertebrate remains (fish, reptiles and mammals) were found, while Borselli et al. (1988) investigated to a fossiliferous mammalian deposit in the Pleistocene lacustrine sediments at Colfiorito (Perugia, Italy). In both cases, the results were satisfactory and encouraging. Carrozzo et al. (2003) described the use of GPR to verify its resolution to locate some vertebrate remains within three biomicrite samples in which the position of fossils was known. The test was performed considering different varieties of "Pietra Leccese" and, although the response of methodology was very different in the three cases, the success of this application was confirmed.

Other studies that have applied GPR to palaeontology were conducted by various authors, especially on dinosaur sites (Gillette, 1992, 1994a, 1994b; Gardner and Taylor, 1994; Schwartz, 1994; Meglich, 2000; Main and Hammon, 2003). Some results are actually positive: for example, Main and Hammon (2003) conducted GPR surveys in two sauropod quarries in the Lower and Upper Cretaceous rocks of Texas. They concluded that the GPR technique was a key tool to locate buried fossils that could hardly be detected using the traditional methods. Both Gillette (1994b) and Schwartz (1994) used GPR surveys at a sauropod site in New Mexico, but without success. Finally, Gardner and Taylor (1994) described the application of GPR to the Bone Cabin Quarry in the Morrison Formation of Wyoming, but they did not confirm the GPR data. Meglich (2000) reached the same conclusion using GPR technique in a dinosaur site in Colorado.

In the past decade, geophysical techniques have been remarkably improved. Surprisingly, although georadar method continues to be used for archaeological prospections, its application in vertebrate palaeontology seems to have come to a virtual stop. This paper reports the first know application of GPR to detect a skeleton belonging to a fossil sea cow (Mammalia: Sirenia), recently discovered in

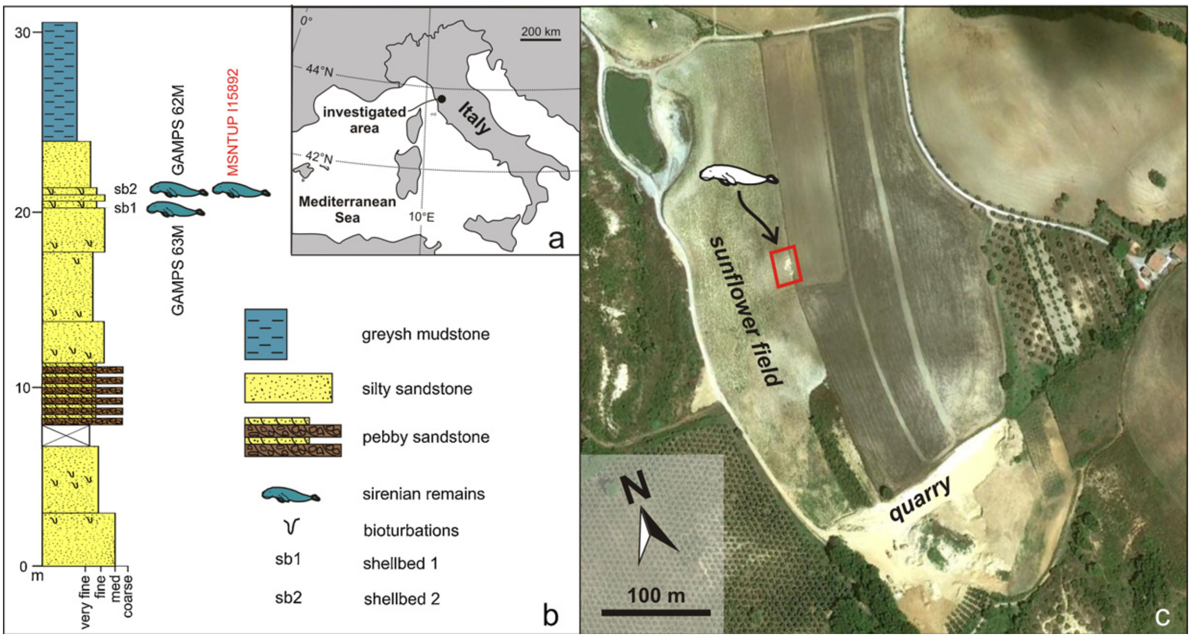

Fig. 1. a: location of the investigated area; b: schematic stratigraphic succession of the Early Pliocene sediments from the Arcille area (Grosseto, Tuscany); c: location of specimen MSNTUP I15892 in the sunflower field, discovered by using Ground Penetrating Radar (GPR).

Fig. 1. a : localisation de la zone d'étude ; b : succession stratigraphique schématique des sédiments du Pliocène Inférieur de la zone d'Arcille (Grosseto, Toscane) ; c : localisation du spécimen MSNTUP I15892, découvert en utilisant le géoradar (GPR).

a lower Pliocene deposits outcropping near Grosseto (Tuscany, Italy).

We carried out several GPR tests on different types of fossils and sediments in Tuscany. Although this region is one of the most important sites in the Italian Pliocene record of marine mammals (Bianucci, 1996; Bianucci and Landini, 1999, 2005; Bianucci et al., 1998, 2001, 2009; Bisconti, 2002; Capellini, 1902, 1904, 1905; Fondi and Pacini, 1971; Lawley, 1876; Pilleri, 1987; Sorbi and Vaiani, 2007; Tavani, 1942a, 1942b; Ugolini, 1900a, 1900b, 1902, 1907), geophysical surveys have never been used to support palaeontological research. Given that the skeletal structure of these mammals is very dense and massive, the fossiliferous sediments are relatively homogeneous, tectonic disturbances in the investigated area are absent, the depth of fossil skeleton from the surface is low and the field surface has a regular morphology, we can state that these factors represent optimal conditions for this type of investigation.

2. The palaeontological site

The lower Pliocene fossiliferous layer where the fossil sirenian was found is exposed in a small area near Arcille (Grosseto, Italy) (Fig. 1a). The succession outcropping in this area consists of shallow marine siliciclastic deposits. They contain a planktonic foraminiferal assemblage consistent with their attribution to the lower part of the Zanclean, in particular to the MPl2 zone of Cita (1975) dated between 5.08 and 4.52 Ma (age after Lourens et al., 2004). The succession, affected by systems of normal faults, is dominated by yellowish, locally pebbly, fossiliferous sandstone overlain by greyish mudstone (Tinelli et al., 2011). In the geological map, the sediments where sirenians were discovered are reported as "Argille, argille sabbiose e sabbie marine con livelli conglomeratici presenti alla base. Pliocene Inferiore", without any formal definition of the formation (Carobbi et al., 1996).

Three partially articulated sirenian fossil skeletons were found in 2007 in a sand quarry located in this area and they are now kept in the museum of the Gruppo Avis Mineralogia e Paleontologia di Scandicci (GAMPS) near Florence. Their catalogue numbers are GAMPS 62M, GAMPS 63M and GAMPS 64M. All specimens belong to *Metaxytherium subapenninum*, a halitheriine dugongid (Mammalia: Sirenia) that lived in the Mediterranean Basin and became extinct in the upper part of the Pliocene because of the progressive climatic cooling that occurred after 3.1 Ma (Sorbi et al., 2008, 2012).

The discovery of these three sirenian skeletons is a result of an excavation in the quarry, during which fossil bones were exposed. Unfortunately this activity also caused the partial destruction of the fossils. Two of them (GAMPS 62M and GAMPS 63M) were found in the upper part of the succession, in the proximity of two shell beds (sb1 and sb2, Fig. 1b), including fragmented and decalcified shells of bivalves, rare gastropods and scaphopods. GAMPS 62M consists of a partial skeleton composed of an incomplete skull and mandible, some teeth, several vertebrae, ribs and sternum; GAMPS 63M is more fragmentary and is composed of teeth, ribs and vertebrae. The third specimen (GAMPS 64M), represented by few ribs and vertebrae, came from sandstone beds whose correlation with the succession containing the other sirenians is unclear. The fourth specimen, which is the main object of this study, also belonging to *M. subapenninum*, was discovered in 2010 in a sunflower field a few ten meters north-west of the quarry (Fig. 1c) in the upper part of the succession near sb2 (Fig. 1b). During palaeontological prospecting, we observed several fossil bones (mostly fragmented ribs) on the field surface particularly concentrated in a small area near a draw. Considering the morphology of the field, we presumed that these bones had not suffered any main displacement but were brought to the surface during the plowing of the field. Our hypothesis was supported by the previous discovery of the three sirenian specimens in the quarry: all of them were represented by more or less complete single skeletons, while no accumulation of bones from different individuals or isolated sirenian bones were collected.

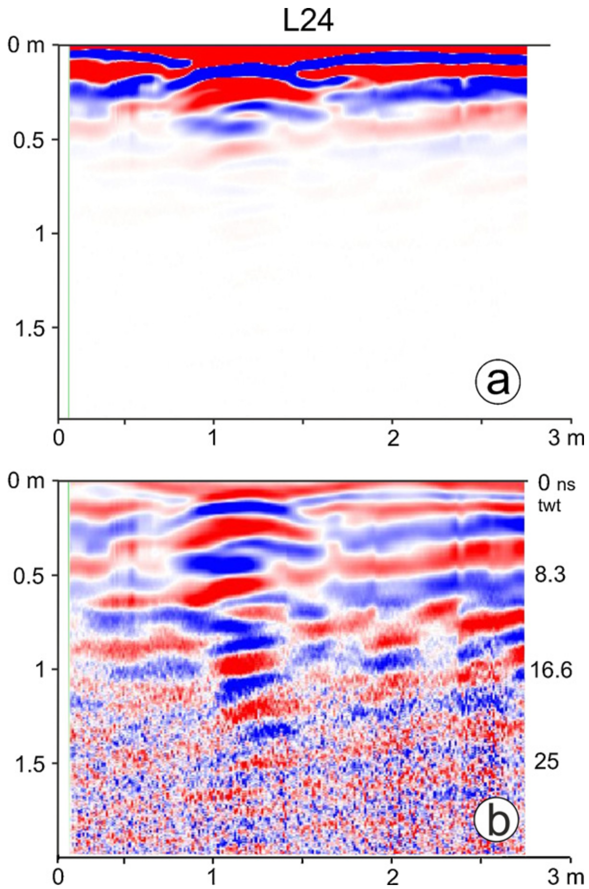

Fig. 2. a: processed GPR data with the time-zero correction, and the application of "dewow" and vertical band-pass filters; b: final processed GPR data with the application of gain functions. Twt: two-way traveltime (time taken by the EM to reach the target and to reflect back to the receiver).

Fig. 2. a : données GPR élaborées avec la correction temps zéro, l'application du filtre dewow et des filtres verticaux passe-bande ; b : données GPR finales élaborées avec la correction des fonctions de gain. Twt : temps aller-retour (temps mis par les ondes pour atteindre la cible et revenir au récepteur).

Therefore we thought that this small area of the sunflower field was particularly suitable to test the GPR technique. This fourth specimen is now kept in the Museo di Storia Naturale e del Territorio, Università di Pisa (MSNTUP) and its catalogue number is MSNTUP I15892.

3. Methods

Because Ground Penetrating Radar is based on the propagation and reflection of electromagnetic (EM) waves, it is sensitive to variations of the EM parameters in the subsoil, especially the dielectric constant and electric conductivity (Davis and Annan, 1989). The lower the frequency of EM waves propagating into the subsurface, the greater their penetration. The latter varies from a few meters in conductive materials to tens of metres for low conductivity media (Annan, 2009; Davis and Annan, 1989; Smith and Jol, 1995). The capability to resolve targets vertically (vertical resolution) increases with the antenna frequency up to centimetre values (> 200 MHz), while it is strongly reduced (several decimetres) when a < 100 MHz antenna is adopted. Lateral resolution depends also on the geometry of acquisition (step size, e.g. the distance between each point where a measurement is made along a GPR profile) and can reach a sub-centimetric resolution. The Nyquist sampling interval, e.g. one-quarter of the wavelength in the ground, is the base value to which the step size of the acquisition refers in order to avoid spatial aliasing effects (Annan, 2009; Davis and Annan, 1989). Despite its relatively low penetration depth (especially in conductive materials), GPR high resolution (lateral and vertical) makes this technique successful in studies of shallow stratigraphy, structural geology and archaeology (Basile et al., 2000; Bini et al., 2010; Grandejean and Gourry, 1996; Grasmueck,

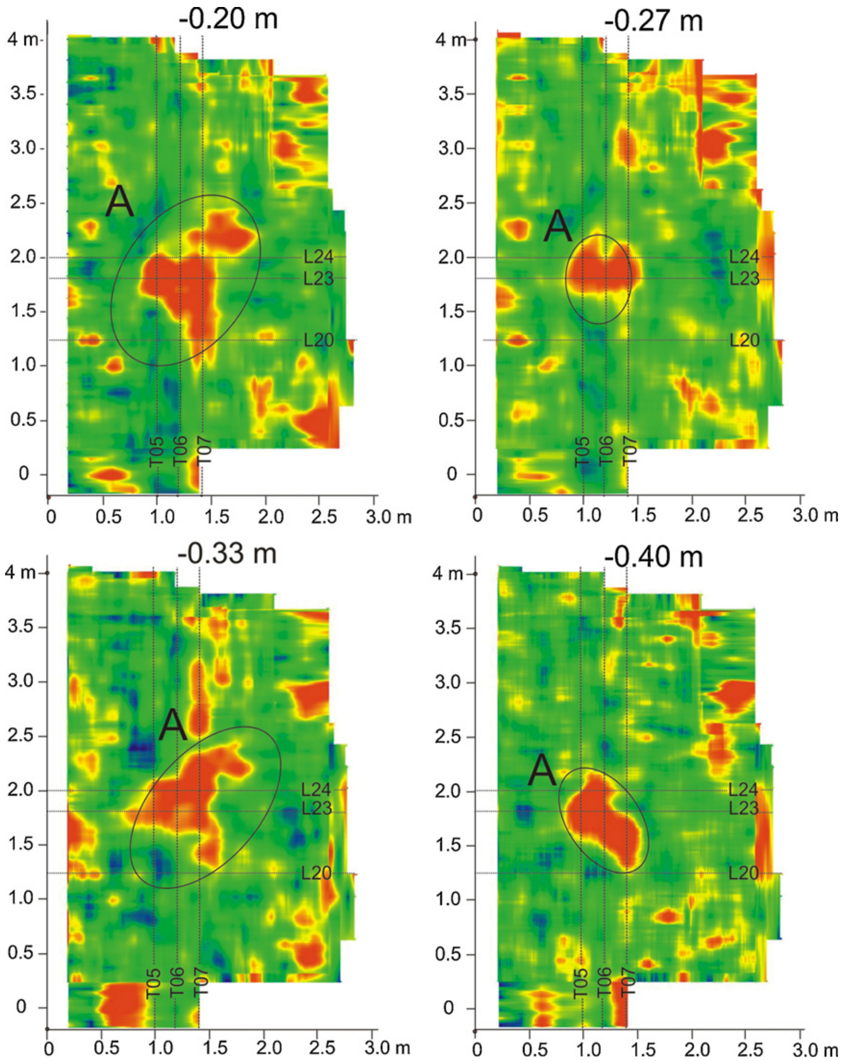

Fig. 3. Depth-slices of the GPR data volume (C-Scan) in Area 1. In red, the most reflective zones. A indicates the reflective zone corresponding to the principal fossil remains. The traces of the vertical radar profiles reported on the figure are indicated.

Fig. 3. Coupes en profondeur (C-Scan) dans la Zone 1. Les zones les plus réfléchissantes sont en rouge. A indique la zone de réflexion correspondant aux principaux restes fossiles. Les traces des profils verticaux réalisés par géoradar sont indiquées sur la figure.

1996; Grasmueck et al., 2004; Leckebusch, 2003; Leucci, 2006; Orlando, 2007; Soldovieri and Orlando, 2009). Further significant advantages are reached by adopting a grid of radar profiles, allowing a pseudo-3D or full-3D visualisation of the subsurface, and facilitating the interpretation of geometric structures, such as joints patterns, geological contacts and archaeological remains (Malagodi et al., 1996; Nuzzo et al., 2002). In this respect, “time slice” (or depth slice) maps are used to display the pattern of radar data at variable depths (Goodman et al., 1995).

Contrary to the bistatic collection mode, where transmitter and receiver antennas are placed side by side on the ground and one progressively increases the distance between them from a fixed point (called Common Mid Point), in the common offset collection mode both antennas are placed at fixed distance and moved at fixed increments along the survey line. The bistatic collection mode is performed with a bistatic antenna and it is useful for the determination of EM wave velocity. The common offset collection mode needs a monostatic antenna whereby transmitter and receiver maintain a constant reciprocal distance, suitable for mapping the underground reflection along the survey line. The transmitter and receiver of a monostatic antenna are commonly contained in a box no larger than a few decimetres, that is easily moved onto the investigated surface.

In this study, the GPR survey was performed using the Radar System device of IDS Company© (www.ids-spa.it), equipped with a monostatic antenna of 200 MHz of nominal peak frequency and HH-polarised. The choice of this antenna frequency was determined by the need to investigate, at a resolution of some centimetres, a fossil likely located in the first 1.5 m of subsurface, or perhaps in a lower depth due to a steep inclination of some fossil bones.

An odometer wheel was used to control the distance of measurement stations of ground response to EM signal along the survey line (step size). A grid of orthogonal survey lines was made with a spacing of 0.2 m. The raw GPR data were processed following a standard procedure (described below), first tested on a single line and then applied to the rest of the data. Finally, the interpretation was based both on the most relevant reflective areas visible in the time slices at various depths and the intersecting vertical radargrams.

To compare the GPR map and the location of fossil remains, we constructed a grid system of squares (0.40 m × 0.40 m) where the relative position of each bones was recorded using an alphanumeric code for each square, as show in Fig. 7a.

4. Results

4.1. GPR survey and analysis

We decided to use GPR in two adjacent areas (Area 1 and Area 2) of the sunflower field (Figs. 2–6), both covered with survey lines 0.2 m apart. In the vertical direction, the subsurface was explored for 60 ns (range) which corresponds to 3 m considering a wave velocity of 10 cm/ns. For each registration 1024 samples were taken, while horizontally the radar source was triggered every 1.2 cm (step size). We considered these sampling frequencies appropriate to reconstruct vertically and horizontally the reflection pattern in the subsurface, avoiding spatial aliasing. The following steps describe the sequence of processing applied to the raw radar data.

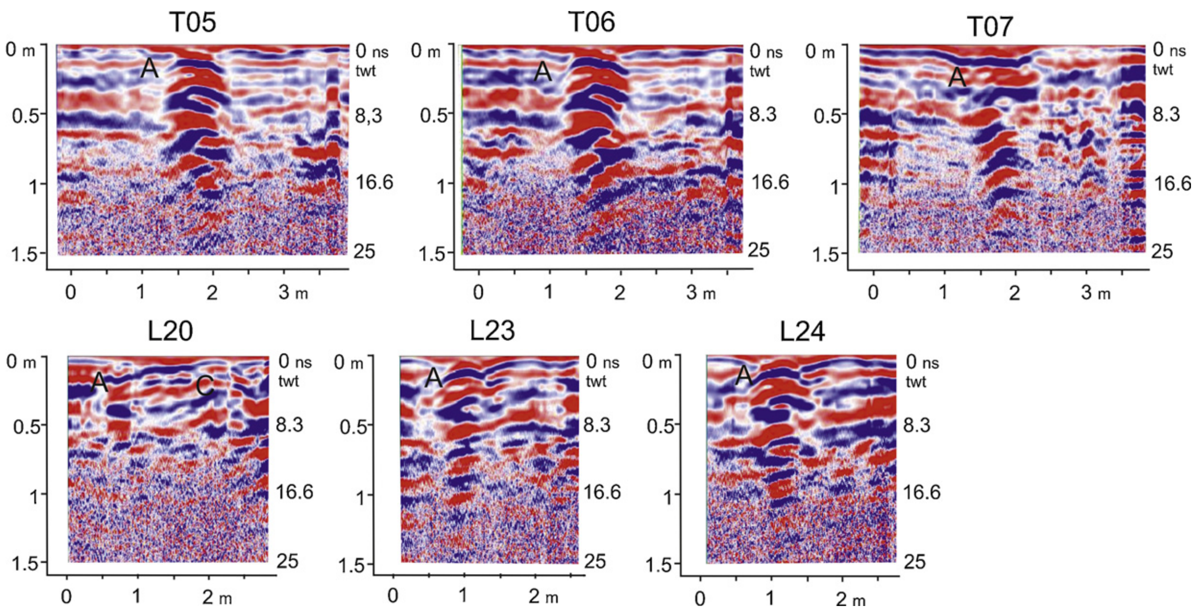

Fig. 4. Selected vertical radar profiles (B-scans) of Area 1. A indicates the reflective zone corresponding to the principal fossil remains. The code indicates the number of the profile. For profile location, Fig. 3. Twt: two-way traveltime.

Fig. 4. Profils radar verticaux sélectionnés (B-scans) de la Zone 1. A indique la zone de réflexion correspondant aux principaux restes fossiles. Le code indique le numéro du profil. Pour l’emplacement du profil, Fig. 3.

The radar acquisition in each measurement point was shifted by the time of the first reflection of the ground interface, adjusting traces to a common time-zero position (time-zero correction).

To remove the saturation effect caused by the EM wave travelling in air ("wow"), a running average filter was applied (Dewow filter). A mean trace was subtracted to filter out continuous flat reflections caused by the breakthrough among the shielded antennae and by multiple reflections between the antenna and the ground surface (Daniels, 2004). Following a spectral analysis of measured signals, a vertical band-pass filter (160–800 MHz) was applied to the data in order to remove undesired frequency components coming from instrumental and environmental noises. A first view of the results after these processing steps is reported in Fig. 2a. To enhance the visibility of deeper reflections due to signal attenuation, gain functions were applied to the data. Specifically, linear gain function (increasing with depth) and smoothed gain function with window-lengths of 2 ns were adopted. To convert the radargram from time to depth domain, an estimate of the average subsurface EM wave velocity is needed. We adopted the method of hyperbolic shape of a reflection from a point source (diffraction hyperbola) for this estimation. To estimate EM velocity, we matched a velocity specified-hyperbolic function to the form of a diffraction hyperbola detected in the radargram (Cassidy, 2009). This operation was repeated in some radargrams to obtain an average velocity of 12 cm/ns, eventually applied to the rest of the data to convert depth in time value. An example of final processed data and velocity determination is reported in Fig. 2b. Time slice sections were generated using the amplitude of reflections recorded by the receiving antenna. The amplitudes recorded along the survey line were interpolated with those recorded along the adjacent lines in a time windows of 0.8 ns, generating 2D images of reflections pattern at selected depths.

After the sequence of data processing described above, time slices at various depths in Area 1 indicated the presence of a large irregular reflective zone (A) approximately in the centre of the area (Fig. 3). This zone is persistently irregular in shape, appears at about 0.20 m in depth and shows a progressive size decrease in depth. The inlines and crosslines radar profiles crossing this zone coherently

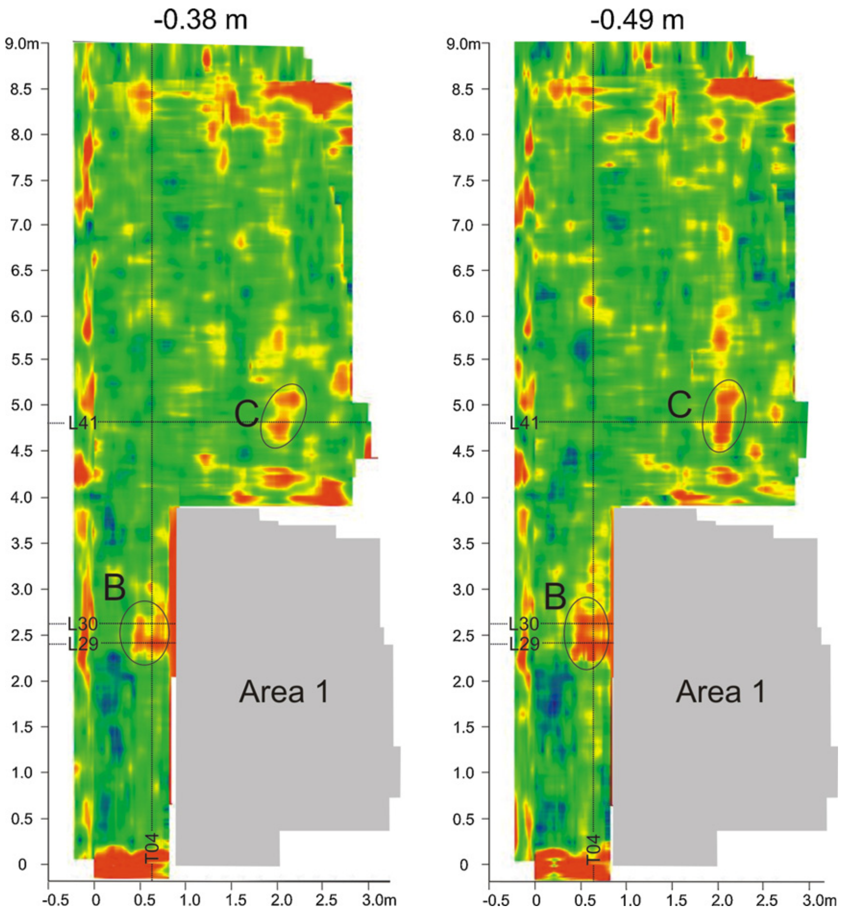

Fig. 5. Depth-slices of the GPR data volume (C-Scan) in the Area 2. In red, the most reflective zones. Letters indicate the reflective zones discussed in the text. The traces of the vertical radar profiles reported on the figure are indicated.

Fig. 5. Coupes en profondeur (C-Scan) dans la Zone 2. Les zones les plus réfléchissantes sont en rouge. Les lettres indiquent les zones réfléchissantes discutées dans le texte. Les traces des profils verticaux réalisés par géoradar sont indiquées sur la figure.

highlight strong reflections starting at about 0.2 m in depth and propagating to more than 1 m in depth. The reflections are mostly hyperbolically shaped (e.g. T05 and T06), locally overlain by flat horizons, gently concave upward (e.g. T07) (Fig. 4). At the right upper corner of Area 1, some minor zones of high back scattered energy appear. Here the presence of a small scarp did not allow us to perform the crosslines acquisition, resulting in a distortion in the time-slice generation. In Area 2 we used a grid formed by 15 transvers lines and 46 longitudinal lines, placed to generate an acquisition area matching the adjacent Area 1 (Fig. 5). Just a few bone fragments were found on the surface of this area. A reflective zone was recorded at 0.5–2.5 m of coordinates (B), and results persistent up to 0.5 m depth showing a globular to pseudo-rectangular shape. A second zone with high reflection energy was placed at 2.3–4.8 m (C) and it is evident up to 0.5 m. Radar profiles crossing these zones do not show evident reflections, likely in part convoluted in the reflections of horizontal discontinuities in the subsurface. In detail, the B zone corresponds to a part of the radar profile characterised by flat reflectors of high back scattered EM energy. C zone lies in correspondence of an energetic reflector below 0.3 m of weak and disturbed signal (Fig. 6). In both cases these zones do not present a distinct shape as compared to others reflectors in the radar profiles.

4.2. Palaeontological data

Following up the obtained GPR results, we decided to verify these signals through an excavation extended to the whole investigated surface for Area 1 and in correspondence with the reflective zones for Area 2. For additional verification of GPR mapping process, we compared the GPR map with the map of skeletal elements reported in the grid system (Fig. 7a,b).

In correspondence with the central reflective zone (A) of Area 1, some fossil bones emerged: in particular, a skull with tusks at a depth of 0.20–0.25 m, a mandible and several ribs (in D4, D5, D6 and E6) at a depth of 0.26–0.30 m; an axis, one dorsal vertebra and a considerable number of ribs (in E3-4 and F3-4) at a depth of 0.31–0.36 m; and an atlas, an undetermined bone (between D3 and E3) and some fragmented ribs (in E5 and F5) at 0.36–0.40 m in depth.

A humerus, a cervical vertebra, a scapula and other fragmented bones were found nearby the skeleton: the cervical vertebra at a depth of about 0.26–0.30 m and the humerus at a depth of about 0.31–0.35 m. The scapula and

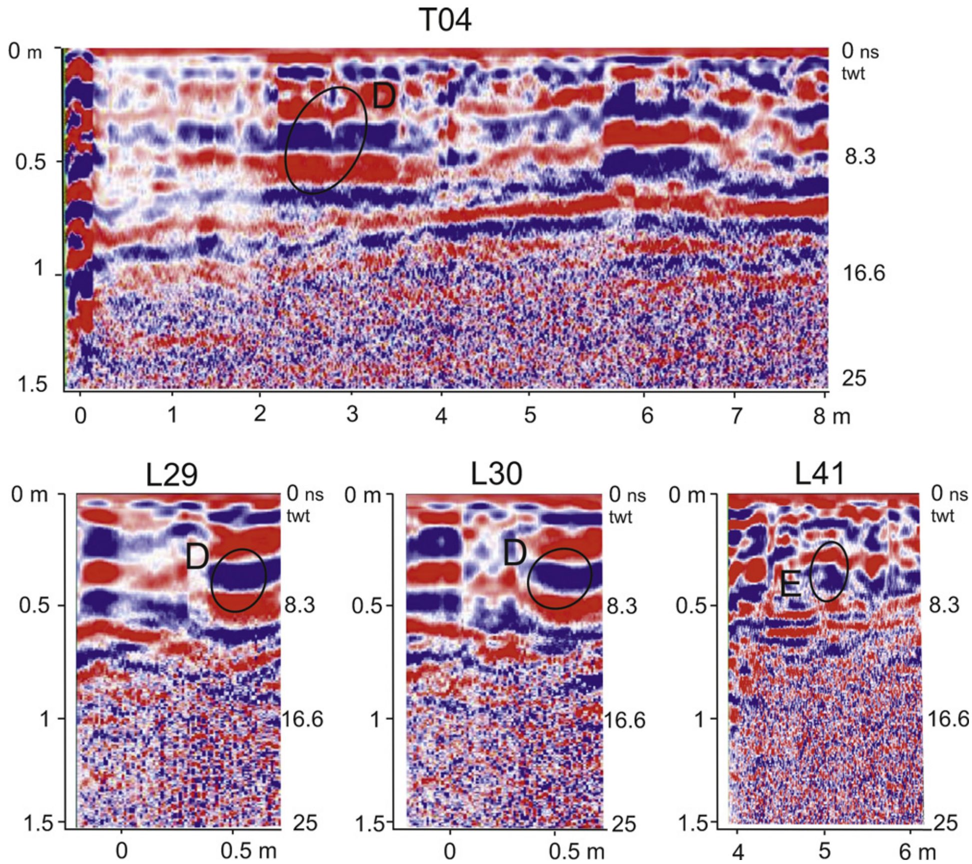

Fig. 6. Selected vertical radar profiles (B-scans) of Area 2. Letters indicate the reflective zones discussed in the text. The code indicates the number of the profile. For profile location, Fig. 4. Twt: two-way traveltime.

Fig. 6. Profils radar verticaux sélectionnés (B-scans) de la Zone 2. Les lettres indiquent les zones réfléchissantes discutées dans le texte. Le code indique le numéro du profil. Pour l'emplacement du profil, Fig. 4.

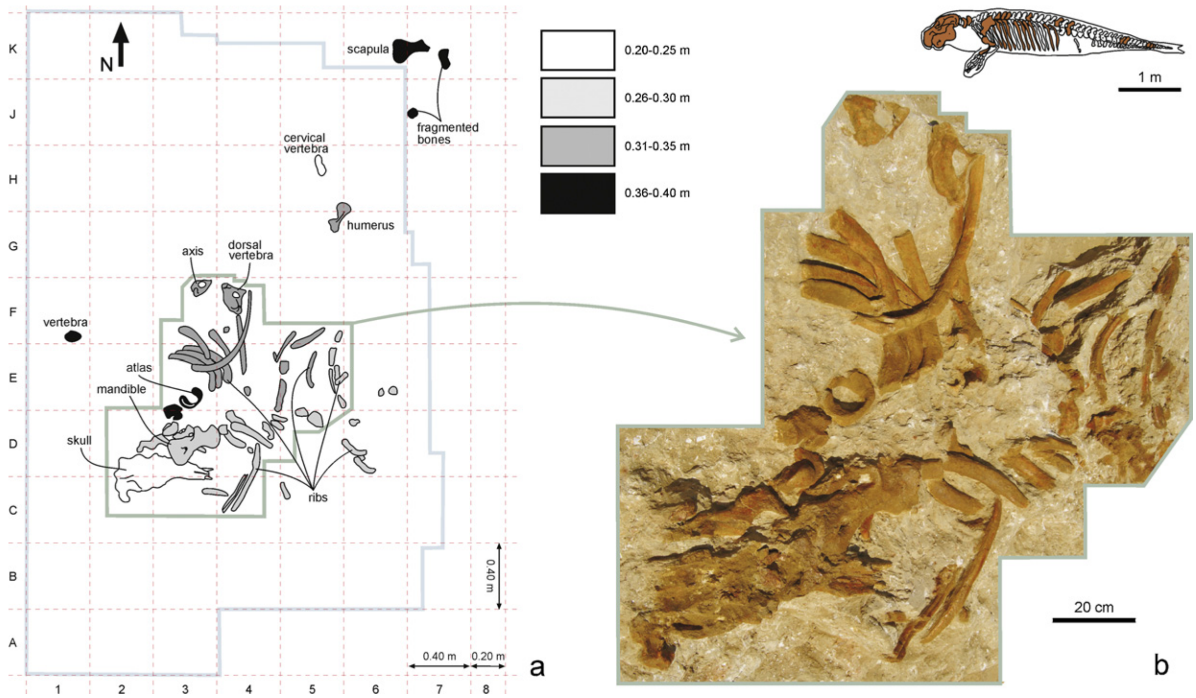

Fig. 7. a: grid system reporting all the bones discovered during the excavation and the range of depths at which each bone was found (the largest polygon indicates Area 1); b: detail of the area with bone concentration. The skeleton at the top right highlights the discovered bones.

Fig. 7. a : système de grille positionnant les ossements découverts lors des fouilles et la gamme de profondeurs à laquelle chaque os a été trouvé (le plus grand polygone indique la zone 1) ; b : détail de la zone avec la concentration d'os. Le squelette en haut à droite met en évidence les ossements découverts.

the fragmented bones – the furthest from the skeleton – were 0.36–0.40 m in depth. Neither the cervical vertebra and humerus nor the scapula and other bones were in correspondence with the central reflective zone. The comparison between the GPR map and the distribution of skeletal elements in the grid system revealed that these bones were found near the border of the area where some minor zones of high back scattered energy appear. These reflective zones can be ascribed to environmental noises generated by out of line reflections or ploughed soil by the agricultural activity.

At the transition between the two areas, we discovered some fragmented caudal vertebrae at the depth of 0.4 m (they are not reported in Fig. 7a). The lateral position and the depth of these bones could be compatible with those of the reflective zone B of the Area 2, but we are not able to confirm this correspondence, also because some flat reflectors of high back scattered energy are located near the B zone (Fig. 5).

No fossil remains emerged where the second reflective zone C of Area 2 was localized. We only observed a concretionary level that might have generated the reflection.

5. Discussion and conclusions

The GPR prospecting undertaken near the out cropping of several fossil bones on the field surface indicated the presence of reflective zones in the subsurface at various depths. The excavation confirmed that these zones mostly corresponded to buried bones. In order to compare reflectors and fossil remains in the subsurface, during the excavation each fossil bone was mapped using a grid system. By comparing geophysical and palaeontological data, we observed the effectiveness of GPR for detecting fossil bones, with clear reflections corresponding to the skull, the mandibles, some cervical and dorsal vertebrae and ribs.

However, we noted that some reflections were not generated by fossil remains. These types of reflections are mostly related to a concretionary level in the silty sands or soil clumps locally associated with voids caused by agricultural activity. In other cases, fossil remains either did not reflect back electromagnetic energy, or the shape of the backscattered energy is not fully consistent with the shape of the fossil assemblage. Heterogeneous bone density and GPR vertical resolution may be the explanation of these missed or partial targets. In general, sirenians have heavy skeletons that help them to stay submerged. Sirenian bones are both swollen (pachyostotic) and dense (osteosclerotic), especially the ribs, which are often found as fossils (Domning, 2002). We observed that the central reflective zone (A) corresponds to a high concentration of ribs: therefore we inferred that due to their massive and dense structure, a GPR antenna could very easily detect the sirenian ribs. However, laboratory experiments to determine EM characteristics of different types of bones (mainly electric permittivity) are needed to support this hypothesis. Following the first experiments of Keller (1987) and the indications of Main and Hammon (2003), new tests should be performed directly on bones and sediments in order to constrain the contrasting EM proprieties and simulate different situations through synthetic diagrams.

Vertical GPR resolution (e.g. the minimum vertical distance between two objects in the subsurface to be distinguished with two separate reflections) is assumed to be 1/4 of the signal wavelength (λ). In our case, this means that bones vertically spaced of less than 0.12–0.13 m may be represented by a single reflection instead two distinct events in the radargram. Hence, the missed reflections of some undetected bones may have been convoluted in the reflective event of shallower objects. In order to overcome this problem, a higher frequency antenna should be used, provided that the fossil remains are assumed to be found at a very shallow depth (< 1.0–1.5 m), thus avoiding the loss of signal caused by the EM wave attenuation with depth. In this respect, we must consider the attenuation of GPR signal when a conductive material, e.g. clay and saline sediments, is crossed by EM waves. Indeed, the ease of electron movement typical of conductive material led to a decrease of the of initial energy because it is partly converted into heat. A multifrequency radar system might supply the better compromise between resolution and penetration depth.

Based on all the above considerations, we conclude that GPR surveys, applied to palaeontological field research, turned out to be a time-cost effective solution and a tool for the local planning. Despite the encouraging results, in order to refine this application in vertebrate palaeontology we deem that further experimentations need to be conducted in different geological and palaeontological contexts and with higher frequency antennae (> 200 MHz), especially when we presume that fossil remains lie at shallow depths. However, considering that geophysical technologies and techniques evolve continuously, it is clear that much more testing will have to be conducted to further improve the use of this methodology in vertebrate palaeontology.

Finally, the most strictly palaeontological result of this study is the discovery of one of the most complete *Metaxytherium* specimens ever found in the Mediterranean area. In fact, all the sirenian remains discovered in Area 1 and Area 2 surely belong to a single individual considering that all the identified unpaired bones are single (skull, mandible, atlas and axis) and paired bones were recognised (a scapula and a humerus). Moreover several bones (e.g. the ribs) are in relative anatomical position and the others are disarticulated but still closely associated (Fig. 7). The detailed systematic and taphonomic study of this specimen will sensibly increase knowledge about extinct sirenian anatomy, biology and behaviour. This new discovery also further improves the relevance of the Arcille area as an extraordinary deposit of marine vertebrates, also because, besides the four sirenian skeletons, fishes (sharks and teleosteans) and odontocete cetaceans have been recently collected in this area.

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