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Ground Penetrating Radar to detect dinosaur bones within a Cretaceous hard limestone in Sicily

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ABSTRACT

Ground Penetrating Radar (GPR) can be important in facilitating planning for the identification and extraction of buried vertebrate remains, particularly at sites that are difficult to access, where excavation would be costly and labor-intensive. This is the case at Grotta Lunga (northwestern Sicily), one of the southernmost European dinosaur sites, a key site for understanding the relationships between African and European dinosaurs. An incomplete theropod bone was discovered at this site in 2005, and to date there have been no further finds due to the difficulties of excavation in hard rock and in a cave environment. With the aim of exploring deeper into the rock volume around the bone, we tested GPR as a method to investigate the Cretaceous limestone at Grotta Lunga. Despite its potential, GPR has been rarely applied in paleontology and very seldom has led to the successful detection of buried dinosaur bones. Our analysis identified some remarkable GPR reflections on the cave wall, in the vicinity of the dinosaur bone, indicating the existence of reflective objects embedded in a position stratigraphically compatible with the dinosaur remains. Data processing was carried out to show the best result without compromising data quality. For this purpose we used the synthetic hyperbola method, Kirchhoff migration and Hilbert transform. The GPR signals detected at Grotta Lunga in the graphical form of hyperbolas are interpreted as the result of reflections produced by fossil bones embedded in the Cretaceous limestone investigated and indicate the presence of additional dinosaur remains. Our investigation provides useful information for planning future excavations.

1. Introduction

The processes of identifying and excavating fossil vertebrates usually require much effort and funds, especially when these remains are buried in heavily indurated rocks and/or exposed in geological sites that are difficult to access. This is the case with an incomplete dinosaur long bone discovered in 2005 in northwestern Sicily (Italy). The bone, which has a cross-sectional area of 32 × 70 mm with a large medullary cavity, is still embedded in the western wall of Grotta Lunga, a cave formed in a late Aptian-early Albian limestone (Randazzo et al., 2021) that originated in a marginal marine-lagoon paleoenvironment (Garilli et al., 2009). Because of the high degree of cementation of the surrounding limestone and its very partial exposure, the bone was studied by histological analysis performed on a small, detached flake (Garilli et al., 2009). As a result, the bone was considered as belonging in all likelihood to a theropod dinosaur. The bone must have been transport from a tidal or subaerial environment into the lagoon system in which the

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limestones were deposited (Randazzo et al., 2021). For these reasons, the opportunity to extract and identify the bone and any surrounding remains from the rock may provide new insights into the taphonomic context of the discovery and the paleogeography of the Central Tethys and into the key role that the Panormide platform played in faunal interchanges between Gondwana and Laurasia (Garilli et al., 2009; Zarcone et al., 2010 and other references; Fanti et al., 2013; Chiarenza and Cau, 2016; Cau, 2021).

Locating additional remains or excavating the already identified bone using the "classical" approach, based on chance, would still involve considerable time, due to the nature of the rock involved and the morphology of the cave, and could cause serious damage to any undetected specimens hidden in the rock. Preliminary investigations are therefore essential to facilitate faster and safer exploration and extraction of already identified bones. In fact, during recent fieldwork in early 2022, it was noticed that the bone was affected by tampering activities caused by vandals or as an illegal excavation attempt (see comparison images in Fig. 1). Therefore, we performed a GPR survey on the cave wall along the layers harboring the Sicilian theropod bone in order to accelerate

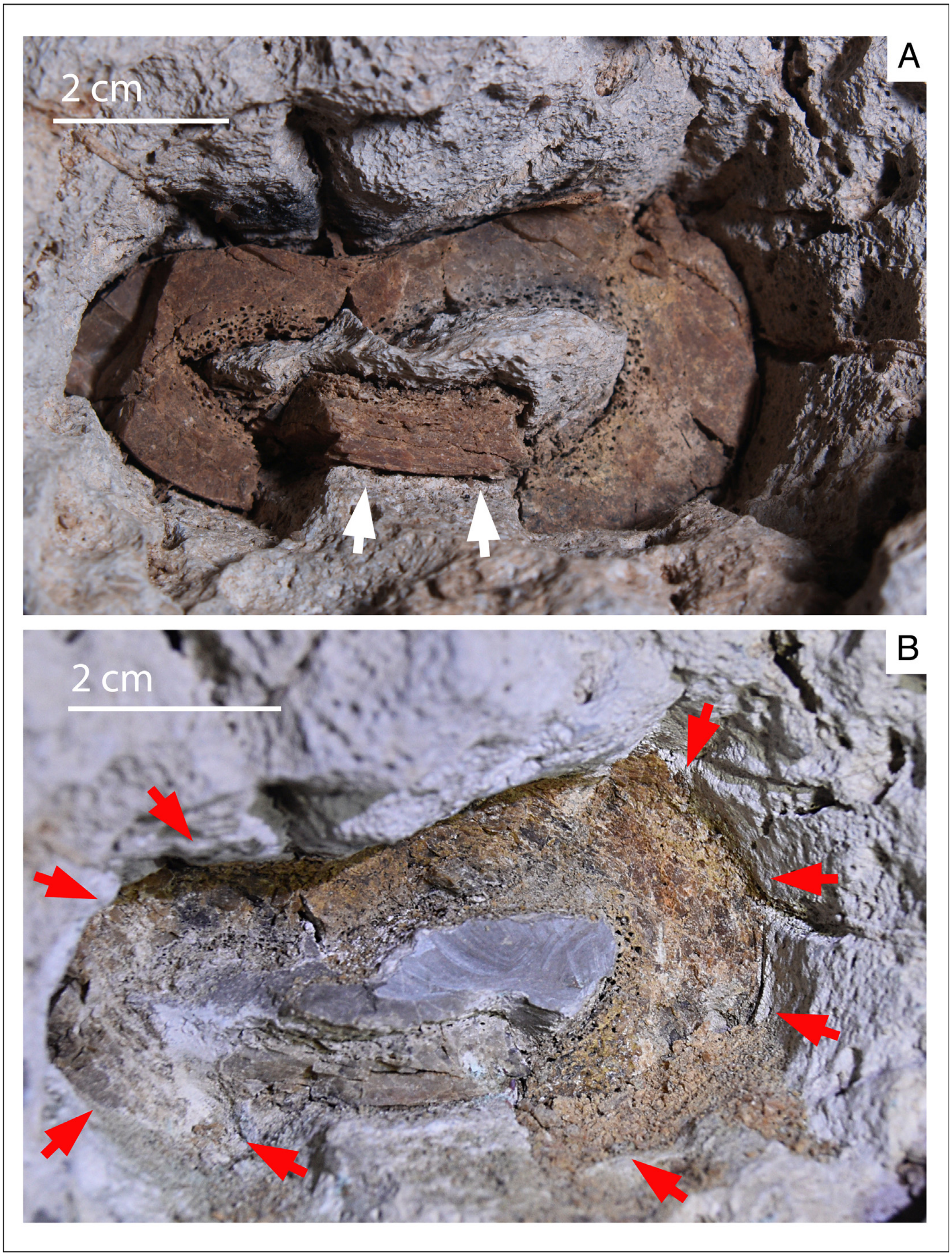

Fig. 1. The Cretaceous bone embedded in the Pizzo Muletta limestone as discovered in 2005 (A) and as found at the time of the GPR survey (B) in February 2022. Red arrows in B indicate damaged parts; white arrows in A indicate the location of the bone piece sampled for the histological analysis published by Garilli et al. (2009).

the removal process and show the potential of the GPR technique for predicting the location of additional dinosaur remains in the rock near the outcropping bone. At the same time, we show the potential of successfully applying standard GPR to an unusual geological context.

1.1. Previous application of GPR in paleontology

Ground Penetrating Radar (GPR) is a nondestructive survey method successfully applied in various fields, such as geology, archaeology, agronomy, and civil engineering, preferably to locate

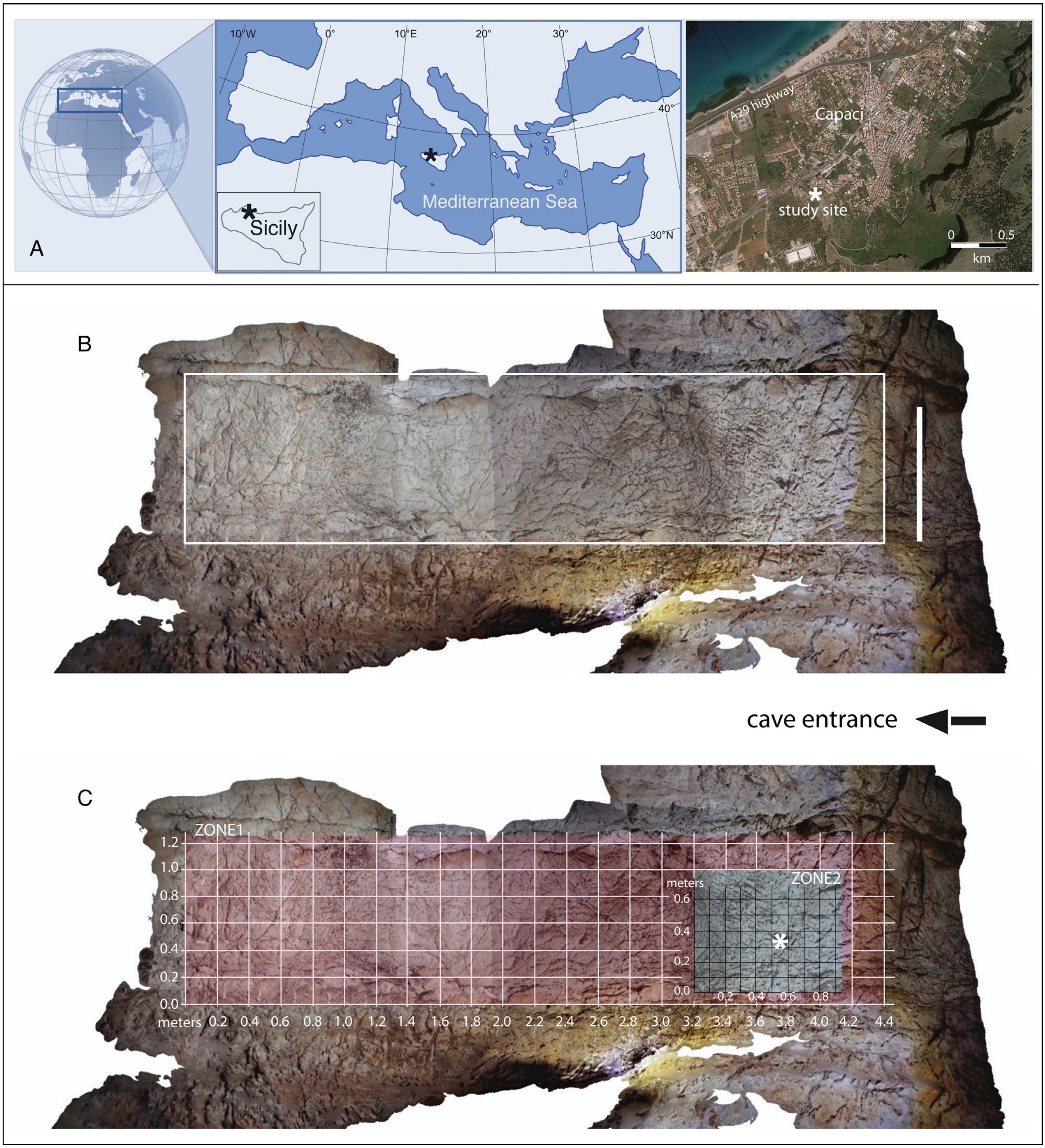

Fig. 2. Location of the study site (A), indicated by asterisks, and digital reconstruction of part of the West wall of Grotta Lunga formed in the Cretaceous hard limestone of the Panormide platform (B–C). (B) The area where the GPR analyses were carried out (scale 1 m). (C) The same area with the two GPR zones investigated: the larger Zone 1, with radar profile traces forming a 20 × 20 cm grid, and the smaller Zone 2, with radar profile traces forming a 10 × 10 cm grid, near the dinosaur bone discovered in 2005 (Garilli et al., 2009). The white asterisk indicates the location of the dinosaur bone.

and investigate buried objects (Jol, 2009) and to reconstruct stratigraphic settings (e.g., Backer and Jol, 2007; Cassidy, 2009; Ribolini et al., 2021). Nevertheless, the use of GPR in paleontology is rare, despite its unquestionable potential and utility to save time in fossil detection and to make excavation planning more efficient (for a review see Main and Hammon, 2003 and Tinelli et al., 2012, but also Lukjanov et al., 2007; Leucci, 2013; Ercoli et al., 2021). In Cenozoic contexts, which are characterized by poorly cemented lithologies, the use of GPR has proven to be a successful tool for the detection of buried bones (Tinelli et al., 2012). In contrast, in Mesozoic contexts, among the few attempts to detect dinosaur bones using GPR made at a few open-air sites (Gillette, 1992, 1994a, 1994b; Gardner and Taylor, 1994; Schwartz, 1994; Meglich, 2000; Main and Hammon, 2003), only a few surveys (e.g., Main and Hammon, 2003) have proven useful for the detection of buried bones.

We chose the Grotta Lunga site to show the potential of the GPR technique in an attempt to predict the location of vertebrate fossils in a difficult-to-excavate lithological context such as the well-cemented Cretaceous limestones of the Panormide platform, thus providing for the first time an account of the application of GPR under such conditions. At the same time, the GPR technique could open up new perspectives on the taphonomic and paleogeographic significance of the Sicilian theropod at the study site.

2. The study site

GPR investigations were carried out inside Grotta Lunga (Figs. 2 and 3), a cave opening in the Aptian-Cenomanian limestones (Garilli et al., 2009; Randazzo et al., 2021) that form the low elevation of Pizzo Muletta, near the village of Capaci, about 10 km west of Palermo (northwestern Sicily). The cave (identified as SI/PA004 in Mannino, 1986) is presumably developed along a straight fault system as a narrow tunnel, 1.5–5 m wide and originally about 65 m long (Mannino, 2001). It is shorter today due to partial roof collapse. The cave is bounded by subvertical walls with a maximum height of about 10 m (Fig. 3). The Pizzo Muletta succession, about 120–130 m thick, belongs to the Panormide platform and is characterized by strongly cemented carbonate rocks of internal to peritidal-lagoon origin deposited along the African margin of the Central Tethys (Garilli et al., 2009). Throughout the succession, the fossil content mainly consists of benthic forams, nerineid gastropods and rudist bivalves, which are closely to loosely spaced (Garilli et al., 2009; Randazzo et al., 2021). At the Grotta Lunga site, a few small, rare gastropods and benthic forams were observed on the cave wall in the bed investigated by GPR (Garilli et al., 2009). In addition, echinoderm remains were reported by Randazzo et al., 2021 in the correlative bed outside the cave. These fossils underwent dissolution and reprecipitation by carbonate minerals, and their composition and physical properties therefore do not markedly contrast with that of the host limestone. No other material contrasting with the composition of the limestone was observed in the bed harboring the dinosaur bone.

3. Methods

3.1. The GPR equipment and basic information on data processing

A Hexagon RIS MF Hi-Mod IDS ground penetrating radar was used for all the investigations discussed in this paper. This GPR was equipped with a sensing wheel encoder and a 2 GHz high-frequency

Fig. 3. The narrow gallery of Grotta Lunga, the Cretaceous dinosaur site at Capaci (western Sicily), during the execution of the GPR survey on the West wall. Note the location of the still encased dinosaur bone (black arrows) discovered in 2005 (Garilli et al., 2009).

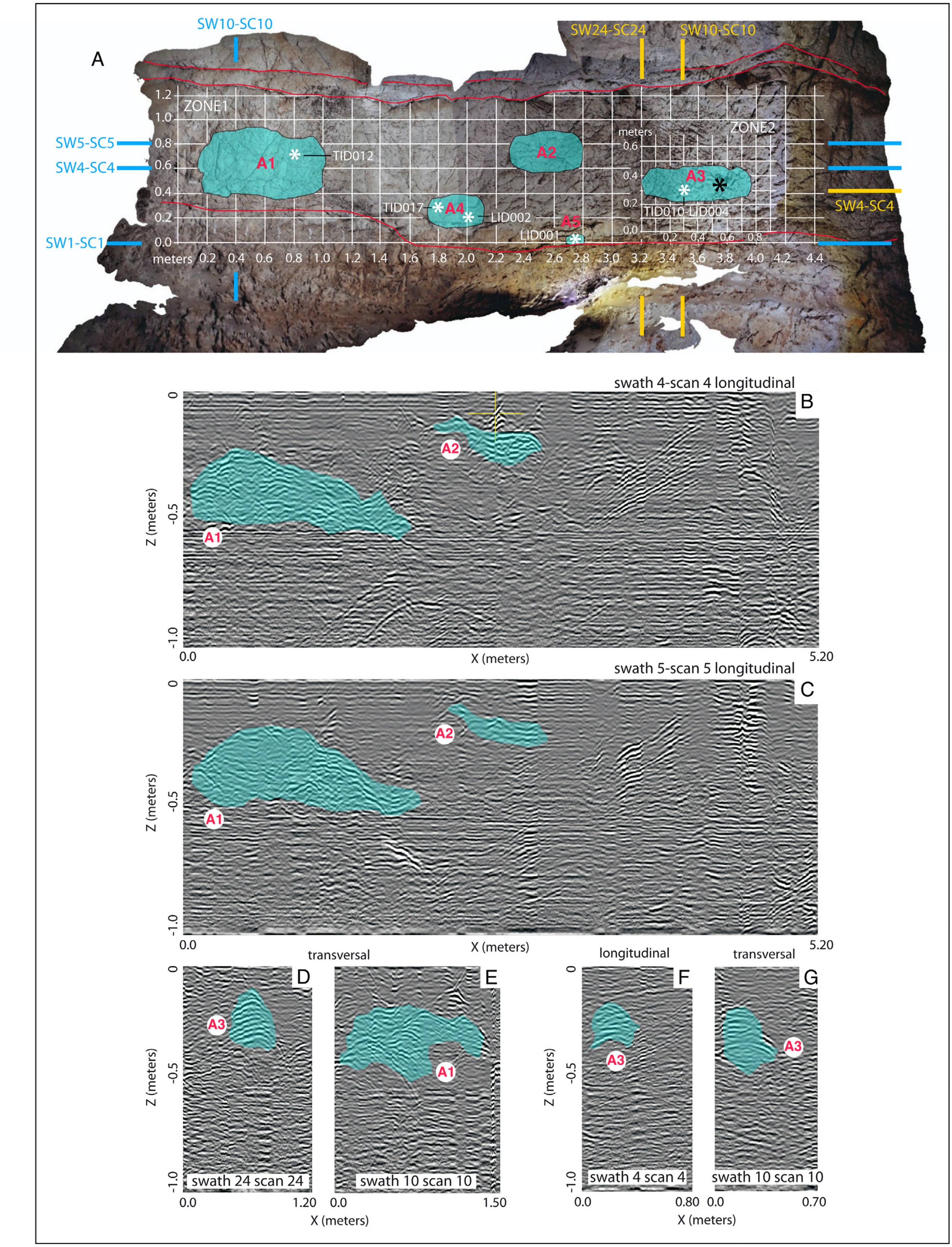

Fig. 4. Digital reconstruction of the west wall of Grotta Lunga showing five areas (A1–A5, in cyan) where GPR analyses detected reflective objects within the Cretaceous limestone (A), and selected processed radargrams for zones 1 and 2, and areas A1, A2, and A3 (B–E), highlighting some hyperbolic reflectors (in cyan). The longitudinal and transverse GPR survey lines that generated the selected radargrams are in A (in blue for Zone 1 and in yellow for Zone 2). The location of the selected hyperbolas used to calculate the EM wave velocity (see Fig. 5) is indicated by the white asterisks in A. The meaning of the grids in A is the same as that in Fig. 2. The location of the known dinosaur bone (Garilli et al., 2009) is marked by the black asterisk in A, which is stratigraphically compatible with the location of the areas A1–A5. The two red lines at the top of A indicate the thin coarser layer indicated by Garilli et al. (2009), which gives indications of the observed stratification in the cave wall section; the lower red line approximates the erosional surface described by Garilli et al. (2009).

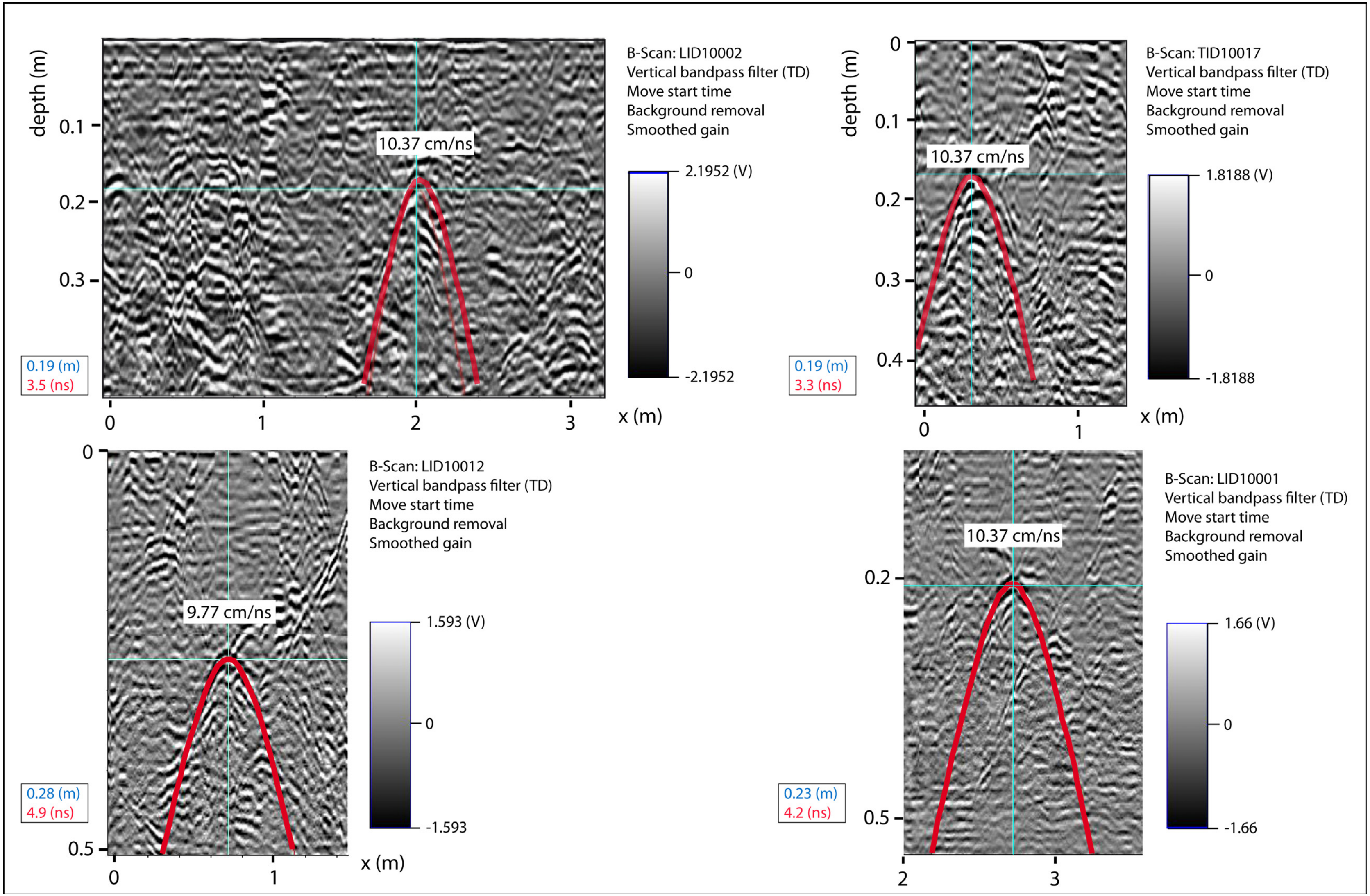

Fig. 5. Propagation velocity calculated by the synthetic hyperbola method from selected hyperbolic reflectors recorded from GPR analyses performed at the Cretaceous dinosaur site at Grotta Lunga.

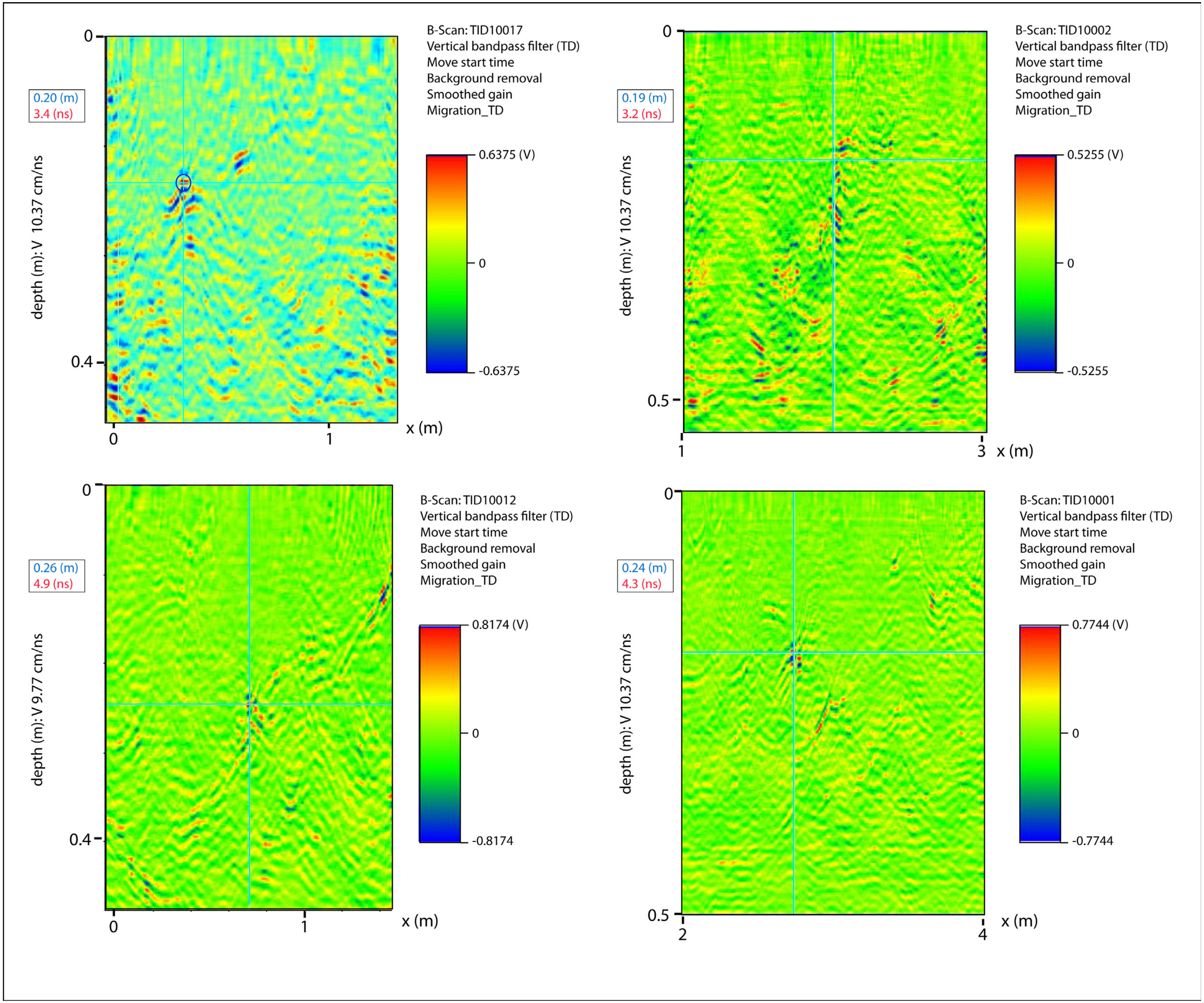

Fig. 6. Kirchhoff migration performed for four of the hyperbolic signals recorded during the GPR survey conducted at the Cretaceous dinosaur site at Grotta Lunga.

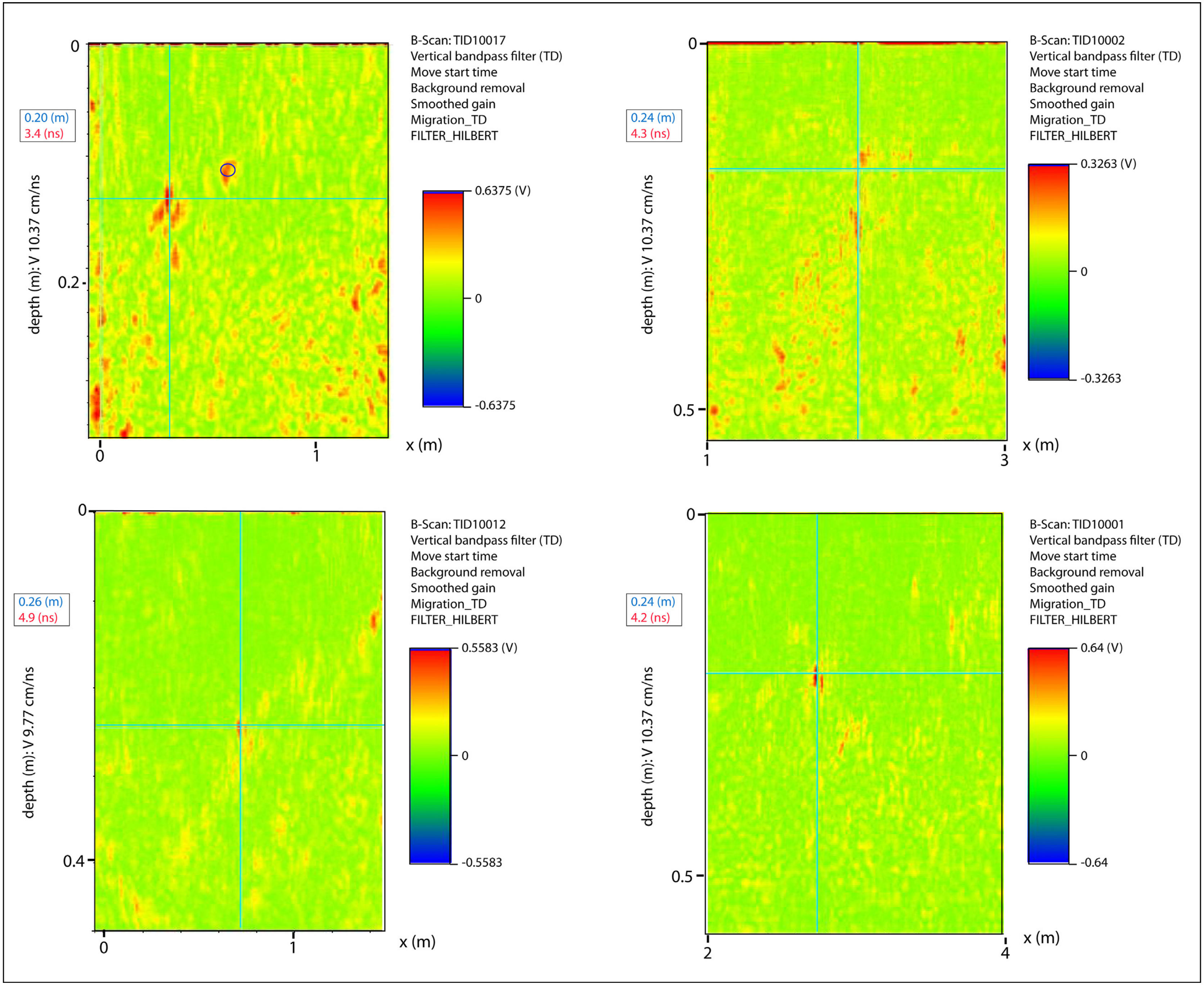

Fig. 7. Hilbert transform performed for the same hyperbolic signals as in Fig. 6.

antenna in a monostatic configuration, which allowed investigations down to a depth of about 50 cm into the lithology (Corrao and Coco, 2021), with a vertical resolution of about 0.1 m. K2 FastWave 02.02 and GRED HD IDS software was used for data acquisition and processing, respectively. Several operations were performed before data acquisition to optimize the instrumental response and GPR calibration.

Basically, GPR works by transmitting electromagnetic (EM) pulses into the material to be investigated and recording the reflections of the signal. Reflections are generated when the EM pulses meet electromagnetic discontinuities in the material, for example embedded objects with different physical properties. Reflected signals from a point object are recorded by GPR as diffraction hyperbolas in a radargram (e.g., Main and Hammon, 2003; Damiata et al., 2013, 2017; Leotta, 2022).

Hyperbolic signals were used to estimate the EM wave velocity. In order to reconstruct the velocity profile and the true location of diffraction in the medium, we applied the synthetic hyperbola method (Sagnard and Tarel, 2016) and the Kirchhoff migration (e.g., Özdemir et al., 2014; Smitha et al., 2016). We also applied the Hilbert transform (e.g., Zheng et al., 2016) with the main aim of estimating the instantaneous amplitude (envelope) of the signal that makes it easier for us to emphasize that the point of reflection corresponds to the hyperbola apex in the radargram. The velocity of the EM waves mainly depends on the physical properties of the material through which they travel.

For more detailed information on how GPR works and methods used for investigating GPR signals, see supplementary text and supplementary Figs. 1–5.

3.2. The GPR survey

The GPR survey focused on the western wall of Grotta Lunga, about 10 m from the entrance, where the dinosaur bone discovered in 2005 is still located (Garilli et al., 2009). The cave wall is irregular and has small to medium-sized depressions. Between the dinosaur bone and the surface of the cave wall is a depression a few centimeters deep (Fig. 1).

The GPR surveyed an area about 1.2 m high and 4.6 m wide. This area was divided into two survey grids: the first (Zone 1), which was as large as the entire area, and a smaller one (Zone 2) of about 0.7 × 0.9 m within Zone 1, near the bone (Fig. 2). The distance between grid lines was 0.2 m for the larger grid and 0.1 m for the smaller one. Twenty-four and six survey lines (swaths) parallel to the Y (transverse scan) and X (longitudinal scan) directions, respectively, were acquired within ZONE 1; eight and seven survey lines were acquired along the Y and X directions within ZONE 2, respectively. Selected radargrams obtained from the survey lines are shown in Fig. 4.

Because of the irregularities of the cave wall, it was not possible to scan the surface of the visible dinosaur bone. As a consequence, it was not possible to obtain the specific GPR signal that the outcropping bone might have produced.

4. Results

The GPR survey revealed four areas (termed A1, A2, A3 and A4 hereafter) with relevant dimensions that generated hyperbolic signals due to the presence of reflecting objects deep in the rock wall. Much smaller areas producing isolated signals were also detected. We have examined five of these signals from areas A1, A3 and A4 (Fig. 4A), and one signal from a much smaller area (A5, Fig. 4A) in the lower part of the Zone 1. Two larger areas (A1 and A2) are about 0.8 × 0.5 m and 0.5 × 0.3 m in extent. They were detected in Zone 1, about 3 m and 1.2 m from the dinosaur bone, respectively, and within the same stratigraphic level. A smaller area (A4, about 0.4 × 0.3 m in extent) within the same zone was detected between the two larger ones, about 2 m from the dinosaur bone. An area (A3, about 0.25 × 0.8 m) was detected in Zone 2 near the bone (Fig. 4A). These areas produced hyperbolic signals diffracted from subsurface objects embedded in Cretaceous limestone. Some hyperbolas are highlighted in the radargrams shown in Figs. 4B-G. The same radargrams show that the reflecting objects are embedded at a depth ranging from about 10 to 50 cm from the surface.

By applying the synthetic hyperbola method to areas A1, A3 and A4 (Figs. 4A and 5), we determined EM velocities. Two hyperbolas selected from area A4 (LID002 and TID017, shown in Fig. 4A) recorded EM wave velocities of 10.37 cm/ns. In area A1, a velocity of 9.77 cm/ns (LID 012) was calculated. In the Zone 2, close to the outcropping bone, velocities of 10.50 and 11.20 cm/ns were recorded for signals TID010 and LID004, respectively. See Fig. 4 for position of these signals in the GPR grid survey and Fig. 5 for hyperbolic fitting of LID001, LID002, TID012 and TID017 signals.

Kirchhoff migration made it possible to identify the point of real reflection in the medium, which means the apex of the hyperbolic signals (Fig. 6). The Hilbert transform (see supplementary text) was used for GPR signal TID017 (Fig. 7).

5. Discussion

Whereas GPR investigations of Recent human remains are relatively common in the archeological literature (Damiata et al., 2013, 2017), detections of vertebrate fossils in paleontological contexts, and particularly of dinosaur bones, by this method are extremely rare, and have usually been performed at open-air sites, where the presence of relevant fossils was expected (Main and Hammon, 2003, and other references). In contrast, our GPR analyses were carried out inside a cave with the main purpose of detecting additional dinosaur remains in the rock near the outcropping theropod long bone discovered in 2005 (Garilli et al., 2009).

Subsurface areas A1–A5 detected in the survey grid (Figs. 2 and 4), in positions stratigraphically compatible with the layer where the theropod bone outcrops, produced hyperbolic signals. The method used for processing these GPR data signals point to the presence of reflecting objects inside the Cretaceous limestone of Pizzo Muletta. The depth of these embedded objects cannot be estimated accurately because static correction of the GPR profiles was not performed. However, considering that minor irregularities, such as those of the surveyed cave wall, are usually not very relevant in GPR surveys, an approximate depth of 0.1–0.5 m for the anomalies might be inferred. As shown in Fig. 4, differences between surfaces of areas A1–A5 (from 0.4 to 0.01 m^2) might suggest that the reflecting objects are of notably different sizes. However, the lateral and vertical resolution of the GPR survey does not allow us to distinguish between each reflective area being generated by a single reflecting surface or by several surfaces close to each other. All reflective areas (Fig. 4) are characterized by large surfaces, except for the one with a subcentral position (A4) and that in the lower part of Zone 2 (A5), which could indicate the presence of isolated objects. One of the more prominent areas (A3) was found near the dinosaur bone.

The reflections appeared from the survey data as hyperbolas within the radargrams. The application of the hyperbola fitting method, Kirchhoff migration and Hilbert transform to some of the more defined hyperbolic signals was effective in estimating an EM wave velocity between 9.77 and 11.20 cm/ns. These values match those reported in the literature for EM wave velocity recorded by GPR in Paleozoic–Mesozoic limestones (e.g., Jeannine et al., 2006; Reynolds, 2011; Mustasaar et al., 2012; Sénéchal et al., 2013; Łyskowski et al., 2014).

We suggest that the embedded objects that produced the studied reflections are additional dinosaur bone remains. The extent of the reflective areas A1–A4, their vicinity to and stratigraphic compatibility with the known bone, and the very low possibility that the investigated rock harbors other reflecting objects that differ in physicochemical nature from the limestone support this hypothesis.

6. Conclusions

The investigation at Grotta Lunga indicated for the first time that GPR can be successfully employed even in conditions that are pioneering for the paleontological field, such as in an indurated rock environment on a nearly vertical rock face inside a cave. The application of GPR to this site provided relatively precise locations of embedded objects that are interpreted as dinosaur bones likely belonging to the same individual discovered in 2005. Our GPR survey thus gave a very useful map to be used for planning future excavations, which are decisive for obtaining a more precise taxonomic picture of the Sicilian dinosaur. Such excavation will serve as the ultimate test of our GPR survey.

Data availability

Data will be made available on request.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cretres.2023.105582.