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Integrated geophysical and geomatic studies at Ghar Dalam Cave, Malta's oldest prehistoric site

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Abstract. The Ghar Dalam cave, southern Malta, hosts the oldest human evidence in the Maltese archipelago. Although the internal stratigraphy of the cave and its biotic record is well studied, the possibility of archaeological / paleontological prospects in the surrounding areas requires additional studies. In this work we use aerial and ground-based photogrammetry to reconstruct the interior and the surface of the cave, and various geophysical techniques (GPR, passive seismic and ERT) to study the subsurface of the cave and its surroundings. The results have clarified the geometry of the soil-rock contact above and at the entrance of the cave and possible karstic structures have been identified. The authors conclude that this multidisciplinary methodology allows more reliable results to be achieved and is essential for studies where direct observation is not possible.

1. Introduction
In the present contribution, we present an integrated geomatics and geophysical study of the Ghar Dalam prehistoric site, in Malta. This site hosts the Ghar Dalam cave, where there exists an uninterrupted sequence of fossiliferous deposits extending from the Late Pleistocene to modern times, where the oldest paleontological fossils and archaeological evidence of the island were found [1].

The cave extends longitudinally to the NE and has a walkable length of 80 metres, a height of 3 to 6 metres and its entrance faces the Wied Dalam valley. It was originally a phreatic tube formed in the Lower Coralline Limestone Formation (LCL) and, during the Pleistocene, fluvial action cut this tunnel resulting in two caves, being Ghar Dalam the largest cave, on the NE side of the valley [2,1] (Figure 1). The cave deposits have been studied since the 19th century; however, the surrounding have not been thoroughly studied and it is supposed that there may be undiscovered areas of archaeological interest.

The aim of this work is to investigate the surroundings of the Ghar Dalam cave seeking for underground features that may be of archaeological, palaeontological or geological interest using various non-invasive geophysical techniques and integrate it in a 3D photogrammetric model.

2. Geomatic and geophysics surveys
The methodologies used for the non-invasive study of Ghar Dalam were photogrammetry, ground penetrating radar (GPR), passive seismic and electrical resistivity tomography (ERT).

Photogrammetry is a geomatic technique that can be defined as the science to reconstruct 3D geometries starting from at least two overlapped pictures that shoot the same object [3]. In this work we performed an accurate 3D photogrammetric reconstruction that allows the geographical integration of the geophysical data. We combined aerial and terrestrial photogrammetric surveys to generate an integrated model that combines the cave and the surface of the area of study.

The aerial survey was carried out with a DJI Phantom 4 Pro drone and 16 ground control points (GCPs) deployed around the survey area. The position and altitude of the GCPs were taken with a differential GNSS with a base and rover configuration and the number of pictures taken was more than 2000. This system allowed us to reach centimetric precision. The 3D model of inside the cave was made in the first 80 metres, with more than 1300 photographs taken with a digital camera. Due to the lack of GNSS signal inside the cave, we used a 3D laser distometer to orient and scale the model. The cave entrance was modelled with aerial and ground images, and using the points in common between the cave model and the surface model we were able to generate a unique model of the site (Figure 1).

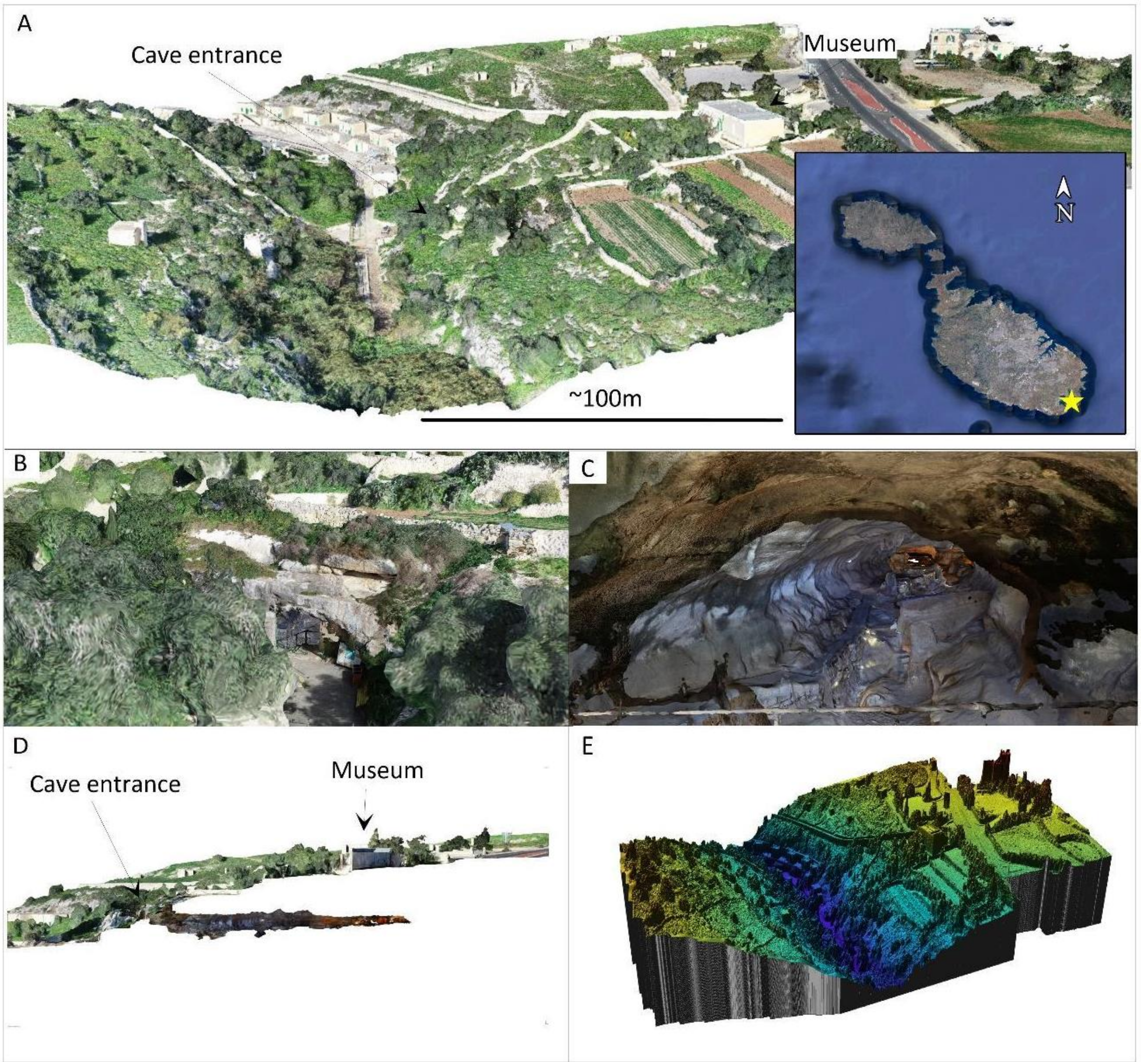

Figure 1: 3D Photogrammetric model. A) General view of the study area and its location in Malta. B) Entrance of the cave. C) View of the cave from the entrance. D) Profile view of the model. E) Digital elevation model derived from photogrammetry.

Regarding the geophysical methods, we carried out two GPR surveys, one with a medium frequency (400 MHz) shielded antenna and one with a low frequency (70Mhz) antenna. The medium frequency survey was applied to determine superficial anomalies that could be related to karst or ancient anthropogenic structures under the soil cover. The survey was planned with two different approaches: in the yards in front of the cave entrance, where we were expecting to find evidence of the old excavations works, we did a narrow grid with a spacing of 25 cm between parallel lines. On the other hand, in the terrain over and on the sides of the cave, we did wider and irregular grids, with an average spacing of 2m between lines, which was a good compromise between the research goals and the difficulties given by the terrain irregularities and obstacles.

With the low frequency GPR survey, given the higher penetrability of this instrument, we seek for larger and deeper structures. We recorded 5 profiles along lines approximately perpendicular to the cave, for above the cave and other at the level of the cave entrance.

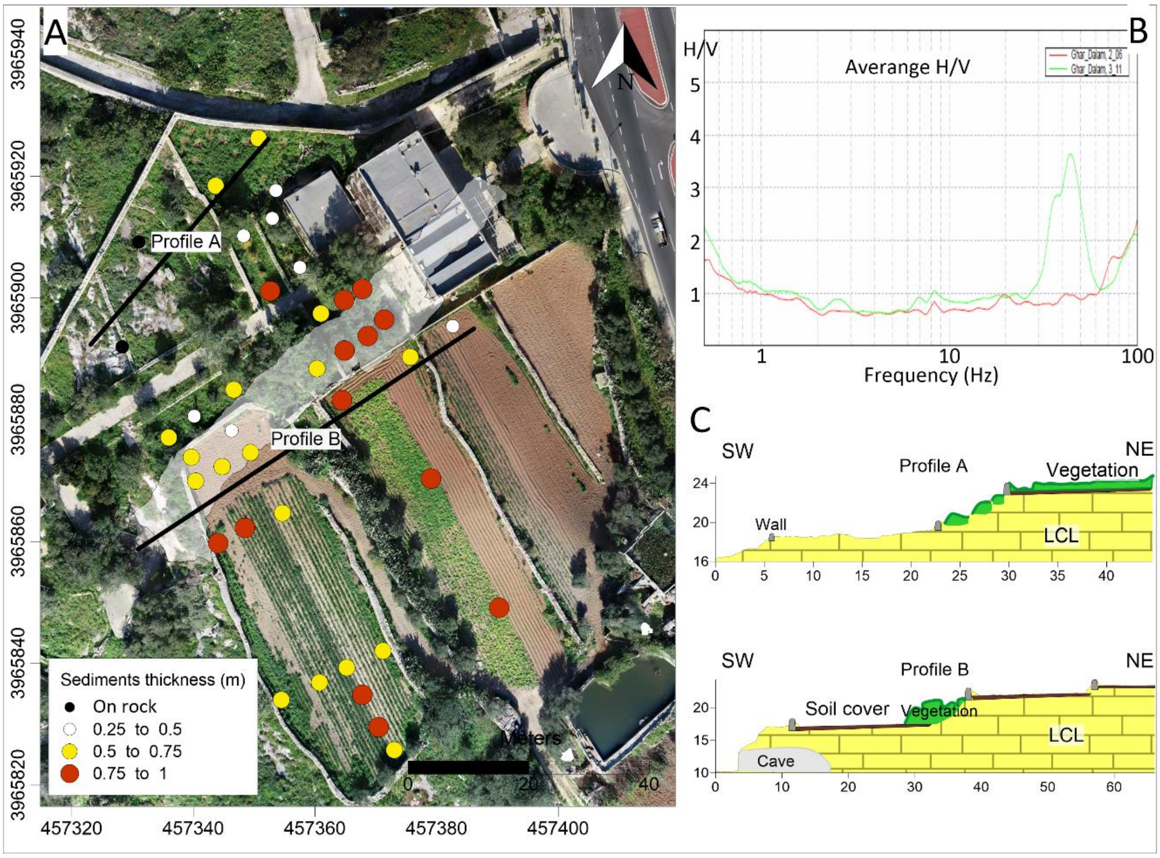

Figure 2: A) Orthophoto with the position of the HVSR sites and its estimated soil thickness. Cave's position is drawn. B) Examples of an HVSR curve of a site with soil cover (green) and with the LGL outcropping (red). C) Interpreted profiles of A.

The processing was similar for the data acquired with both GPR. Data processing sequence consisted of zero timing, background removal or moving-averaging depending on the situation [4], depth-dependent gain compensation and, when needed, one-dimensional Butterworth filtering. The data were then focused using a migration algorithm in time domain [5], taking into consideration the propagation velocity of electromagnetic waves evaluated from the diffraction hyperbola whenever possible, otherwise evaluated from the results of the same migration sequentially performed with different trial values of the propagation velocity [6]. In the case of the data taken in the yards in front of the cave entrance, the high density of the survey allowed us to integrate the B-scans (GPR profiles) in 3D blocks, and to derive horizontal slices from it.

As for passive seismic, we recorded ambient noise vibrations using 3-component velocimeters at more than 50 locations distributed over the study area. The signals were analyzed using the horizontal-to-vertical spectral ratio (HVSR) technique, which is a good approximation of the depth of contact between a low-velocity sedimentary cover and a higher velocity source rock [7, 8]. With this technique, we aimed to determine the thickness of the ground cover to compare with the GPR results. Also, we use this data to detect if there was a different seismic behavior of the ground above the cave that could be used for cave prospecting (Figure 2).

ERT is a classical geophysical technique based on the construction of a model of subsurface electrical resistivities based on measured apparent resistivity data. In this work, we obtained six 2D ERT profiles with a multi-channel resistivity meter (64 channels), testing various configurations to achieve good vertical and lateral resolution. Four of the profiles were taken perpendicular to the cave, one was taken inside the cave parallel to its longest axis, and one was taken at the entrance of the cave, crossing the two pavement courtyards (Figure 3). The processing was carried out with a commercial software that uses a non-linear least-squares optimization technique for the inversion routine [9,10] and that allows inverting the data taking into account the topography along the profiles.

3. Results and discussion

The combined photogrammetric model has allowed the integration of the geophysical data into a 3D environment, resulting in an in-depth understanding of this complex study area. The geophysical survey clarified some important questions of the subsurface of the site. Thanks to the low frequency GPR, we obtained information on the soil-rock boundary geometry in the area above and next to the cave, which will be an important input for future archaeological investigations. This information was supported by the interpretation of the HVSR curves and the ERTs, showing consistency.

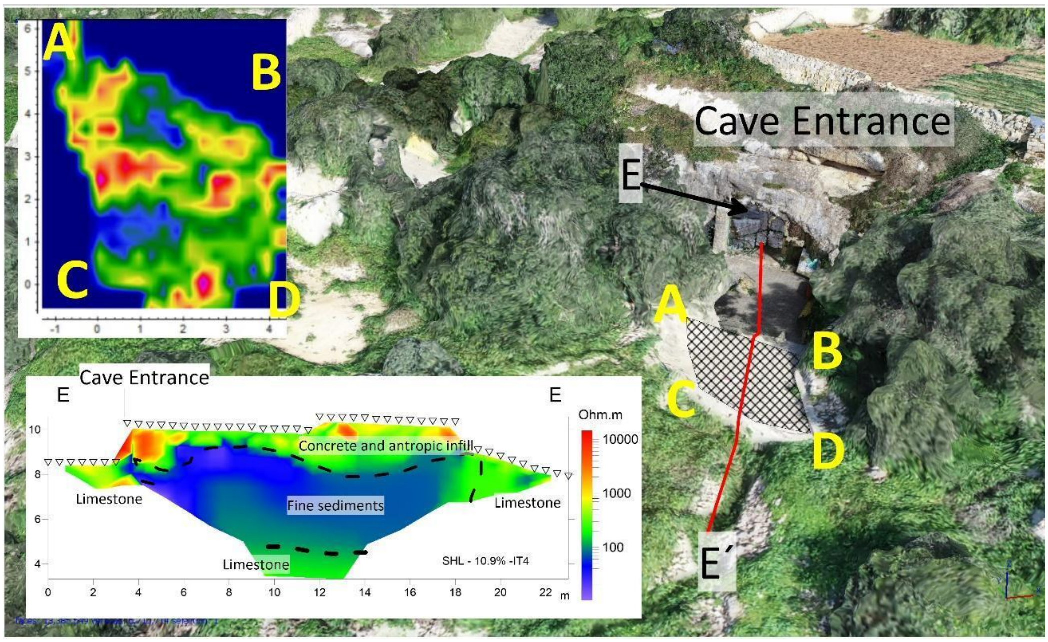

Figure 3: GPR slice (400 MHz GPR, depth ~ 1.2 m) of one of the yards of the cave's entrance (top left) and ERT from inside of the cave, crossing the yards (bottom left).

The cave entrance area was surveyed in detail using a low frequency GPR grid and an ERT with a smaller spacing than the other ERTs (0.5m), which means a higher lateral resolution (and lower penetrability). The ERT results show a medium to high resistivity zone in the shallowest part, a low resistivity zone in the middle part and a medium resistivity zone in the lowest part. We interpreted this geoelectrical profile considering information about the excavation of the cave, and we think that some of the sedimentary material extracted from the cave interior is represented by the low resistivity zone and is located under the cave entrance yards, represented by the medium to high resistivity zone. The lowest medium resistivity zone would be associated with the original limestone. The information obtained from the mid-frequency GPR data is consistent with this interpretation in the first 2 m, at which depth it loses resolution (Figure 3).

As for the methods that allowed us to obtain deeper information, in general the ERT models made perpendicular to the cave were able to show a zone of high resistivity that we can link through the 3D photogrammetric model to the cave. In addition, some ERT models show another high resistivity zone with circular shape that could be evidence of other karstic structures nearby, such as a phreatic tube, which could mean an increased geological value of the area (Figure 4). Although some low frequency GPR B-scans results show anomalies where the cave is located and not where this possible new karstic structure is, we cannot discard its existence given the low resolution of the low frequency GPR b-scans, probably given the presence of external signals that affect such not-shielded GPR. Regarding the HVSR curves, they showed no significant differences between those stations set above the cave and those that were not, so they would not be able to show information of this type of structures in the area.

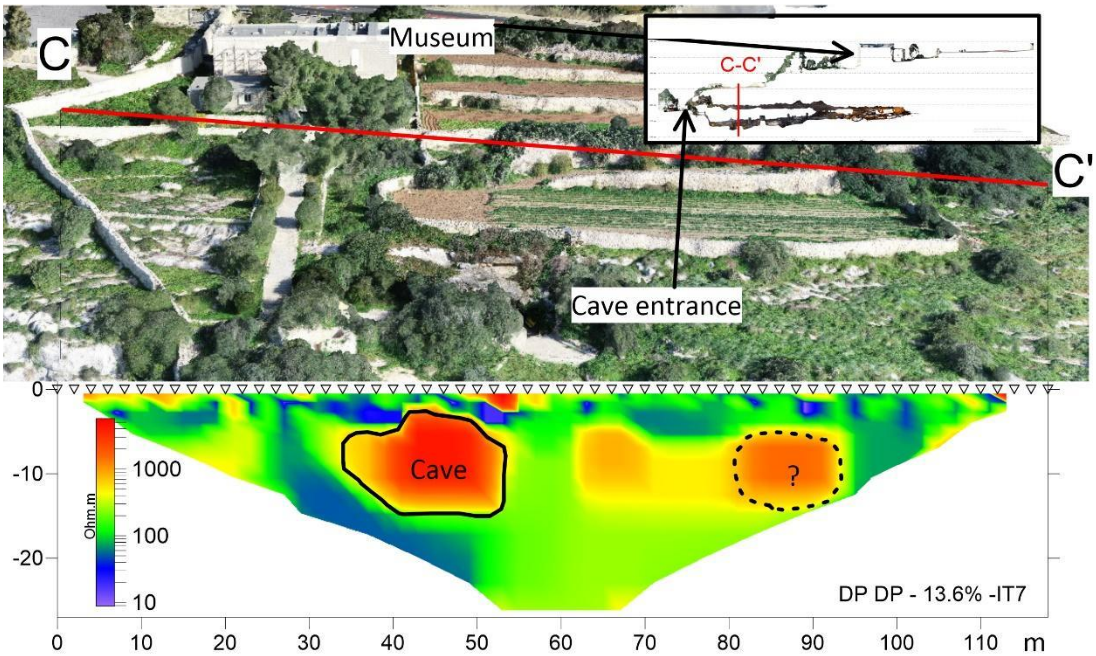

Figure 4: Photogrammetric model showing the position of the C-C' ERT, its position in a profile (top right) and the interpreted result.

4. Conclusion

In this work, we carried out a high-resolution, multi-approach, geophysical and photogrammetric survey of Malta's oldest archaeological site. The results achieved are promising and open the door to future research in the field of both archaeology and geology.

We consider that the integrated approach used in this contribution, i.e., the use of different geophysical signals with different penetrability and resolution plus the 3D photogrammetric model, allowed us to achieve confidence interpretations with a high degree of reliability. We believe that this is an essential approach when direct observation is impossible.

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