

High – Resolution 3D Reconstruction of Sea Caves in Malta Through Underwater Photogrammetry Techniques

By Paul Tickle



Supervisor: Dr Emanuele Colica

Co-Supervisor: Prof. Sebastiano D'Amico

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Abstract

This thesis aims to develop a high-resolution, three-dimensional photogrammetric model of a selected sea cave in the Maltese Islands, this will allow for the monitoring of geomorphic change and the rate of coastal erosion. The resulting model will provide a spatially accurate and visually detailed baseline for scientific analysis of coastal geomorphology and long-term monitoring of erosional processes with data integrated from aerial, terrestrial, and underwater sources. This model will combine data sets from terrestrial, submerged and aerial views of the cave, something that at the time of writing has yet to be done.

Data collection was accomplished via the use of two GoPro 7 Black editions for the photogrammetric model and an iPhone 15 for a LiDAR model of the terrestrial component of the cave, used by hand as a team member walked the accessible regions of the cave. A GoPro 13 black edition was carried by a second team member whilst snorkelling in grid patterns at the surface of the submerged portion. Finally, a DJI Mavic 3 multispectral drone was used for the aerial components of the site, flown from a promontory above the cave site itself.

The data collected was processed through Agisoft Metashape Professional v2.2.1 (Agisoft LLC, St Petersburg, Russia) with a model being created for each component of the cave. The four models once processed were integrated to form one model with scaling accuracy confirmed by the LiDAR model. The level of accuracy in the model allowed for specific measurements to be taken such as width or height, these measurements could allow for the calculation of the mass of rock likely to fall or give bathymetric data on the current submerged section.

The combination of terrestrial, underwater, UAV, and LiDAR photogrammetry proved to be a robust approach for capturing both the external and internal morphology of the cave. Each method contributed complementary datasets: UAV photogrammetry effectively mapped the promontory and entrance geometry, while underwater and terrestrial images documented the cave's internal surfaces in high detail. The integration of LiDAR scanning from the iPhone 15 enhanced the scaling accuracy of the final model, compensating for the potential geometric distortion associated with freehand image capture. This multi-platform approach aligns with recent studies that advocate for the combination of close-range photogrammetry and LiDAR to improve the geometric precision of complex natural structures (Colica et al., 2021; Furlani et al., 2023).

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1. Introduction and Literature Review

1.1 Aim and Research Objectives

This thesis aims to develop a high-resolution, three-dimensional photogrammetric model of a selected sea cave in the Maltese Islands, this will allow for the monitoring of geomorphic change and the rate of coastal erosion. The resulting model will provide a spatially accurate and visually detailed baseline for scientific analysis of coastal geomorphology and long-term monitoring of erosional processes with data integrated from aerial, terrestrial, and underwater sources.

Previous surveys in Malta have catalogued sea caves, however, at the time of writing none have produced high-resolution 3D photogrammetric models with integrated aerial, terrestrial, and underwater components. This study will identify a sea cave/cavern in a coastal region of the Maltese Islands and reconstruct it by means of photogrammetry, a 3D representation of this cave/cavern will be created to provide a visualisation of the major defining characteristics and so create a baseline for future studies on the erosional forces along the coast. The creation of a baseline model of the features along the coast will have multiple benefits; understanding the rate of loss of land will allow for better coastal planning, and giving assessments of the stability will increase safety for visitors in areas likely to suffer landslides or sudden collapse. The mapping process will have immediate benefits, such as allowing potential visitors to understand the area they were going to and plan accordingly before arrival, or as a type of virtual museum for future generations or those who cannot physically visit the area. This type of virtual museum has been created with regard to wartime heritage, with detailed photogrammetric models creating virtual reality experiences. The literature from previous studies will identify a region as yet not investigated and highlight the best methods of data acquisition to achieve the desired results. Photogrammetry will be obtained using GoPro sports cameras (series 13 and 7), an Insta360 camera, and iPhones. Underwater wide-beam torches and narrow-beam spots will be utilised to restore colour and to balance the light in both the surface and underwater cave/cavern components with additional surface lighting as required. The photographic data obtained will then be processed using Agisoft Metashape to provide the 3D visualisation.

1.2 Literature Review and Past Work

Studies previously undertaken in the Mediterranean area have been mainly limited to specific points along parts of the Italian coastline. These expeditions, known as the Geoswim programme, involved swimmers travelling along specific sections of coastline, collecting data from both above and below the water (Furlani & Antonioli, 2023). The Geoswim programme has a quite simple aim to collect a database of various observations along the local coastline to intercontinental to create a baseline for future biological, geological and environmental observations. Extended sections of coast were surveyed each day, with any distinguishing features being documented by video or time-lapse footage, taken at 1-second intervals, increased to 0.5 seconds to ensure a better

resolution, via the use of a bespoke raft that is pushed through the water manually by the surveyor. Scuba divers were used in specific instances, such as to document underwater caves or items of archaeological importance (Furlani & Antonioli, 2023). Where available, old photographs or postcards were obtained to lend insight into past erosion that had already taken place. Furlani et al., (2023) looked more closely into two expeditions carried out around the Maltese islands, along the coastlines of Comino and Gozo in 2013 and Malta itself in 2015. The two expeditions aimed to firstly identify and confirm the locations of sea caves, and then specific caves were identified for further investigation. A total of 79 sea caves were identified during the survey, with 13 being described using photogrammetry, however, no minimum size was specified for the definition of a sea cave, with even notable indentations being mapped.

The caves being surveyed presented issues of scalability, according to Furlani et al., (2023), as global positioning signals (GPS) could not penetrate deep inside the caves. Markers were used that could be identified in the mapping software and measured for scale. LiDAR (light detection and ranging) was also used as a means of determining the scale of the cave. LiDAR using an iPhone has a range of 5 metres from the user's position and is still reliant on a GPS signal, but the resulting model can be integrated with that of the photogrammetric model, improving the accuracy (Furlani et al., 2023).

The photogrammetric process can have other benefits besides monitoring of the coastline, as it can aid divers by offering mapping and virtual training of a dive area before actually undertaking the dive mission. Milka, (2024) states that photogrammetry is a useful research tool in several fields, namely, archaeology, mine or cave documentation, and as maps for divers or dive centres. Public interest and education via the use of virtual reality has already been conducted in Malta, with virtual tours available to the public via Heritage Malta's Dive into History 360 experience (Heritage Malta, n.d.).

The Dive into History virtual tour allows the public to view a site that is inaccessible to all but the most experienced of technical divers due to its depth of 110 metres. Similarly, many of Malta's historically important wrecks have been mapped into 3D models, offering divers and the public the chance to familiarise themselves or just observe the sites using virtual reality technology. The Underwater Cultural and Heritage Unit of Malta (UCHUM), tours schools and public locations offering this experience or via their website, <https://underwatermalta.org/discover/> (Underwater Cultural Heritage Unit Malta, 2025). Many of the dive sites exist past 60 metres of depth, requiring high levels of technical diver training and financial commitment due to the cost of helium gas (He), which is required to reduce the narcotic effects of diving to these depths.

Another team, composed of divers, studied a cave in New Zealand using new 360° camera inside a housing with a lighting rig (Bush & Simpson, 2021). This equipment set up led to them being able to map a 100 metre long fully submerged cave in one dive. Taking still images from the video recording they managed to create a 3D model. The aim behind this project was not for a scientific basis but like has been done in Malta, by

Heritage Malta, to create a virtual reality environment. Bush & Simpson, (2021) went one step further using their model to create a diving simulator to allow prospective visitors to the cave to undergo a dry run, experiencing the environment without the risks of undertaking the actual dive. Whilst their work initially was not with the intention of achieving a scientific basis the attraction it created sparked the interest of researchers in New Zealand with the potential applicability to real archaeological sites.



Figure 1: Insta360 Pro2 inside Mantis Sub housing with lighting rig mounted above: Image Credit: Andrew Simpson

Photogrammetric reconstruction has been used for other geological purposes within Malta already; Malta's most famous geological attraction, a sea arch, was formed by the erosional forces of the sea and wind. This arch, found at Dwerja in the north of Gozo, was known as the Azure Window, which collapsed on March 8th, 2017, during rough weather. Normally, when a sea arch collapses, it leaves behind a stack that previously formed the seaward leg of the arch, for the Azure Window, this was not the case. Caruana et al., (2022) proceeded to investigate the collapse using photogrammetry to create a 3D model that could be compared to models made before the collapse; this was done with the intention of determining why no stack had been left behind and discovering the dynamics of the arches' fall. Caruana et al., (2022) discussed that from their photogrammetric model, they found evidence that suggests the pillar collapsed first and the bridge fell second after its support was lost. The paper concludes by stating the value and importance of photogrammetry to collect data and to allow for the reconstruction of events.



Figure 2: Before and after the collapse of the Azure Window, Gozo: Image Credit: Tickle (2014 vs 2022)

Another instance of using photogrammetry in similar applications was a case study of the Selmun Cliff promontory. Colica et al., (2021) used photogrammetry to reconstruct a three-dimensional model of the promontory which lies on the northern Maltese coast. The photogrammetry data collection was done with the use of Unmanned Aerial Vehicles (UAVs), also described as drones, due to the difficulty of actual access to the area. This study was undertaken with the aim of measuring the fracture zones linked to the cliffs' erosion and in so doing demonstrate how the improving technology in digital geological surveying allowed for the mapping and surveying of features not detectable by traditional surveying techniques where access is not safely possible. This study also led to the creation of one of only two geomorphological maps available of Malta at this time, giving long-term value and meaning to the photogrammetric project.

Milroy et al., (2015) looked directly at photogrammetry and its usefulness in producing three-dimensional models. They concluded that, as a method of digitising objects, it was inexpensive and not reliant on experts or large equipment. Their criticisms based on time of processing or time of taking photographs are possibly redundant now, with advances in computer technology giving more power to the processing phase and automation in image acquisition, reducing fatigue for the user obtaining the images and so speeding up the acquisition process.

Photogrammetry can be used as a valuable tool to help with the understanding of the coastal erosional process by creating a 3D model of specific landmarks, giving an accurate current interpretation of the coastline that can be reviewed in the future to estimate the speed and extent of erosion that is occurring (Colica, 2022). Multiple overlapping images are taken, from which the 3D model is then created; depending on the rate of erosion, repeating the modelling process can indicate the loss of landmass over time (Milka, 2024).

In the past, photogrammetry has presented financial and logistical challenges, requiring the use of heavy equipment and skilled experts to operate (Rahman, 2021). Technology has changed and moved on, allowing photogrammetry to use other data capture equipment, from mirrorless digital cameras to GoPro action cameras and even smartphones (Dabove et al., 2019; Joshi et al., 2022). Research into the accuracy and reliability of using smartphones to create 3D models was undertaken by comparing the

model created by the smartphone to those created using a high-end digital camera. Dabove et al., (2019) stated that in their opinion there was a negligible difference between the two models when processed in the same software; using app software on the phone led to a less complete model. This research could have implications for future geomorphological modelling, as they present a cheap and commonly available tool to obtain data sets.

Collectively, these studies demonstrate the increasing feasibility and scientific value of photogrammetric documentation in both terrestrial and marine environments. While large-scale programmes such as the Geoswim project provide broad contextual data, localised studies in Malta (e.g., Caruana et al., 2022; Colica et al., 2021) highlight the potential of high-resolution modelling for geomorphic analysis. However, none have yet integrated aerial, terrestrial, and underwater photogrammetry into a single workflow to reconstruct a coastal cave environment. This methodological gap provides the foundation for the present research.

2. Test site and geomorphological settings

2.1 The general geological situation in Malta

The Maltese Islands are primarily composed of five distinct types of rock: Blue Clay, Upper Coralline Limestone, Greensand Formation, Globigerina Limestone, and Lower Coralline Limestone (Figure 3). In the central and south-eastern areas of Malta, the presence of globigerina limestone is evident, while in the south-western area, an outcrop of Lower Coralline Limestone Formations can be found. In the northern and north-western areas of Malta, there is the presence of Upper Coralline Limestone Formations and blue clays. On the island of Gozo, a more differentiated geology, with a greater presence of blue clay can be found. Biolchi et al., (2014) proposed six different coastal characteristics for the island of Malta; these being plunging cliffs, scree, sloping coasts, shore platforms, pocket beaches, and artificial coasts. The high cliffs run along the north-western shoreline, with a few pocket beaches and scree areas scattered along the northernmost part. These cliffs are primarily made up of globigerina limestone with a covering layer of blue clay and are exposed to the dominant wind direction for the islands, the north-westerly, and therefore exposed to the wave forces created by those winds (Continental Shelf Department, n.d).

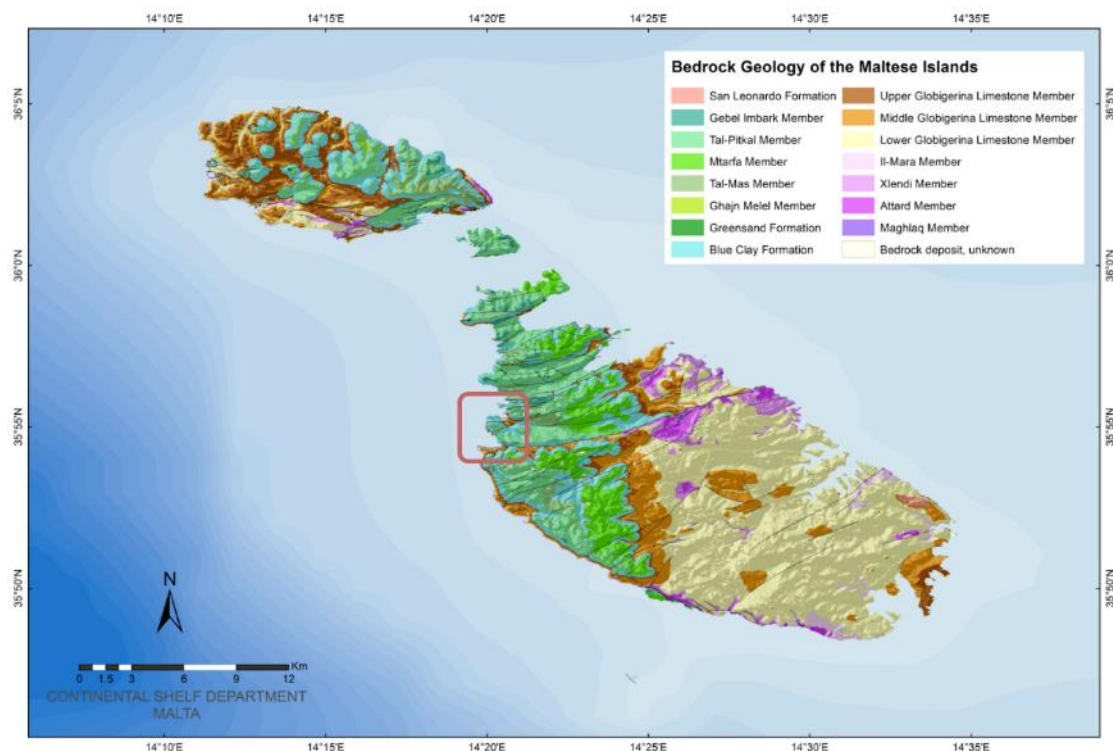


Figure 3: Geological map of the Maltese Islands: Image credit: Continental Shelf Department, Malta

The stratigraphic sequence of the Maltese Islands provides the geological foundation for understanding coastal erosion and cave development. The following subsections describe each formation in stratigraphic order, highlighting their lithological properties and relevance to the geomorphological setting of the study area.

2.1.1 The Lower Coralline Limestone formation

Lower coralline limestone (LCL) is the oldest rock layer of the Maltese Islands and is visible in the areas of Xlendi (Gozo) and Dingli Cliffs (Malta). It is also visible at Fomm ir-Riħ along the Victoria Line Fault (Pedley et al., 2002) (Figure 4) and in inland outcrops where faults occur. This layer was formed during the Oligocene in a shallow gulf-type sea (Magri, 2006) and has a maximum thickness of 140 metres. Due to this condition, the sunlight was able to reach the seabed, allowing the proliferation of fauna and flora. The fossils of algae and coral can still be found on this layer, giving basis to the name of the layer (Pedley et al., 1976). The hardest limestone of all the layers is the light grey one, and it is also the most resistant to the natural phenomenon of erosion. The Lower Coralline Limestone is composed of four members as follows, from the oldest to the most recent:

- Magħlaq member
- the Attard member
- Xlendi member
- Il-Mara member

This rock formation, although coarse and hard, is not homogeneous. In fact, it presents five different facies which indicate the type of depositional environment (Pedley et al., 2002). The facies include barrier limestones made up of coral algae, shallow limestone muds sheltered by reefs containing fossils of foraminifera and bivalve shells, and crisscross layers of sediment accumulated from coarse material that constitute dunes. The foraminiferal limestones, which developed in deep seas with enough sunshine to allow for the survival and proliferation of foraminifera and bryozoans, are then formed. Ultimately, the formation of the Scutella bed with fossils of sea urchins. Fossils of sea urchins can be found because of a shallower sea depth during that time, which then deepened afterwards.



Figure 4: The Lower Coralline Limestone cliffs at Dingli (southwestern coast of Malta): Image Credit: Tickle (2020)

2.1.2 The Globigerina Limestone formation

The Globigerina limestone formation (GL) sits above the lower coralline limestone layer and has some unique details. GL has a finer grain and a yellowish colour when compared to LCL. A variation in thickness can also be seen depending on the area in which it is found. In the north-western area of Gozo, the thickness is 20 metres, while in the south-eastern area of Malta the thickness reaches 207 metres (Pedley et al., 2002). This layer has homogeneous characteristics because, during the period of formation, the sea level rose, allowing for the formation of this layer in deep waters and with greater tranquillity. The presence of planktonic foraminifera gives rise to the name of this type of limestone. Globigerina is widespread in the Maltese archipelago but is scarcely visible as it is covered by infrastructures and houses (Pedley et al., 1976). The colours of yellow, dark brown and light brown layers in the map indicate Globigerina, which we can further divide into three layers, lower, middle and upper Globigerina limestone, respectively.



Figure 5: Image showing Upper Globigerina Limestone members at Ras il-Pellegrin, Malta: Image Credit: Tickle (2025)

2.1.3 The Blue Clay formation

The Blue Clay formation (BC) is located above the GL and also varies in thickness according to the area of the island, and as such, is not homogeneous. The BC layer has an overall maximum thickness of 75 metres in Xaghra in Gozo and on the west coast of the island of Malta, where it can reach 70 metres, while, in the eastern and southern parts of the island, this layer is not found. It has a formation similar to globigerina,

considering that it is deposited in deep water and consists of fine grains of sediment with an abundance of planktonic organisms. Blue Clay owes its name to the presence of clay, which has a colour tending to blue and grey. Depending on the amount of clay and carbonate present, we can observe lighter or darker streaks (Pedley et al., 1978). This layer has also terrigenous sediment of mountainous origin that originated from the erosion process of the mountains of Sicily which had risen following the movements of the continental plates of Africa and Europe. The clayey material could be of volcanic origin, as a result of volcanic eruptions in Sicily. This formation is very soft, and the presence of kaolinite makes it highly prone to erosion (Pedley et al., 2002).



Figure 6: Aerial drone image of the Blue Clay formation at Ras il Pellegrin, Malta: Image Credit: Colica (2025)

2.1.4 The Greensand formation

Between the Upper Coralline Limestone and layers, we can find the Greensand formation (GS). This layer has a reduced thickness compared to the other rocky and massive layers, and for this reason, it is not considered to play a role in the geology of the island or the topography of the Maltese archipelago. We can observe the maximum thickness of this layer at Il-Gelmus in Gozo (Figure 7), as it reaches 11 metres, with a minimum thickness of 1 metre (Pedley et al., 2002). This limestone formation has a dark green colour tending to grey, given by the presence of the mineral glauconite, which was deposited in a relatively warmer and shallow marine environment during the late Miocene epoch (Pedley et al., 1976). As a consequence of atmospheric agents, we can observe that this limestone varies in its colour, tending to brown and orange.



Figure 7: Greensand outcrop at Il-Gelmus mesa (Gozo): Image Credit: Colica, E. (2022)

2.1.5 The Upper Coralline Limestone formation

The Upper Coralline Limestone (UCL) is the most superficial layer and consequently also the layer that was formed after the others. It is widely visible on the island of Malta (Figure 8) and is particularly present in the areas west of Malta and Gozo. The maximum thickness that has been observed is 140 metres. The UCL was formed in shallow marine environments and consists mainly of several intertidal/marine deposits (Pedley et al., 2002). The various grey shades of this material are given by the presence of various fossils, including coral, algae and also different sand deposits based on the current. This layer is divided into four members listed below from oldest to newest (Pedley et al., 1976):

- the member of Ġħajn Melel
- the member Mtarfa
- the member Tal-Pitkal
- the member of Ġebel Imbark.



Figure 8: Upper Coralline Limestone plateau at Ras il-Pellegrin, Malta: Image Credit: Colica (2025)



Figure 9: Aerial view of Ras il Pellegrin showing the layers of UCL, BC, and GL: Image Credit: Colica (2025)

2.2 Sea Cave Formation

Sea caves typically develop along coastal cliffs where zones of structural weakness, such as faults, joints, or bedding planes, are exploited by wave action (Furlani et al., 2023). These cliffs have their geological weaknesses attacked by the power of the sea, carving into specific areas where layers or cracks in the rock cause the cliff to be more vulnerable. These fractures or faults are gradually eroded by waves impacting on the waterline until an opening occurs and a cave is gradually formed. Over time, the wave impact can continue eroding the fault area of the cave and, in some cases, cause an arch to be formed where the cave is open at both ends, such as in the former Azure Window

of Gozo. In the case of some arches, the collapse of the roof can leave the leg remaining as a sea stack (NPS, n.d).

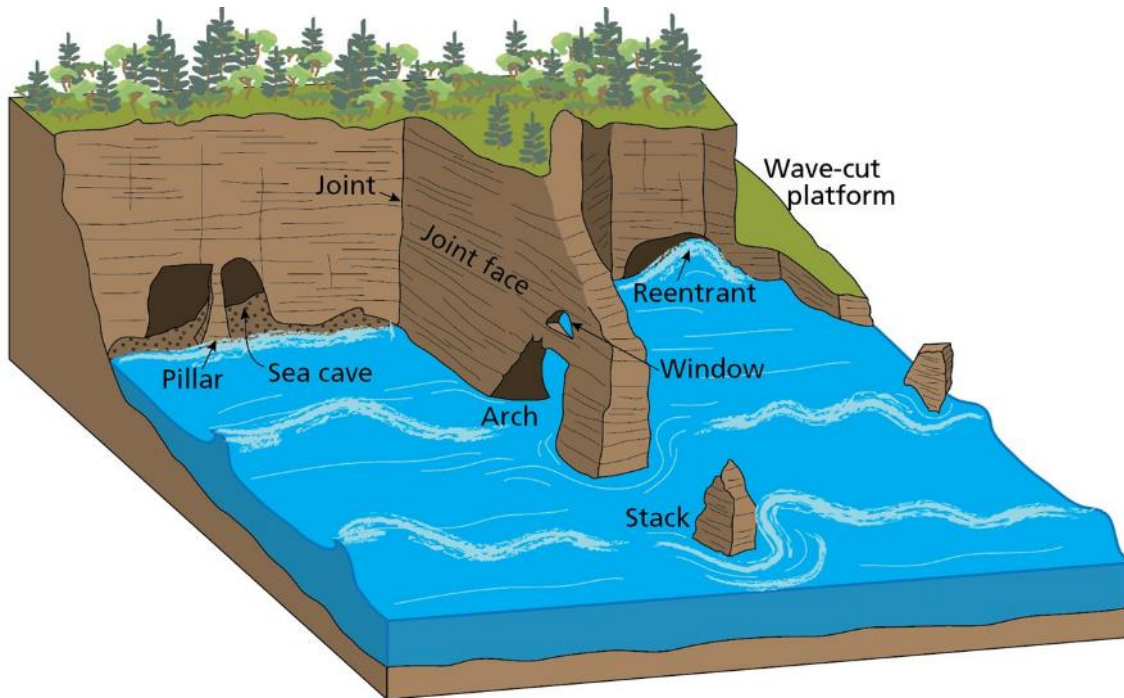


Figure 10: Coastal Erosional Features: Image credit: NPS illustration by Trista L. Thornberry-Ehrlich (Colorado State University).

Constant action of the sea especially during stormy conditions as shown in Figure 11 create wear on the stone which in some cases can cause exceptionally fast erosion, in the case of the Azure Window below it is believed to have taken approximately 193 years from its formation until its collapse (Caruana et al., 2022).



Figure 11: Azure Window in stormy sea conditions: Image Credit: Tickle (2010)

For this study, the selected site Ta' Marija Cave is located along the north-western coastline of Malta, near Ġnejna Bay (Figure 12). To the north of the cave lie the pocket beaches of Gnejna, Ghajn Tuffieha and Golden Bay, to the south of the site are sheer cliffs located within are more caves but with much higher levels of difficulty to access. The Ta' Maria cave has a large deep opening allowing for data collection by foot inside the cave as well as from the water for the submerged portions, the Ras il Pellegrin promontory directly above also gives aerial access of the front cliffs and cave entrance. The cave is developed within the Upper Globigerina Limestone, overlain by Blue Clay and capped by an Upper Coralline Limestone plateau. The site is exposed to the prevailing north-westerly winds and high-energy waves, providing ideal conditions for the investigation of marine erosion and cave evolution within the Maltese coastal environment (Biolchi et al., 2014).



Figure 12: Gnejna Bay area and Ta' Marija Cave: Image credit: Continental Shelf Department, Malta

3. Methodology

3.1 Photogrammetric survey design and integration workflow

Identification and selection of a study site based on geomorphological and logistical criteria. Malta has many sea caves around its coastline; the site to be chosen must meet the aforementioned criteria but also not have been studied in previous work.

Planning of fieldwork logistics, safety measures and the evaluation of environmental conditions (weather, sea state, underwater visibility), as well as environmental and operational conditions, will determine the equipment to be selected not only to carry out the data collection tasks involved but also to ensure the safety of those collecting the data. Strong sun exposure and remote locations of sea caves are two examples of the environmental conditions that will be faced.

Identification of the most suitable data acquisition method, such as the use of Unmanned Aerial Vehicles (UAVs), Remote Operated Vehicles (ROVs), terrestrial and submarine photogrammetry, and Light Detection and Ranging (LiDAR). UAVs give an aerial perspective to the collected data, giving access where a person cannot reach, similarly, ROVs are designed to extend human reach into areas where it would be too dangerous or difficult for a person to go. ROVs differ from UAVs, as they are for use specifically underwater, with harsher environmental conditions such as salt water, pressure and reduced visibility. ROVs typically are tethered with an umbilical to provide power and directional instruction, as the wireless signals used by UAVs would be unusable underwater due to the rapid absorption of the signal by the water (He et al., 2020).



Figure 13: Blue ROV2 platform. Image credit: Blue Robotics Inc.

An ROV such as the BlueROV2 platform can be outfitted with multiple GoPro units deemed a suitable and inexpensive means of photogrammetric data capture (Joshi et al., 2022), and can offer a stable, powerful platform controlled via the tether system using a real-time connection via laptop or tablet, giving reliable coverage of the space to be mapped. (Blue Robotics Inc., n.d). This would be combined with handheld footage for areas deemed more suitable for the flexibility of a manual mapping.

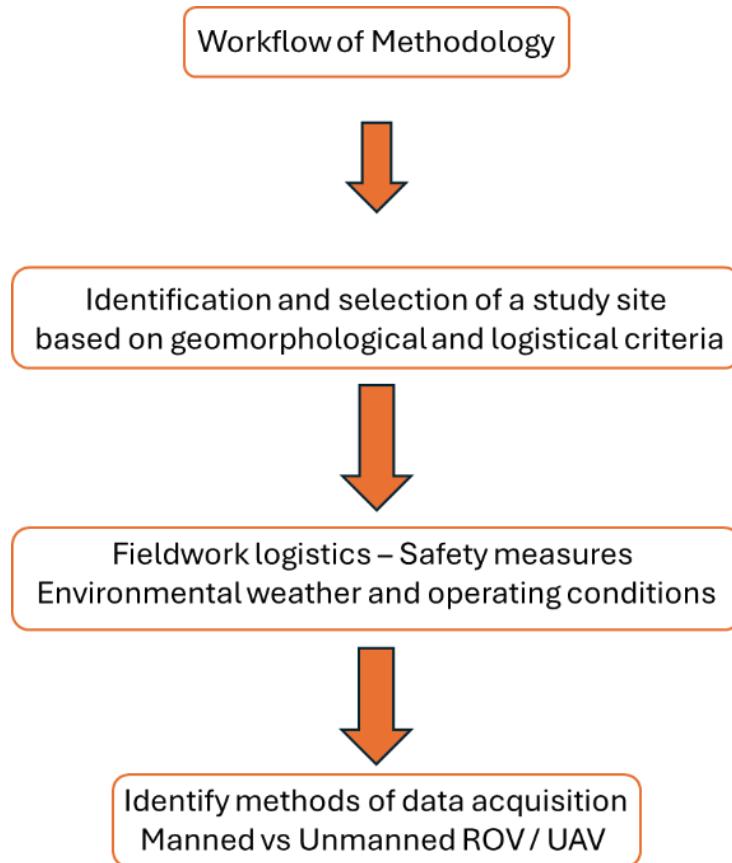


Figure 14: Workflow outlining site selection, fieldwork planning, and data acquisition method identification: Image Credit: Tickle (2025)

3.2 Identification and selection of a study site: Ta’Marija Sea Cave

Analysing past studies conducted within the Mediterranean showed that whilst the Maltese Islands have been subject to investigations in the past, these have been primarily done around Gozo (Furlani et al., 2023). Furthermore, only minor 3D modelling was undertaken, as there was an emphasis on cataloguing the caves and locations.

Ta’Marija cave was chosen as the subject to be mapped and documented, with its location being both a benefit and a hindrance alike. The cave is located towards the north of Malta on the west coast at Ras il Pellegrin, around a kilometre and a half from the popular Gnejna Bay. The cave is formed in globigerina limestone with a blue clay covering below the plateau formed from upper coralline limestone and is subject to wave action from the common north-westerly wind (Biolchi et al., 2014). Access to the cave is difficult, whilst hiking is possible, the descent to the cave is not for the faint of

heart, and with temperatures reaching high into the 30s (celsius) the hike is made more arduous. Visitors commonly access the cave by kayak or small boat, meaning that the number of people visiting is very limited, allowing data to be collected without the disturbance associated with Malta's more accessible scenic areas. To access the cave for the purposes of data collection would not be a case of simply jumping in a kayak and heading off. Internally the cave shows evidence of new fracturing with the potential of large areas of collapse in the coming years. Evidence of this can be seen in figure 15 where the roof level differs from the entrance to an area approximately five metres in. The lower roof level further in has evidence of cracks and fractures suggesting it will fall at some point in time.



Figure 15: Interior of Ta'Marija Cave: Image Credit: Tickle 2025



Figure 16: GL Limestone formation at sea level at the landing site: Image Credit: Tickle (2025)

3.3 Planning of fieldwork logistics, safety measures and equipment.

Data collection took place during the month of August to allow for more guaranteed sea conditions and ensure the safety of the data collection team. The time of year, though, presented other problems, with all of Malta's beaches occupied by tourists and daytime temperatures well above 30 degrees celsius. Access to a small dinghy with an outboard motor was available, this allowed for the transportation of considerably more equipment than a kayak or other available means. Water, food and a first aid kit were considered essential for the comfort of the team, as well as sun protection, hats and creams given the duration of sun exposure. Further equipment to be taken included life vests in case of capsizing, snorkelling equipment to allow for in-water data collection and markers to be included in the photogrammetry to scale the model. With an increasing load of equipment, it was decided to not use the ROV, as the benefit from it was outweighed by the space it would require to be transported. As Ta'Marija cave was quite narrow at sea level but still wide enough to allow for a snorkeller to pass easily, it was decided to focus on hands-on data collection both in the water and on the terrestrial side of the cave, meaning only GoPros and extendable arms needed to be taken.

As the sea cave covers both underwater and terrestrial space, a variety of data collection tools were to be used. Terrestrial work was undertaken using two GoPro Series 7 Black on extendable arms and held at slightly differing angles, and time-lapse images were taken every two seconds, whilst carried by a team member who walked along the surface edge of the cave as far as the cave allowed for safe access. A LiDAR 3D image

was also constructed using an iPhone 15 over a five-meter area from where the team member walked or stood. This 3D LiDAR model, produced from the phone, whilst limited in range, would be useful in determining scale for the photogrammetric model being produced. Markers were also placed at points throughout the surface cave area; these markers had known dimensions of 50cm by 50cm and could be located later on in the software and used to confirm or correct scaling.

Specification	GoPro 7	GoPro 13	iPhone 15
Sensor	1/2.3" CMOS*	1/1.9" CMOS*	2'nd generation sensor shift
Processor / Aperture	GP1/F2.5	GP2/F2.5	A17 Pro / F1.78
Image Resolution	12MP, 4000 x 3000	27.6MP, active 5599 x 4927	48/24/12 MP, depending on camera used
Video Resolution	4K (16:9) 60/50/30/24 fps	5.3K (16:9) 60/50/30/25/24 fps	n/a
Focal Length	n/a	23-27mm levelling in camera "superview"	24mm "superview"
Scanner	n/a	n/a	LiDAR
Price	€360 at time of purchase (discontinued)	€360	€1000

* CMOS (complimentary metal-oxide semiconductor)

Table 1 GoPro and iPhone specifications used during data acquisition

In water data was taken by a snorkeller making multiple passes through the cave from the entrance until the innermost accessible point. The depth of water in the cave was not greater than two metres, and as such, it was not necessary to use scuba equipment, as surface work was enough to survey the bottom. In the case of the underwater data, every 24th frame was taken from a high-resolution 5.3k video and was used instead of time-lapse to obtain the maximum number of frames available due to the more changeable light conditions.



Figure 17: *Diver making a handheld survey with GoPro13. Image credit: Colica (2025)*

A UAV was used on a separate occasion by walking to the top of the Ras il Pellegrin ridge directly above the Ta'Marija cave, visited by boat before, to take photogrammetric data of the facade and entrance of the cave. The UAV was not used inside the cave due to concerns over the loss of GPS signal to the drone and therefore the possible loss of the drone itself to the sea. UAVs, or drones, are becoming essential in the field of remote sensing with the wide variety of aerial drones available, from fixed wing for large areas to multirotor drones that can navigate tight spaces. Mounted with a normal RGB imaging camera on a gimbal stabiliser to remove vibration effects or unwanted movement, the drone would be able to produce photogrammetric data to be processed. The drones can be remotely controlled by a person on the ground nearby or autonomously via onboard computers (Colica et al., 2021; 2023).



Figure 18: Data Collection at Ras il Pellegrin: Image Credit: Tickle (2025)

A multirotor drone controlled by a person could be considered the most suitable option for the data collection from sea caves thanks to the ability to hover and access tight spaces easily. Images collected from the drone could allow for a greater 3D rendering of the site, bringing inaccessible areas into reach. Limitations still prohibit complete use of the drone for mapping purposes due to the range of GPS coverage once the drone goes further back into the cave.



Figure 19: DJI Mavic 3 multispectral drone. Image credit: DJI Agriculture Benelux

Photogrammetry is one technique of many used in the field of geoinformatics and geospatial information, also known as geomatics. Geomatics involves collecting, analysing, processing and presenting data of a geographic nature (Colica, 2022). Photogrammetry could be described as measuring the boundaries of an object or space from photographic images without physical contact with the object, giving the benefit of a non-invasive documenting technique. Photogrammetry has applications in the fields of geology, engineering, and the environment for 3D reconstructions of slopes or quarries and monitoring of infrastructure or the state of landfill health (Colica, 2022). Accurate and repeatable data is obtained by the taking of overlapping images. These images would then be processed using the Structure from Motion (SfM) technique. SfM was developed in the 1990's as a technique to transform images into a 3D representation of the photographed scene (Spetsakis and Aloininess, 1991). SfM digital photogrammetry operates under the same principles as stereoscopic photogrammetry with a minimum of two frames detailing the same object and is widely considered a consistent, inexpensive and accurate data collection method. Modern computer data handling capabilities have transformed photogrammetry from analogue to a digital process, increasing speed and simplicity and reducing cost. A further advantage and the main difference between SfM photogrammetry and stereoscopic photogrammetry is the absence of the need to have known 3-D locations. Position information is generated automatically from common points on an image, generating converging lines that can be intersected mathematically to define the coordinates, in three dimensions, of the points (Colica, 2022).

3.4 Data collection

Photogrammetry is the process of mapping a feature or area by taking multiple overlapping images, either via time-lapse or scene capture from video collection (Rahman, 2021). These images, taken in the hundreds, will then be analysed by specific software such as Meshroom, Agisoft Metashape, or 3DF Zephyr to produce a three-

dimensional (3D) representation. This 3D model can be created via the angle of separation of the pictures taken, creating a depth map, or by a point cloud created by extrapolation of the common lines of sight, creating intersects that give a coordinate for the image in space (Colica, 2022). Photogrammetric techniques vary when taken in an underwater environment due to water transparency (visibility), colour absorption at depth by the water column, and challenges presented in site access due to coastline topography at these potentially remote locations (Milka, 2024).

Data collection for this study was undertaken in mid August 2025, although care had been taken to choose a day with ideal wind conditions residual swell still remained making launching and beaching the dinghy challenging to prevent the craft flipping and loosing equipment in the process. Temperature was 35° celsius in the air with a surface sea temperature of 29°, the journey to the cave took approximately 45 minutes having launched the dinghy at Gnejna bay. Sea conditions at the cave mouth were turbid due to the residual swell although further into the cave visibility improved and maintained a constant level.

Data was collected as follows:

Terrestrial (cave entrance and inner walls above the water line). The process involved; camera setup: Two GoPro Hero 7 Black mounted on adjustable poles at slightly different angles (~20 cm baseline). Shooting mode: Time-lapse, one image every 2 seconds. Camera movement: Slow, continuous walking pace (~0.3 m/s) along the accessible ledges. Image overlap: ≈ 80 % forward and 70 % side overlap between successive frames. Distance from wall: Maintained at 1.5–2.0 metre to ensure good coverage without parallax distortion. Lighting: Natural light supplemented by handheld LED lamps to minimise shadow variation. Total images: Around 400–600 photographs captured for the terrestrial component.

Underwater data collection (snorkelling inside the cave). Camera setup: GoPro Hero 13 on handheld pole. Recording mode: 5.3K video at 60 fps, later processed by extracting every 6th–12th frame (≈ 5–10 fps equivalent). Swimming path: Multiple passes along and across the cave (~2 metres deep), maintaining 1.5–3 metre standoff from walls and seabed. Lighting: Two underwater torches (wide beam + narrow beam) used to improve colour balance and visibility. Image overlap (after extraction): Minimum 70 % overlap between consecutive frames. Total images: Approximate frames extracted: 500–700 usable images for reconstruction of the underwater component.

Aerial data collection (UAV façade and surrounding area). Platform: DJI Mavic 3 Multispectral RTK. Altitude: 50 metres above the ground. Camera settings: 4:3 ratio, 20 MP images at 80 % forward and 70 % side overlap. Acquisition pattern: Three façade strips (nadir and two oblique angles of ~25° and ~45°). Georeferencing: Real-time RTK corrections; GSD ≈ 5–10 mm/pixel. Total images: 200–300 aerial photos.

Scaling and reference targets: Waterproof coded targets (50cm x 50cm) and two rigid scale bars (1.0 metre) placed at the cave entrance and interior, both in the terrestrial and submerged areas. Georeferencing: The UAV model provided absolute coordinates via

RTK. The terrestrial and underwater models were scaled with targets and then aligned to the UAV model using common markers.

3.5 Photogrammetric 3D Reconstruction

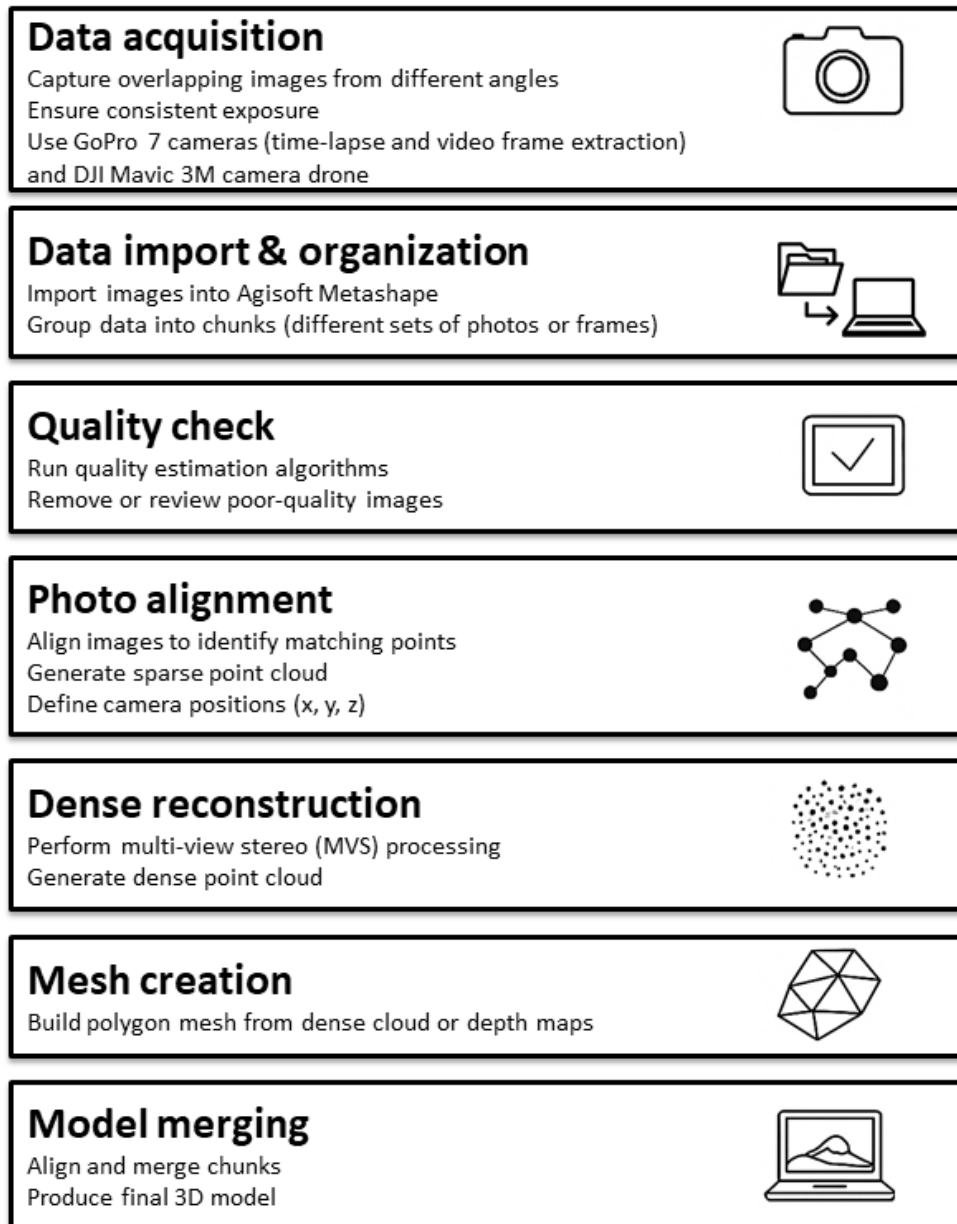


Figure 20: Photogrammetry workflow illustrating the main processing stages, from image acquisition to final model merging; Image Credit: Colica (2025)

Data acquisition is the first step in creating a photogrammetric 3D model; overlapping images taken from differing angles are taken throughout the entire environment intended to be documented and mapped. These overlapping images allow for intersecting points and allow depth to be perceived to generate location points. Ideally these images would be with as close as possible to the same exposure throughout the area to give the best output later.

Once data has been collected, it needs to be processed through software on a computer with a minimum of 16 GB and a recommended minimum of 32 GB of RAM (although even with 128 GB RAM the model required nearly two hours of processing time), and graphics card ability. Software that could be used can vary between purchased software, such as 3DF Zephyr or Agisoft Metashape, or free software, such as Meshroom. Agisoft Metashape™ (Agisoft LLC, St Petersburg, Russia), being available to use, thanks to a university subscription and believed to be the standard in software for photogrammetry (Hostettler et al., 2024), was chosen. Firstly, it needs to have images imported into the software. Time-lapse images taken at two-second intervals are uploaded to a working folder directly from the two angled GoPro 7s, whilst data obtained by video is processed with every 6th – 12th being selected, essentially 5 – 10 frames per second and sent to a separate working folder. The working folders, known as 'chunks' in Agisoft parlance reflect different batches of photos that can be aligned individually and checked before being merged together to create the mesh for the 3D model (Milroy et al., 2015)

With all of the data uploaded, it is possible to use estimation algorithms to assess the quality of image data presented before processing starts; this would allow for the dismissal of any images deemed to be of poor quality, although, given the subject being mapped, a review of the images rejected by the computer would be prudent before casting them to the reject pile.

The alignment of the photos is the most crucial aspect in the construction of the model, images that are not aligned correctly create random outlying areas that must be removed before processing. Alignment entails the software analysing the overlapping images and comparing them for common points to assign coordinates in space. Extrapolation allows the software to indicate a camera position for the images at each key point allowing an x,y,z coordinate to be found and displayed. This process creates a sparse point cloud and is followed by a multi-view stereo (MVS) reconstruction, creating a dense point cloud and mesh production to allow a virtual surface to be obtained from polygons, the vertices of which are the points within the cloud. The model can be created using this point cloud and polygon mesh or via depth maps using the disparity between overlapping images to indicate a spatial dimension. Each chunk can be aligned separately, checked and modelled individually before overlaying the chunks to create the final model.

The photogrammetric reconstruction of the Ta' Marija Sea Cave followed the Structure-from-Motion (SfM) and Multi-View Stereo (MVS) workflow implemented in Agisoft Metashape Professional v2.2.1 (Agisoft LLC, St Petersburg, Russia). Data from the three acquisition domains—UAV, terrestrial, and underwater—were imported into Metashape and organised into separate chunks to allow independent processing and error control before merging. Images were first subjected to quality estimation algorithms, and those with a score below 0.6 were discarded or manually reviewed. Photo alignment was performed at High accuracy with a key-point limit of 40,000 and tie-point limit of 10,000, generating the sparse point cloud and estimated camera positions (Figures 21 & 22). The dense reconstruction was then computed using the

MVS approach at High quality and *Mild filtering*, producing a detailed dense point cloud (Figure 23). Subsequently, a polygon mesh was generated using an arbitrary surface model with approximately 10–15 million faces, textured at 8192 px resolution using mosaic blending to maximise surface detail (Figure 24). Scaling and referencing were achieved using waterproof coded targets placed within the cave and visible across multiple datasets. The UAV model, georeferenced through RTK corrections, served as the spatial reference for aligning the terrestrial and underwater models, ensuring all sections of the cave were represented within a unified coordinate framework. The final merged model was subjected to quality control, including reprojection error evaluation, scale bar verification (RMSE < 0.01 m), and manual mesh cleaning to remove artefacts caused by reflections and water movement. The reconstructed 3D model, integrating aerial, terrestrial, and underwater components, provides a high-resolution, georeferenced representation of the Ta’ Marija Cave and serves as the foundation for the analysis and visualisation presented in Chapter 4.

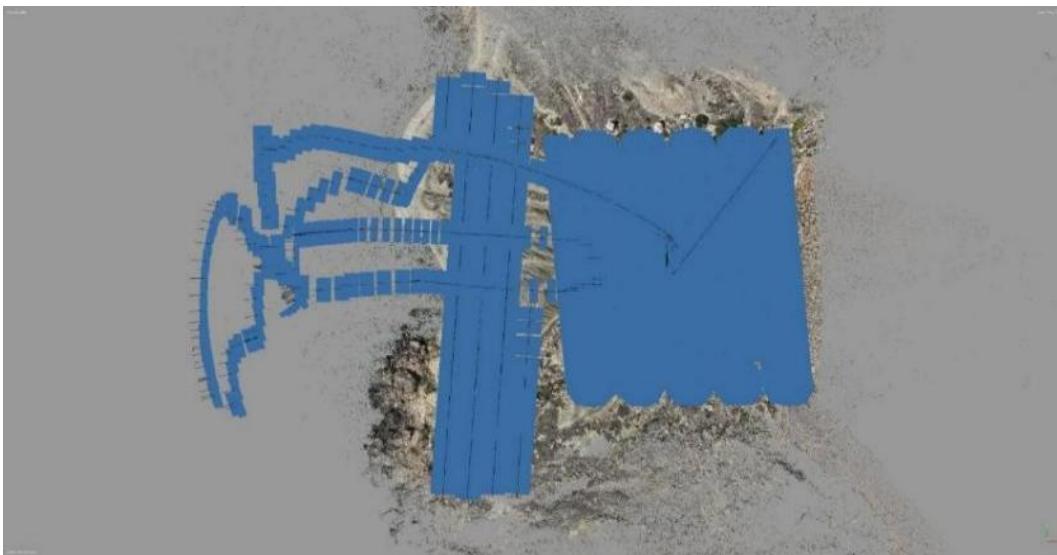


Figure 21: SfM workflow camera positions: Image Credit: Colica (2025)

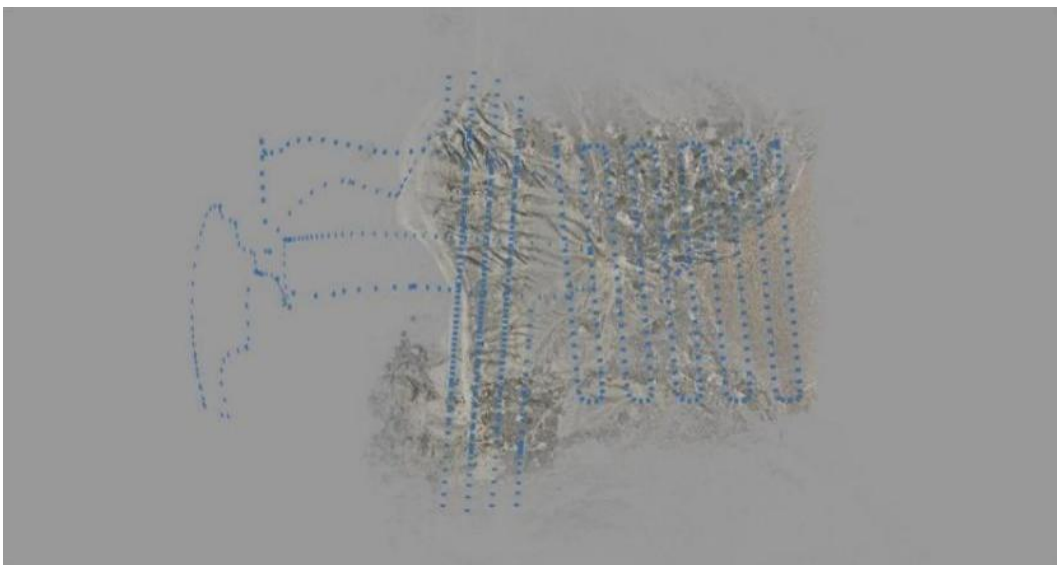


Figure 22: SfM Workflow sparse point cloud: Image Credit: Colica (2025)

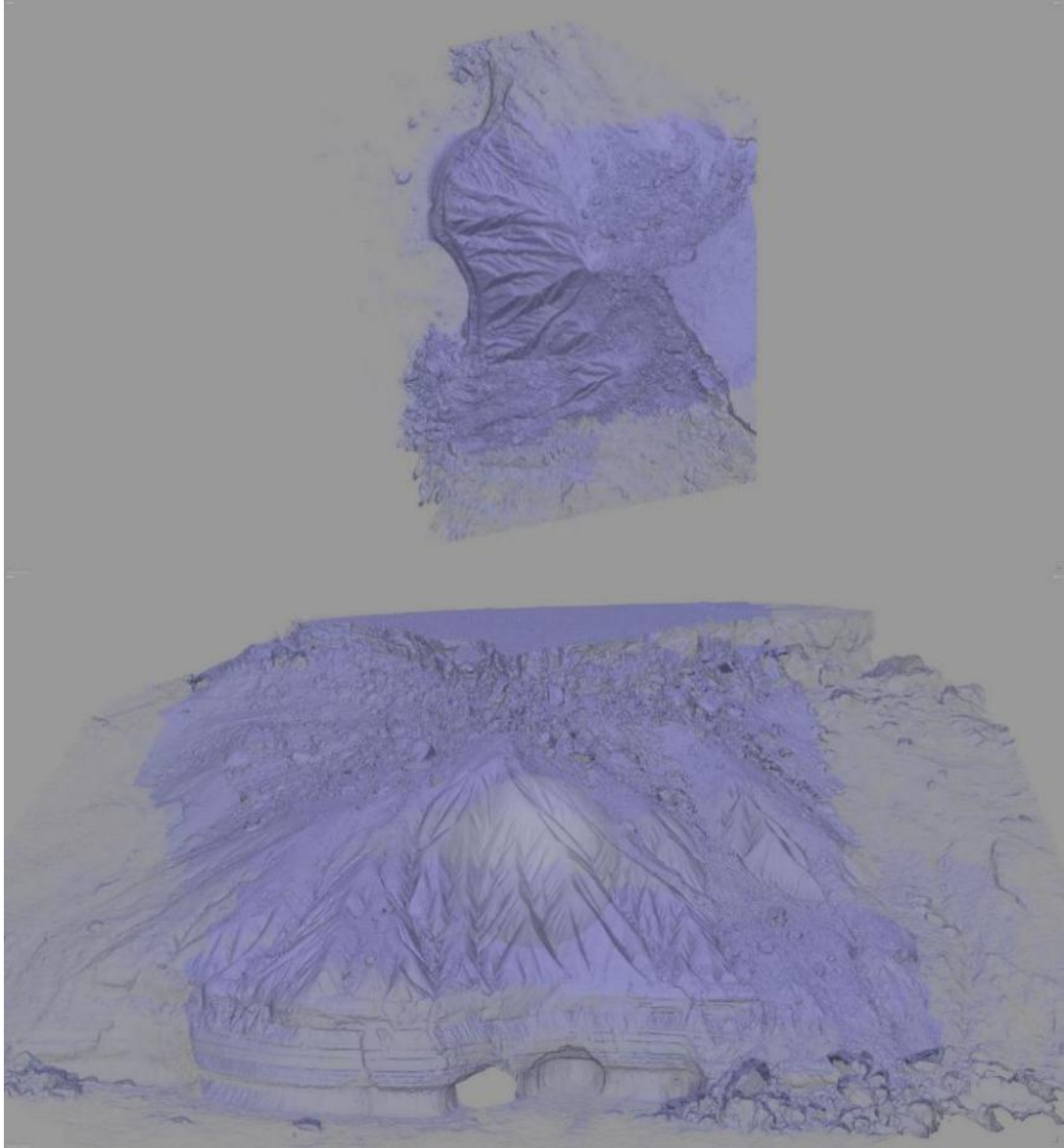


Figure 23: SfM Workflow dense point cloud; Image Credit: Colica (2025)



Figure 24: SfM Workflow mesh creation: Image Credit: Colica (2025)

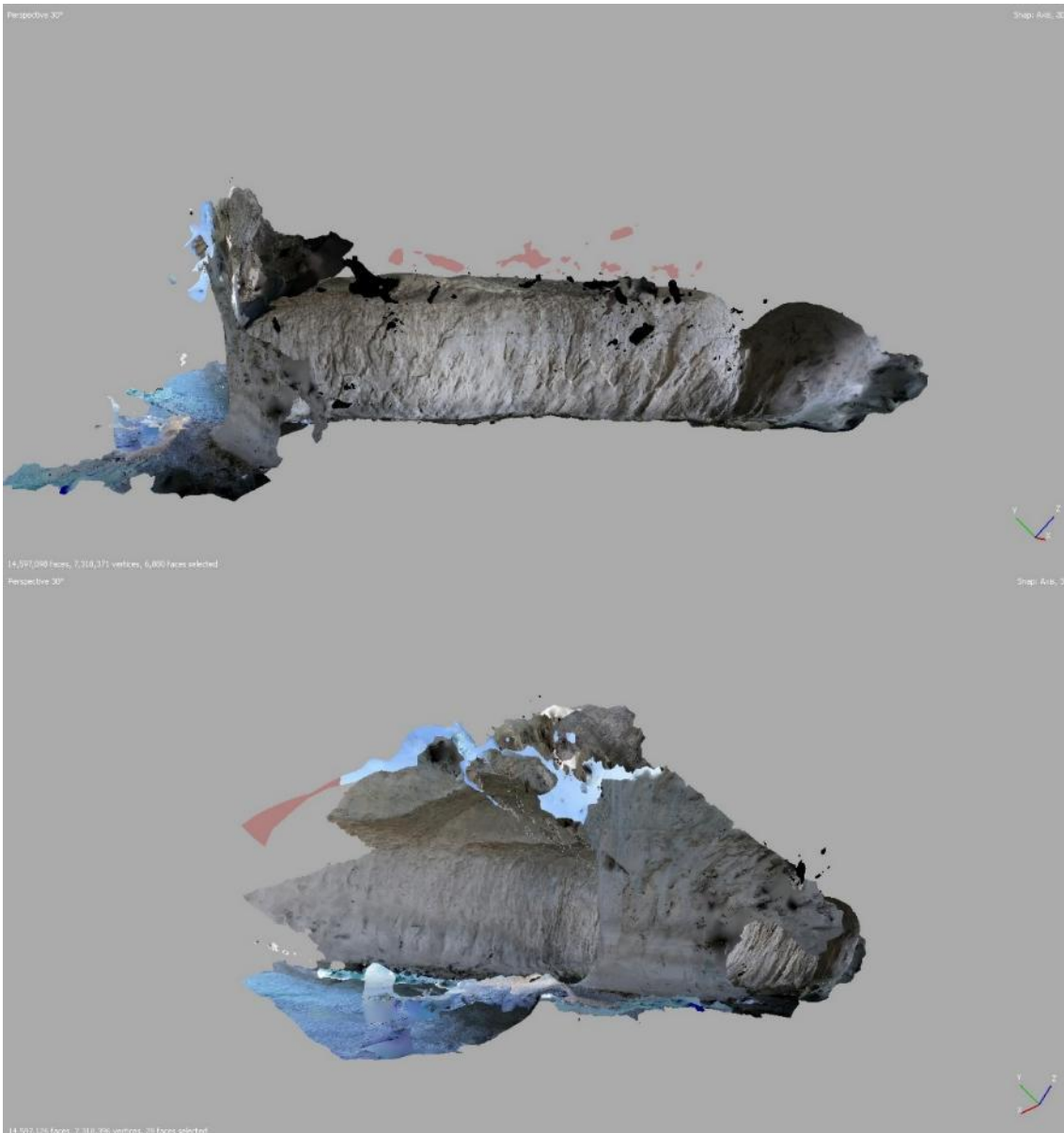


Figure 25: Mesh manual cleaning: Image Credit: Colica (2025)

In photogrammetry, manual mesh cleaning is often required to eliminate artefacts generated during the Structure from Motion (SfM) reconstruction process, particularly those caused by water surface reflections, refractions, or moving objects. Such artefacts typically arise due to the inability of the SfM algorithm to correctly match keypoints in regions with specular or dynamic surfaces, leading to erroneous 3D geometry in the resulting dense point cloud and mesh, (Figure 25).

4 Results and Discussion

4.1 Results – Model creation and integration

Data acquisition led to the creation of four separate models, these being an external model showing the general geomorphology of the Ras il Pellegrin promontory (Figure 26), an interior terrestrial model of the cave (Figure 27), an interior model of the cave below sea level (Figure 28), and a partial LiDAR model of the southernmost entrance pillar of the cave (Figure 29). The four models created all presented some problems or difficulties with their creation, the external model of the promontory was difficult to access with a long walk with the UAV and supplies. The distance from the actual cave also gave concern with the GPS range and communication with the device, ideally if a larger vessel had been available collecting this data from the sea in front of the cave would have been more desirable. The processing of the data, however, was standard as light sources were uniform, and the programmed track of the drone ensured an accurate coverage of the area.



Figure 26: Photogrammetric model of Ras il Pellegrin area with Ta'Marija Cave: Image Credit: Colica (2025)

The two internal models of the cave access wise were easier, as had been described earlier the small dinghy available was sufficient to transport the team to the cave with all the equipment necessary. The day of the survey itself was a few days after some moderate westerly winds and a slight residual swell was still present, making the launching and beaching difficult. The terrestrial portion of the cave was walked through by a team member and was extremely slippery to navigate through with only narrow areas to pass. Lighting throughout was highly changeable, reducing constantly the deeper into the cave the team went. An even lighting setup would have been useful but would have required a raft, such as that used by Furlani et al., (2023) on their swim surveys, the use of a raft would also have reduced the risk to the team member

collecting the data of the terrestrial area. Processing of this data to form the image was more challenging as more artefacts were evident due to water reflections and with the swell the constantly changing divide between land and sea, resulting in some cleaning of the mesh manually before an accurate model could be created.



Figure 27: Photogrammetric model of Ta'Maria Cave terrestrial area: Image Credit: Colica (2025)

The submerged area of the cave presented no difficulties to the team member after the slippery foreshore had been negotiated. The cave being quite narrow meant a good overlap of images was easy to obtain with multiple passes being made at the surface only, with a maximum depth of only three metres a scuba dive was not necessary. The swell did compromise some images especially at the cave entrance as the sea was frothing and foaming as waves struck the shore, blurring some images and changing light conditions as well. After processing, the data gave a good representation of the area documented.

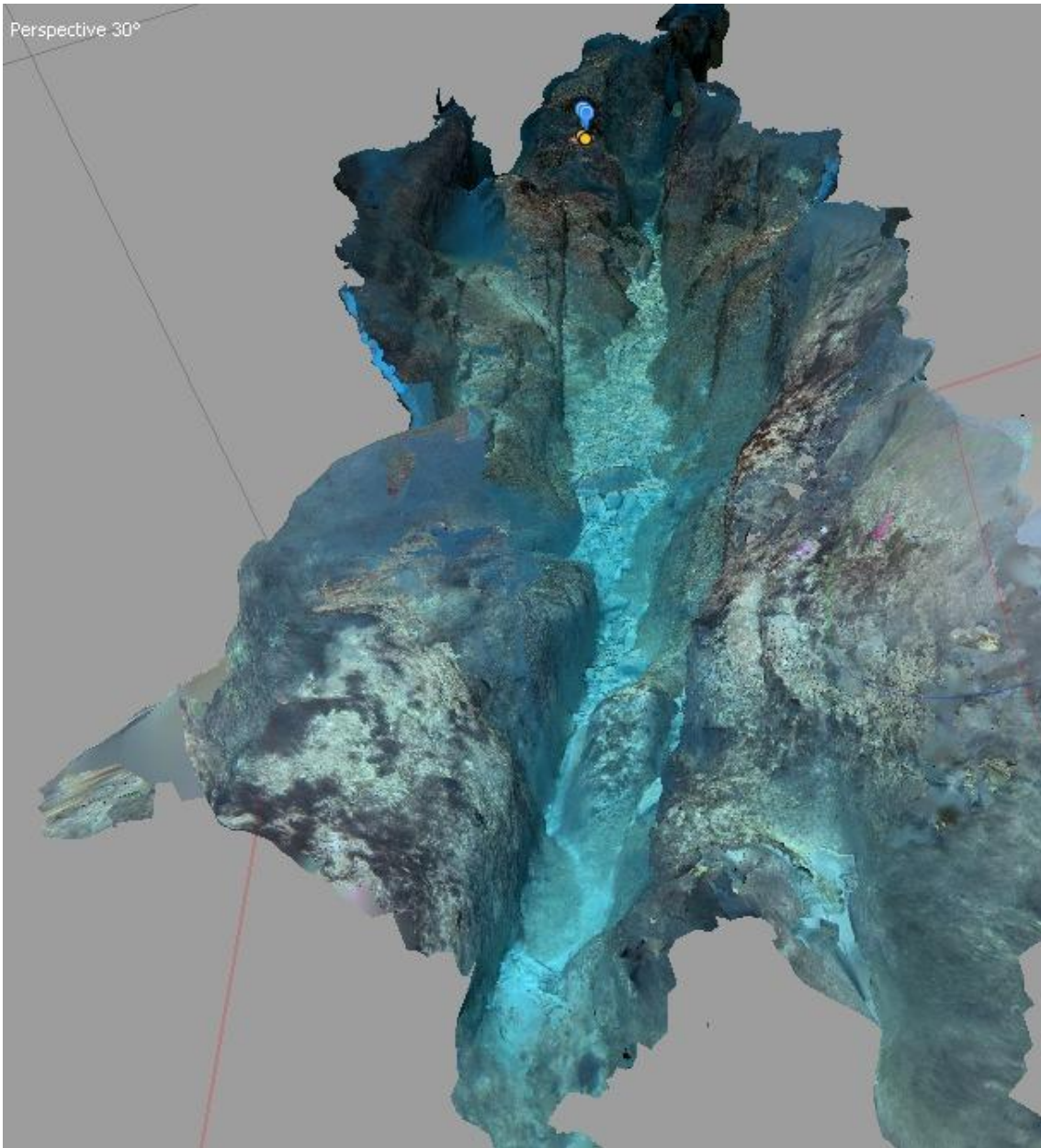


Figure 28: Photogrammetric model of Ta'Marija Cave below sea level: Image Credit: Colica (2025)

The final model to be made was the LiDAR model made from a standard iPhone 15pro, this was the easiest model to create and process as the intent here was to not try to cover the entire terrestrial area of the cave but a sufficient amount to aid with scaling in the final model. The LiDAR sensor of the phone has a maximum range of five metres so a selfie stick would have actually been of use to extend the mappable area. The mouth of the cave was the main focus of this data collection due to the slippery nature inside the cave itself. Processing of the data was handled by a free app called Scaniverse (Scaniverse, 2025) which produced a, cloudcompareproject.bin, file which could be edited using open source software from, www.cloudcompare.org, to produce a model that could be used in conjunction with those already produced.

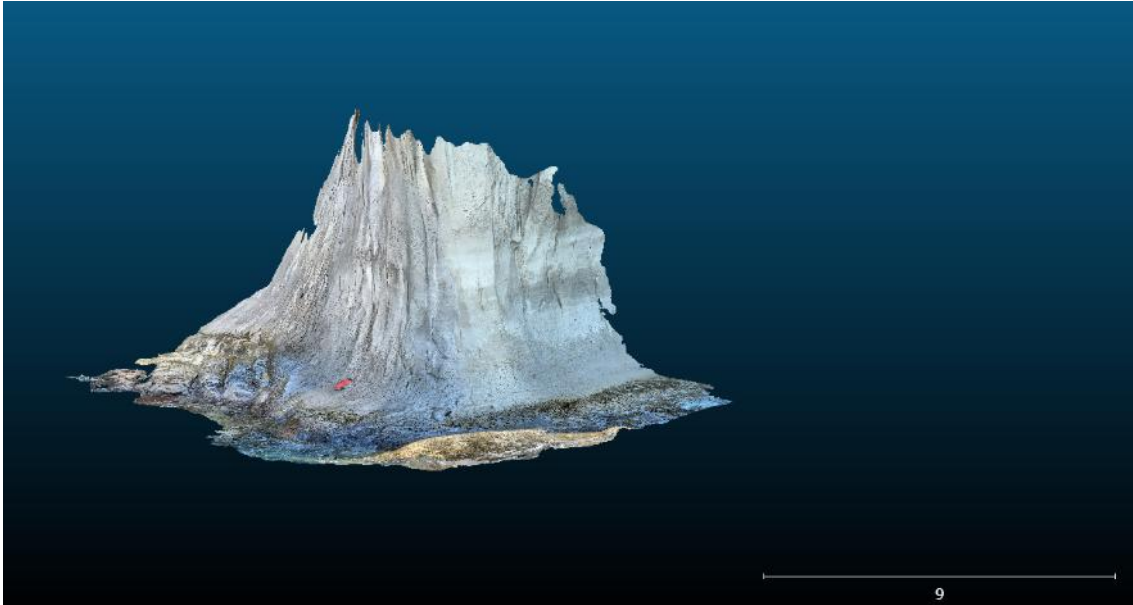


Figure 29: LiDAR model of cave entrance: Image Credit: Tickle (2025)

The four models were looked at closely with the consensus that visually they were accurate to the cave itself. To give the models purpose and meaning they were integrated together to give one model showing a representation of the cliff face with the cave shown in detail as well. The integration of the LiDAR model increased the accuracy of the scaling. Square markers had been laid out during the data collection, but as no completely flat surfaces were available there was the possibility the software might misread the dimensions whereas those from the LiDAR model would have a much higher degree of accuracy.

In figure 30 the below two images show the front elevation of the cliff face with cave being central in each image.



Figure 30: External view of the four merged models: Image Credit: Colica (2025)

Figure 31 presents a general and zoomed side view of the area indicating a length of penetration into the cliff face of the cave.

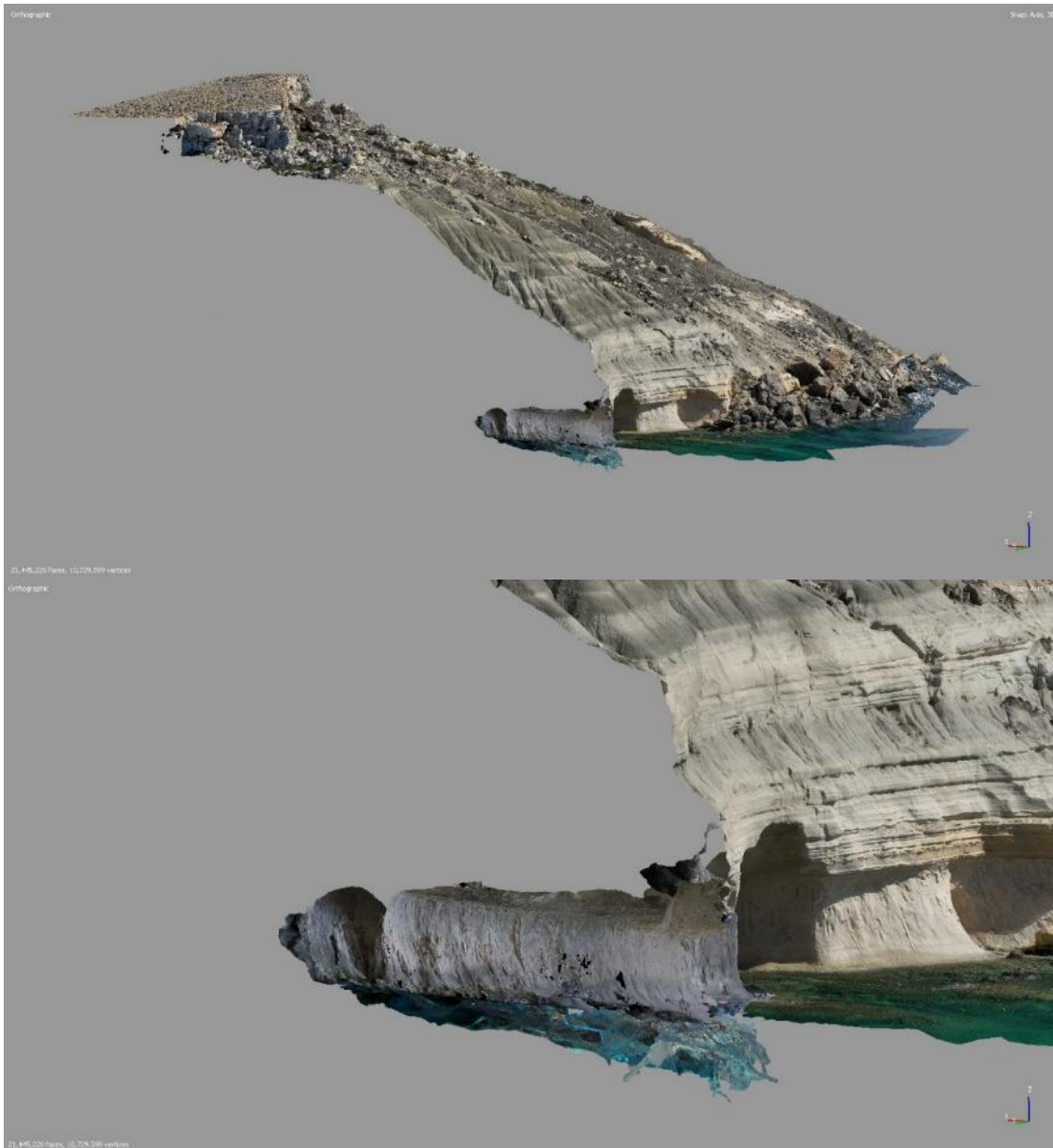


Figure 31: Side view showing external and internal models: Image Credit: Colica (2025)

Figure 32 shows a closer view of the cave itself with both terrestrial and submerged portions of the model evident.

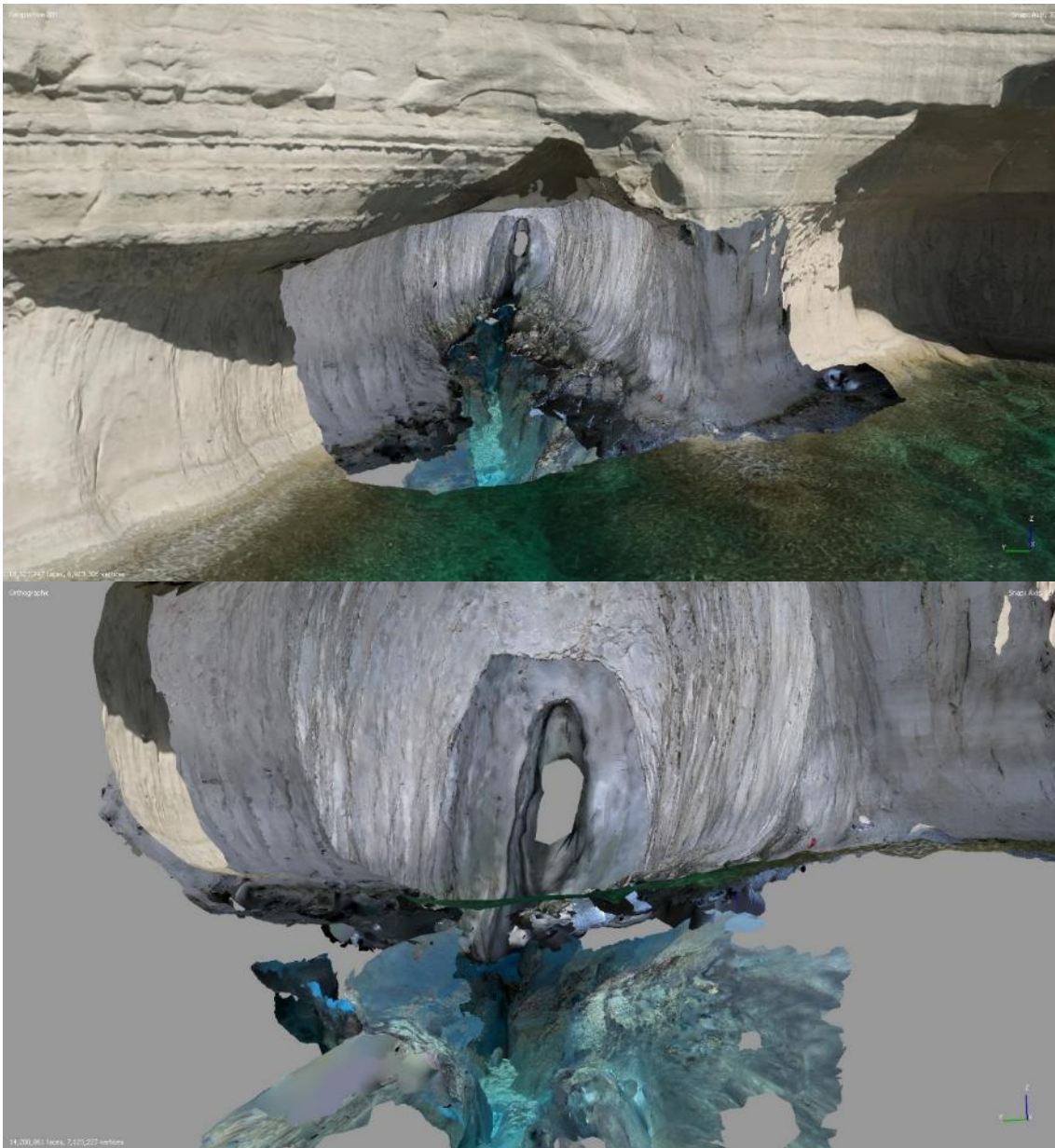


Figure 32: View of interior merged models with localised facade: Image Credit: Colica (2025)

Having this degree of detail available in the models allows for specific measurements to be taken as required. It is possible to make bathymetric measurements of the submerged sections or measurements of the extent of the current opening which could be compared with future studies to show the rate of erosion of the cliff face. Figures 33 and 34 show width and height measurements of the current situation. Measurements could also be taken of specific parts of the cave where cracks and fissures are already visible which

could allow for the calculation of the volume and mass of rock which is at risk of falling.

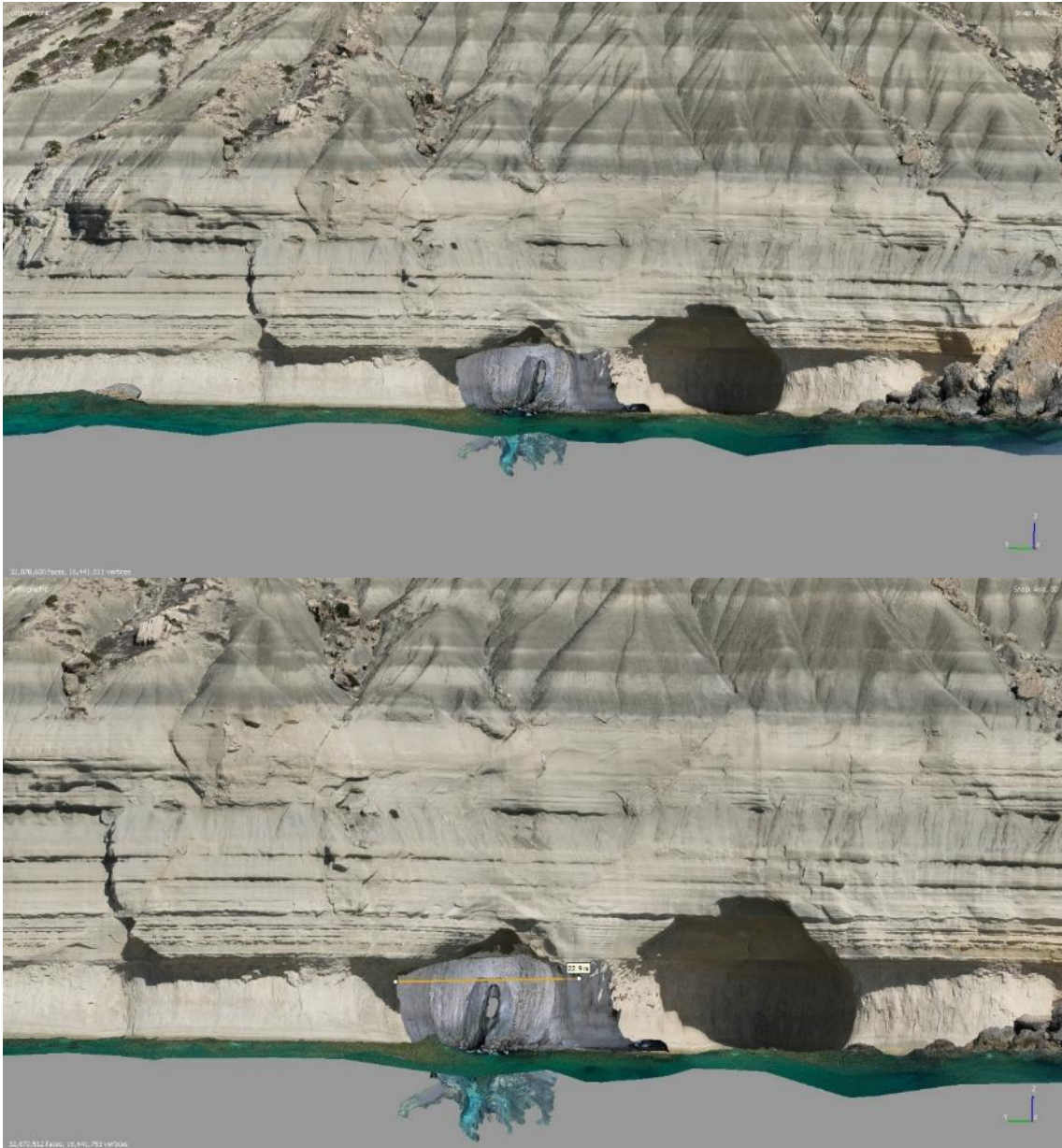


Figure 33: Frontal elevation with cave width measurement: Image Credit: Colica (2025)

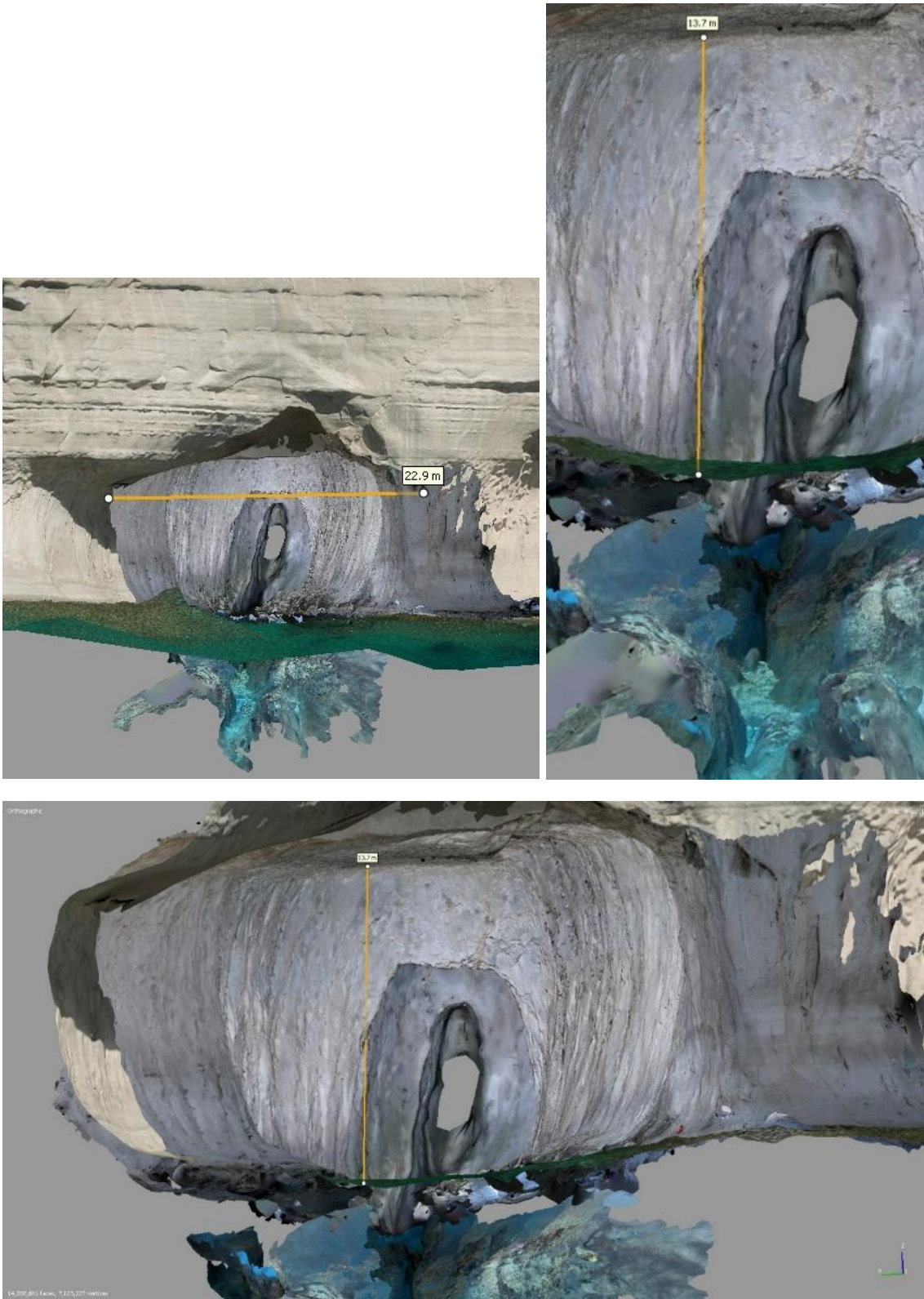


Figure 34: Internal cave height and width measurements: Image Credit: Colica (2025)

4.2 Discussion – Interpretation and implications

The selected site Ta’ Marija Cave was chosen to give the best compromise of access versus disturbance by tourism. The site is exposed to the prevailing north-westerly winds and high-energy waves, (Biolchi et al., 2014). These waves being the main instigation of the cave formation, the Ras il Pellegrin bluff protrudes past the cave entrance giving some protection but possibly causing eddies and currents that increase the erosion of the stone. This could also explain why the secondary indentation to the immediate south of the cave whilst larger in opening has almost no depth to it as of yet. Unfortunately, possibly due to the access restrictions, photos of the site date only to the last decade and thus do not give us an idea of the rate of erosion, although warnings have appeared on social media concerning the stability of the cave roof. The results obtained from this study demonstrate the effectiveness of integrating multiple photogrammetric techniques for the documentation and analysis of coastal and submarine geomorphological features. The 3D models of Ta’Marija Cave generated from terrestrial, underwater, aerial, and LiDAR data collectively provide a detailed and accurate representation of the cave’s current morphology. The integrated dataset serves not only as a visual record but also as a baseline for future monitoring of coastal erosion and structural instability in similar geological contexts.

The combination of terrestrial, underwater, UAV, and LiDAR photogrammetry proved to be a robust approach for capturing both the external and internal morphology of the cave. Each method contributed complementary datasets: UAV photogrammetry effectively mapped the promontory and entrance geometry, while underwater and terrestrial images documented the cave’s internal surfaces in high detail. The integration of LiDAR scanning from the iPhone 15 enhanced the scaling accuracy of the final model, compensating for the potential geometric distortion associated with freehand image capture. This multi-platform approach aligns with recent studies that advocate for the combination of close-range photogrammetry and LiDAR to improve the geometric precision of complex natural structures (Colica et al., 2021; Furlani et al., 2023).

However, the results also confirm that multi-sensor data integration introduces certain challenges. Variations in lighting, water turbidity, and surface reflectivity produced artefacts in the Structure-from-Motion (SfM) reconstruction, particularly in areas affected by wave motion or poor illumination. These limitations required extensive manual cleaning of the mesh, consistent with findings by Schmidt and Rzhanov (2012), who reported similar issues in underwater stereo photogrammetry. Despite these difficulties, the integrated models were visually consistent and spatially accurate when cross-validated against LiDAR-derived reference points.

Environmental conditions were a major determinant of data quality. The survey was conducted during the summer season to ensure calm sea conditions, yet residual swell and variable light inside the cave introduced noise in some image sequences. In particular, the highly reflective water surface and the alternating shadow zones caused by the cave geometry affected colour uniformity and point matching. This resulted in small gaps and deformations in the dense point cloud, especially near the interface

between terrestrial and underwater datasets. Nevertheless, the redundancy of images acquired through multiple passes and from varied angles, ensured sufficient overlap for successful alignment in Agisoft Metashape. Similar challenges have been documented by Milka (2024), who emphasised that underwater photogrammetry is particularly sensitive to variations in light intensity, sediment load, and motion-induced blur.

From a practical standpoint, the choice of handheld GoPro cameras and smartphones for image acquisition proved highly efficient and cost-effective. Although these devices lack the calibration and sensor stability of professional photogrammetric cameras, the resulting accuracy was adequate for geomorphological and documentation purposes. This finding supports the conclusions of Dabove et al. (2019), who demonstrated that smartphone-based photogrammetry can yield results comparable to those obtained with professional digital cameras when processed in high-quality software environments.

The results of this study expand on previous work conducted by Furlani et al. (2023), which focused primarily on the regional inventory of sea caves rather than on detailed 3D reconstructions. By producing a scaled and integrated model of Ta'Marija Cave, this study provides a finer resolution dataset capable of supporting geomorphological analysis, hazard assessment, and virtual representation. Compared to similar studies, such as the photogrammetric reconstruction of the Azure Window collapse (Caruana et al., 2022), this research applies the technique to a smaller but morphologically complex feature, demonstrating that photogrammetry can be successfully adapted for both large-scale and confined environments.

In addition, the results align with findings by Pulido Mantas et al. (2023), who highlighted the potential of photogrammetry for ecological and structural analysis of marine caves. The detailed models obtained in this study could, in future applications, be used to analyse not only geomorphology but also biological colonisation patterns or sediment deposition within the cave. The integration of terrestrial and underwater domains provides a valuable reference for long-term environmental monitoring in coastal karst systems, which are particularly vulnerable to climate-induced sea-level changes and increasing storm intensity.

Despite its success, the study faced several operational and methodological limitations. The absence of ground control points (GCPs) with precise georeferencing limited the absolute positional accuracy of the models. Future surveys should incorporate GCPs obtained through total station measurements to ensure that models can be compared quantitatively over time. Moreover, while LiDAR scanning improved scale accuracy in confined areas, its limited range (5 metres) restricted coverage within larger sections of the cave. The use of professional terrestrial or mobile LiDAR systems would greatly enhance completeness and geometric consistency.

Lighting remained a major constraint during both terrestrial and underwater data acquisition. Uniform artificial lighting systems or synchronized strobe arrays would significantly improve colour balance and texture quality in future work. The potential integration of ROVs equipped with calibrated camera rigs could also extend data

collection to deeper or more hazardous parts of the cave, as suggested by Nocerino et al. (2018). Finally, while post-processing using Agisoft Metashape was effective, future analyses could employ automated error detection algorithms or machine learning-based noise reduction to further optimise the workflow.

The final integrated 3D model of Ta’Marija Cave provides a precise and reusable digital baseline for monitoring geomorphological changes along Malta’s western coastline. By enabling non-invasive measurement of parameters such as cavity volume, entrance width, and structural fractures, the model offers a framework for future comparison and erosion-rate estimation. The resulting model also enables a site-focused interpretation of Ta’ Marija Sea Cave within its local geomorphological setting. Importantly, neighbouring sea caves in the same coastal sector should not be expected to follow identical evolutionary pathways. Even over short distances, cave growth can diverge due to (i) differences in entrance orientation relative to prevailing wave approach, (ii) wave-energy focusing controlled by nearshore bathymetry and cliff geometry, (iii) structural controls (fracture density, joint connectivity, bedding-plane persistence) that localise quarrying and roof instability, and (iv) lithological heterogeneity that influences erodibility. These factors can produce markedly different cave morphologies and growth rates among adjacent cavities that are otherwise hosted in comparable coastal formations.

In this context, Ta’ Marija’s more developed geometry may reflect a combination of favourable structural pathways and more efficient coupling of wave energy at the entrance, compared to nearby recesses that remain sheltered, structurally less connected, or dominated by discontinuities that do not promote progressive backwearing. At present, we treat this interpretation as a testable hypothesis rather than a definitive explanation, because a systematic inventory of adjacent caves (orientation, geometry, discontinuity patterns, exposure) has not yet been completed. Nevertheless, the georeferenced 3D model provides the framework for such an inventory: key descriptors (entrance width/height, planform shape, ceiling span, submerged extent, orientation) can be measured consistently and compared across caves, allowing the identification of morphometric outliers and the formulation of site-specific evolutionary scenarios.

The methodology also has broader implications for heritage and environmental management, contributing to initiatives such as virtual museums and digital conservation platforms (Heritage Malta, n.d.). The possibility of repeating the photogrammetric survey at regular intervals would allow the creation of temporal datasets capable of quantifying erosion, collapse, or sediment infilling.

Beyond scientific applications, the 3D reconstruction serves an educational and outreach function. High-resolution models can be integrated into interactive visualisations and virtual reality experiences, promoting awareness of Malta’s geological and coastal heritage while reducing the need for physical visitation to fragile environments. Such virtual documentation contributes to sustainable tourism practices by balancing access with preservation.

5 Conclusion and Future Work

This study successfully developed a high-resolution, three-dimensional photogrammetric model of the Ta' Marija sea cave in the Maltese Islands, integrating aerial, terrestrial, underwater, and LiDAR datasets into a unified and georeferenced reconstruction. The results demonstrate that multi-platform photogrammetry can accurately capture the geometry of complex coastal environments, even under challenging lighting and sea conditions. The integrated model provides a precise and reusable baseline for future monitoring of erosion, structural instability, and morphological change, and contributes to the documentation and preservation of Malta's coastal heritage.

Future research in this area would be highly desirable to have a complete overview of the changing state of our coastline and that of other mediterranean countries. With the plethora of sea caves on the island of Malta alone allowing for a large scope of study. If a thorough program were to be considered bespoke equipment could be purchased or created, this being a purpose-built raft for terrestrial and underwater data collection. This could be along the lines of that created and used by Furlani et al., (2023) for their swim survey, although for the Maltese coastline it could also be slightly larger allowing for the deployment of an ROV. Due to distances around the Island being relatively small, this raft could be towed by a small boat rather than having to be pushed for kilometres as the proposed emphasis would be more on cave mapping than that of the entire coastline. A larger raft would also potentially allow for the mounting of more constant light sources to give better quality data collection.

With a large number of caves existing well below the sea level underwater photogrammetric rigs could be considered such as those used by Heritage Malta and Seamagination for their virtual wreck tours, Mantis Sub for their reconstruction of an underwater cave, or that used during the reconstruction of the collapsed Azure Window (Busch & Simpson. 2021; Underwater Cultural Heritage Unit Malta & Malta Tourism Authority. n.d; Milka. 2024; Caruana et al., 2022). These purpose-built rigs allow for easy and safe data collection over wide areas even at depths exceeding 100 metres with lighting and camera equipment often mounted onto diver propulsion vehicles (DPVs) to reduce stress and workload by the diver.

Future studies could also look into advancing technology such as the use of iPhones (Dabove et al., 2019), or 360° cameras (Busch & Simpson, 2021), with higher specifications being produced each year these devices could speed up or facilitate data collection methods. Reducing the time required to collect data would be of immense benefit to mapping caves at deeper depths where time is limited due to the increased pressures of depth.

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