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AUGMENTED FOSSIL TOUR, AN AR APPLICATION FOR EXPLORING AND STUDYING FOSSILS

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Abstract

Fossils constitute a significant part of Earth's biodiversity, holding considerable heritage value. With an aim of improving and enhancing dissemination of knowledge and by integrating augmented reality technologies, this paper presents an AR application to identify fossils in two fossil sites, that of Agia Marina (Aegina Island) and Rafina (Attiki peninsula). An application compatible to mobile devices that enables the user to identify the fossils in situ, promoting learning through interactive experiences. It offers virtual tours that transport users back in time to the palaeo-environments where these fossils were originally found. This application seeks to make science, and especially palaeontology, accessible and engaging to a wide range of people. To achieve this, we employed advanced photogrammetry techniques. By utilizing these methods, we were able to create detailed and accurate 3D models of marine fossils and environments. This approach not only enhances the visual *representation of these palaeo-environments but also provides precise data for scientific analysis and educational purposes. The AFT project allows us to capture the intricacies of invertebrate species and their habitats, ensuring that their importance within the marine ecosystem is effectively communicated and appreciated by a wider audience.*

Keywords: *Geological heritage; fossils; augmented reality; photogrammetry; Aegina; Rafina.*

ΠΕΡΙΛΗΨΗ

Τα απολιθώματα αποτελούν σημαντικό μέρος της βιοποικιλότητας της Γης και έχουν σημαντική αξία σε όρους πολιτιστικής κληρονομιάς. Έχοντας ως στόχο τη βελτίωση και την ενίσχυση της διάδοσης της γνώσης και ενσωματώνοντας προηγμένες τεχνολογίες, όπως οι τεχνολογίες επαυξημένης πραγματικότητας (AR), η παρούσα εργασία παρουσιάζει μια εφαρμογή AR (augmented reality) για τον εντοπισμό και την αναγνώριση απολιθωμάτων σε δύο απολιθωματοφόρες περιοχές. Η εφαρμογή αυτή παρουσιάζεται πιλοτικά στις περιοχές της Αγίας Μαρίνας (Αίγινα) και της Ραφήνας (χερσόνησος της Αττικής). Πρόκειται για μια εφαρμογή που είναι συμβατή με κινητές συσκευές και που επιτρέπει στο χρήστη να αναγνωρίσει τα απολιθώματα επί τόπου, προωθώντας με αυτόν τον τρόπο τη μάθηση μέσω διαδραστικών εμπειριών. Επιπλέον, προσφέρει εικονικές περιηγήσεις που μεταφέρουν τους χρήστες πίσω στο χρόνο στα παλαιοπεριβάλλοντα όπου βρέθηκαν αρχικά αυτά τα απολιθώματα. Η εφαρμογή αυτή επιδιώκει να καταστήσει την επιστήμη, και ιδίως την παλαιοντολογία, προσιτή και ελκυστική σε ένα ευρύ φάσμα ανθρώπων. Για να το επιτύχουμε αυτό, χρησιμοποιήσαμε προηγμένες τεχνικές φωτογραμμετρίας, με τις οποίες μπορέσαμε να δημιουργήσουμε λεπτομερή και ακριβή τρισδιάστατα μοντέλα θαλάσσιων απολιθωμάτων και περιβαλλόντων. Αυτή η προσέγγιση προσφέρει όχι μόνο την οπτική αναπαράσταση αυτών των παλαιοπεριβαλλόντων, αλλά παρέχει επίσης ακριβή δεδομένα για επιστημονική ανάλυση και εκπαιδευτικούς σκοπούς. Το έργο AFT μας επιτρέπει να αποτυπώσουμε τις ιδιαιτερότητες ασπόνδυλων ειδών και των ενδιαιτημάτων τους, διασφαλίζοντας ότι η σημασία τους στο θαλάσσιο οικοσύστημα θα επικοινωνηθεί αποτελεσματικά και θα εκτιμηθεί από ένα ευρύτερο κοινό.

Λέξεις – Κλειδιά: *Γεωλογική κληρονομιά, απολιθώματα, επαυξημένη πραγματικότητα, φωτογραμμετρία, Αίγινα, Ραφήνα.*

1 Introduction

In recent decades, numerous new applications have emerged for various purposes, some of which have been successfully utilized in palaeontology (Lowenthal and Olwig, 2013; Henriques and Pena dos Reis, 2015; Wilson, 2017; Almeida et al., 2023; Konstantakis et al., 2023; Souza et al., 2023). Novel opportunities to enhance the promotion of natural history field has been transformed by the digitization of palaeontological specimen and data. There is significant research interest in creating virtual replicas of physical objects to capture the attention of a broader audience. Fossil sites are of paramount importance to the geological heritage of our planet and must be recognized and appreciated by the broader community to fully grasp their significance. By integrating advanced technologies with the unique characteristics of certain fossil sites, we can facilitate the dissemination of knowledge, making science and culture more accessible to all parts of society (Lowenthal and Olwig, 2013; Wilson, 2017). This project aims to bring science, particularly palaeontology, closer to a wider audience through the development of an Augmented Reality (AR) application for fossil sites.

Although the majestic giant vertebrates remain captivating focal points, commanding the center stage of such innovative techniques, with several projects in the literature focusing on that direction of vertebrate fossils (Henriques and Pena dos Reis, 2015; Almeida et al., 2023; Konstantakis et al., 2023; Souza et al., 2023), the approach presented in this project is unique in emphasizing sea palaeolife. The Augmented Fossils Tour (AFT) highlights underwater life, featuring invertebrate fossils. These fossils, though often portrayed as subtle, are essential for adding realism and depth to the portrayal of ancient marine environments.

The aim of this application is both the scientific and touristic enhancement of areas of related environmental and historical interest. Therefore, the objective was to create an application, compatible with mobile devices, that is suitable for the environmental, touristic, and historical promotion of areas, and to develop innovative and competitive Information Technology and Machine Learning technologies that enable the realization of Augmented Reality applications. The project is piloted at two fossil sites in Attica, which are dated between 5.3 to 2.5 million years old (Radwanska and Radwanski, 2008; Dermitzakis et al., 2009; Ávila et al., 2015) (**Fig. 1**). The first site is in Rafina and the second is in Aegina. Both locations are on the coastline, have easy road access, and are popular for swimming during the summer months. Both locations are small in size. Fossil deposits appear along a coastal stretch of approximately 250 metres in each location. Nevertheless, the concentration of fossils is very high. In other words, many fossils are found in a small area. The goal is for users to easily identify these fossils using an application.

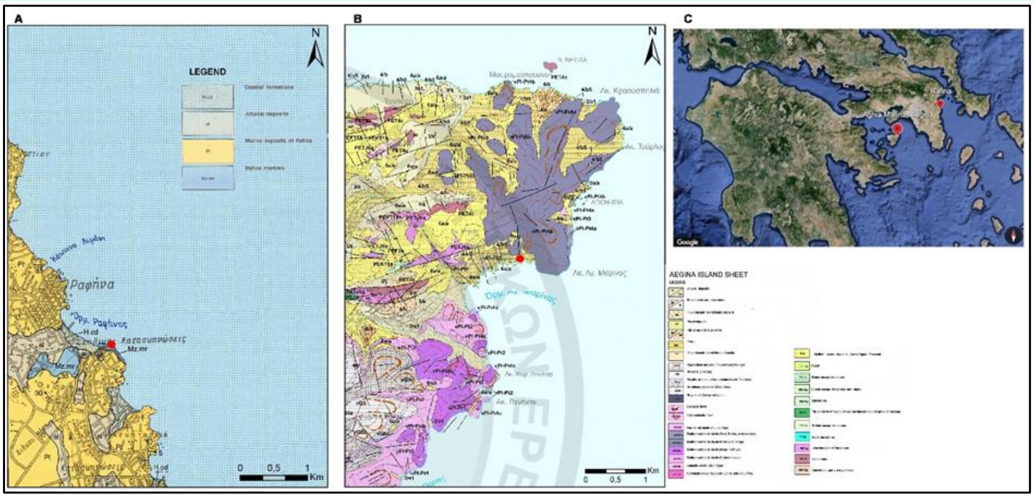

Fig. 1: A) Geological map of Rafina, B) Geological map of Aegina and C) the locations of the two sites of study on Google Earth platform. (Geological maps from IGME, Rafina Sheet and Aegina Island Sheet respectively). Red dots indicate the study sites.

2 Materials and Methods

2.1 Intelligence and methods for the application

The initial step involved taking numerous photographs in situ at the two studied areas using mobile device cameras, similar to those that future users will use (**Fig. 2**). These photographs, capturing fossils from various angles, totaled approximately 2500 for each area. The images were then grouped and imported into the platform. Subsequently we identified the fossils in each photo, creating a dataset of all encountered species (**Table 1**) for training the algorithm for fossil identification.

We used YOLOv8 (https://github.com/ultralytics/ultralytics), an advanced deep learning model for object detection. YOLO is an anchor-free single-stage object detector that significantly improves training convergence time and model accuracy. YOLOv8 is the latest version of the YOLO (You Only Look Once) family of real-time object detection models. It is designed to handle both object detection and segmentation tasks within a unified framework, which makes processing more efficient and accurate by leveraging shared features. The backbone network in YOLOv8 extracts essential features from input images, using advanced architectures like CSPDarknet that include Cross Stage Partial networks for better efficiency and gradient flow. The neck network aggregates feature from different scales, using PANet (Path Aggregation Network) to enhance the model's ability to detect objects of various sizes and shapes. One of the significant changes in YOLOv8 is its anchor-free design, which simplifies the model and reduces computational complexity, making it more adaptable to different datasets and tasks. It also incorporates attention mechanisms that help the model focus on relevant parts of the image, improving accuracy in both detection and segmentation tasks. YOLOv8 has several training and inference optimizations. It uses techniques like Mosaic data augmentation, label smoothing, and self-adversarial training to enhance robustness and generalization. Despite these improvements, it maintains real-time inference speeds, which is crucial for applications requiring immediate feedback.

Fig. 2: The process of collecting in situ photographs from the area of Rafina in (a) and the high concentration of the fossil species *Concavus concavus* in (b).

Table 1: Classification of encountered species used in the AFT application.

Categories	**Phyllum**	**Classs**	**Family**	**Genus**	**Species**
	Mollusca	Bivalvia	Pectinidae	*Pecten*	*Pecten jacobaeus*
					Pecten bipardituss
					Pecten sp.
				Flabellipecten	sp.
				Chlamys	*Chlamys* sp.
				Manupecten	*Manupecten pesfelis*
				Aequipecten	*Aequipecten scabrellus*
					Aequipecten sp.
				Costellamussiopecten	*Costellamussiopecten cristatus*
				Hinnites	sp.
			Ostreidae	*Ostrea*	*Ostrea edulis*
			Cardiidae	*Cardium*	sp.
			Limidae	*Limaria*	*Limaria tuberculata*
			Anomiidae	*Anomia*	*Anomia ephippium*

			Spondylidae	*Spondylus*	sp.
		Gastropoda			
	Arthropoda	Thecostraca	Balanidae	*Concavus*	*Concavus concavus*
		Malacostraca	Upogebiidae	*Upogebia*	ichnofossils
			Ocypodidae	*Ocypode*	ichnofossils
	Echinodermata	Cidaroidea	Cidaridae	*Cidaris*	sp.
		Echinoidea	Parechinidae	*Psammechinus*	sp.
		Irregularia	Fibulariidae	*Echinicyamus*	*Echinicyamus pussilus*
			Echinolampadidae	*Echinolampas*	*Echinolampas hoffmanni*
			Spatangidae	*Spatangus*	*Spatangus purpureus*
	Chordata/ Chondrichthyes	Elasmobranchii			
	Brachiopoda	Terebratulida	Terebratulidae	*Terebratula*	sp.
				Terebratula	*Terebratula ampulla*
	Annelida	Polychaeta	Serpulidae	*Ditrupa*	*Ditrupa arietina*
	Porifera	ichnofossils			

For object detection, YOLOv8 outputs bounding boxes and class probabilities for each detected object in an image. The enhanced backbone and neck networks contribute to higher accuracy in detection while maintaining real-time performance. In segmentation tasks, YOLOv8 generates pixel-wise masks for detected objects, allowing precise delineation of object boundaries. The improved feature extraction and attention mechanisms enable the model to provide detailed and accurate segmentation masks. By performing detection and segmentation simultaneously, it offers coherent outputs without needing separate models or additional post-processing steps.

YOLOv8's versatility makes it suitable for various applications, such as autonomous vehicles, surveillance, healthcare, and robotics. In autonomous vehicles, it can detect and segment objects like pedestrians, other vehicles, and road signs in real-time. In surveillance, it helps monitor and detect suspicious activities or individuals. In healthcare, it analyzes medical images to detect and segment anomalies or specific structures. In robotics, it enables robots to understand and navigate their environments by detecting and segmenting objects. Overall, YOLOv8 is a significant advancement in the YOLO family, offering enhanced accuracy and efficiency for both object detection and segmentation tasks, making it a powerful tool for many real-world applications.

For the project's task, we evaluated two scenarios (80% train, 10% val, 10% test), using the same evaluation protocol with YOLOv8. Ground-truthing was applied with polygonal annotation of images. In the first one (**Table 2**), we consider that all data samples of the species split belong to a single class, so no classification error is considered. Both detection and segmentation results seem promising, with quantitative results similar to those of benchmark databases. Example is shown (labels/prediction) in **Fig. 3**.

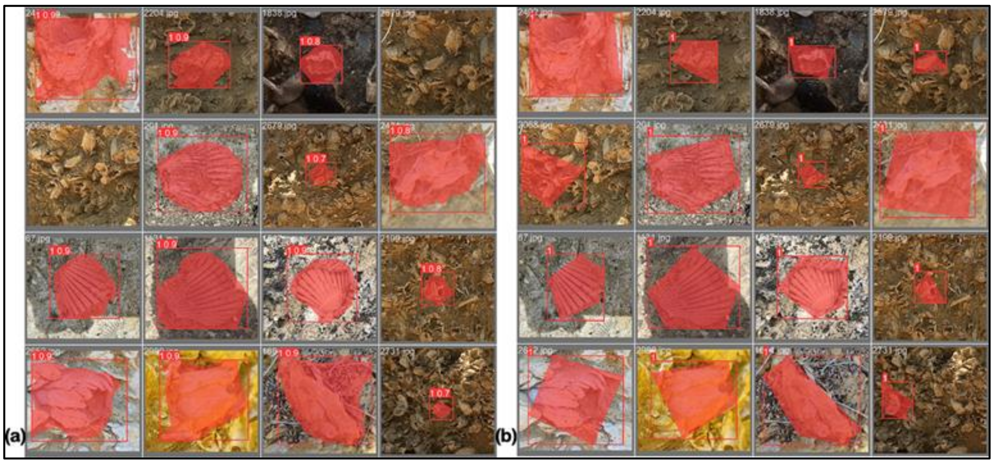

Fig. 3: Data samples for the 1st scenario with prediction in (a) and ground truth in (b).

Table 2: Data samples for scenario 1.

Metric	Detection	Segmentation
map50-95	0.6463	0.4500
map50	0.9861	0.9397
map75	0.7235	0.3329
mp	0.9821	0.9343
mr	0.9546	0.8957

In the second scenario (**Table 3**), we consider some taxa (*Pecten jacobaeus, P. biparditus, Pecten sp., Aequipecten scabrellus, Chlamys sp., Manupecten pesfelis, Costellamussiopecten cristatus, Ostrea edulis, Spatangus purpureus, Concavus concavus*) for which we had representative number of samples. Results are lower when considered in the first scenario, but this is expected when taking into account classification errors and our somehow imbalanced dataset. Example is shown (labels/prediction) in **Fig. 4.**

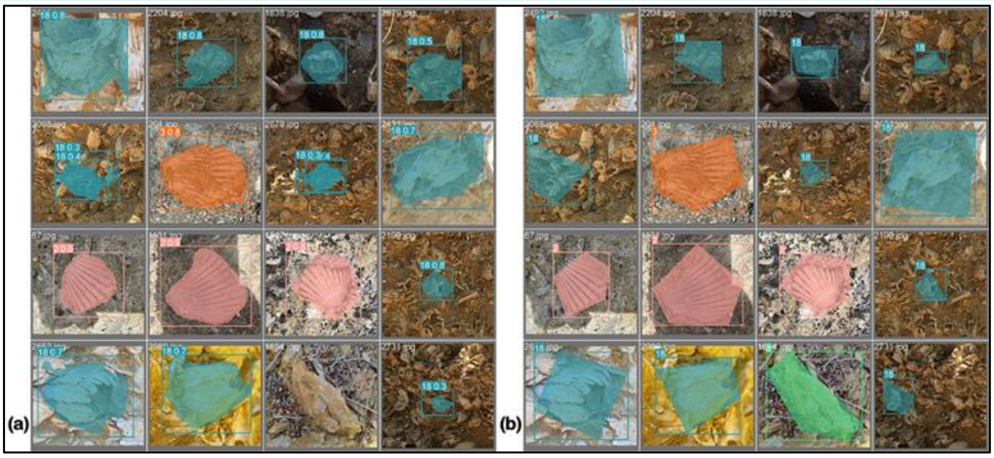

Fig. 4: Data samples for the 2nd scenario with prediction in (a) and ground truth in (b).

Table 3: Data samples for scenario 2.

Metric	Detection	Segmentation
map50-95	0.5675	0.5027
map50	0.7649	0.7614
map75	0.6835	0.6180
mp	0.4905	0.4864
mr	0.7882	0.7834

2.2 Fossil reconstruction and palaeo-environment reconstruction.

Detailed information on all species present at the two fossil sites was gathered to ensure enough data for the three-dimensional reconstruction of the species and the virtual recreation of the palaeo-environment of these areas (Jiménez et al., 2009; Ávila et al., 2015; Koskeridou et al., 2017; Coletti et al., 2021; Kontakiotis et al., 2023). These depictions include reconstructions of palaeo-environments, showcasing not just the fossilized organisms but also their habitats. They present complete ecosystems, emphasizing the interrelationships between the depicted species. To achieve a 3D reconstruction of each specimen, we employed photogrammetry. This technique involves capturing multiple high-resolution photographs from various angles, which are then analyzed using specialized software to produce detailed and accurate 3D models (Falkingham, 2011; Mallison and Wings, 2014; Minaroviech, 2017; Cunningham, 2021; Mune, 2022). By leveraging photogrammetry, we ensured precise and lifelike digital representations of the specimens, preserving intricate details and textures. We used Agisoft Metashape that is a specialized photogrammetry software designed for generating high-quality 3D models from collections of 2D images. By organizing photos into multiple chunks based on angles, we were able to create detailed point clouds and 3D model files that accurately reproduced the fossils in digitally. Key aspects of this process involved fine-tuning photogrammetric parameters and algorithmic precision within the software, aiming to convert the captured scenes into precise and complex 3D models. The methodology employed on the project integrated techniques for aligning data from various angles. We took photographs from multiple angles and perspectives for fossil species found into the two studied areas. We ensured that there is sufficient overlap between images (typically 60-80% overlap) in order to have a better outcome. The process begins with importing all available photos from High resolution cameras into Agisoft Metashape software. These photos, often numbering up to 400 per object, are organized into groups based on the shooting angle, and capture time, which aids in the alignment process. Next, the alignment process itself is undertaken, which is both time-consuming and computationally demanding. Various parameters are tested to achieve precise alignment of all photos, ensuring each is accurately positioned. Factors such as varying camera positions, shadows, and slight differences in photo distances can pose challenges during alignment. Following this, is to generate a dense point cloud by estimating the 3D coordinates of matched features, which is preferred to be of high-density, because accurate point clouds are crucial for capturing detailed textures and geometry. Various settings and resolutions were tested to achieve the optimal integration of all available data. Subsequently, the final dense point cloud, combining data from photos and using triangulation algorithms produces a rough mesh. This mesh is imported into Blender 3D, Mudbox or 3ds Max for refinement, where we reduce polygon counts, remove erroneous points, and fill gaps in the texture, optimizing the mesh for mobile device compatibility (**Fig. 5**).

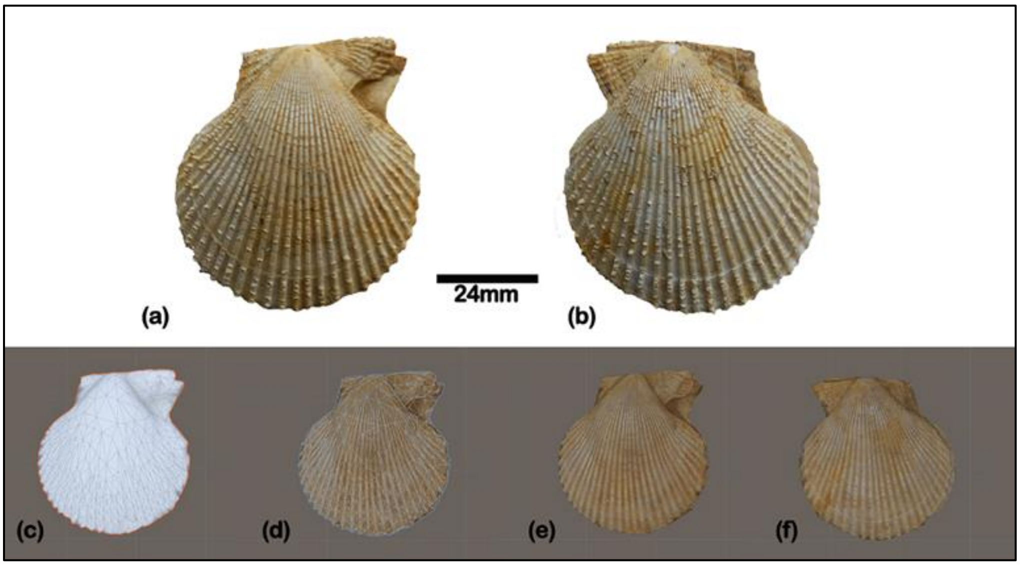

Fig. 5: Photographs of both valves left and right respectively of the fossil *Mimachlamys varia* in (a) and (b). In (c) and (d) three-dimensional processing and reducing of polygon counts of fossilized *Mimachlamys*. In (e) the final 3D model of the right valve and in (f) the final 3D of the left valve.

Finally, we cleaned up the 3D model by removing noise and outliers, and improving the mesh quality if necessary, and exported the 3D model as an .obj or .stl file. Depending on the artifact's complexity and data sources, resulting 3D models can range from thousands to several million polygons, ensuring detailed and accurate digital representations. For optimization purposes we compared the photogrammetric results with independent measurements or known reference data to assess accuracy and precision. By following these photogrammetry steps, we produced highly accurate and detailed 3D models as shown in **Fig. 6** and **Fig. 7**.

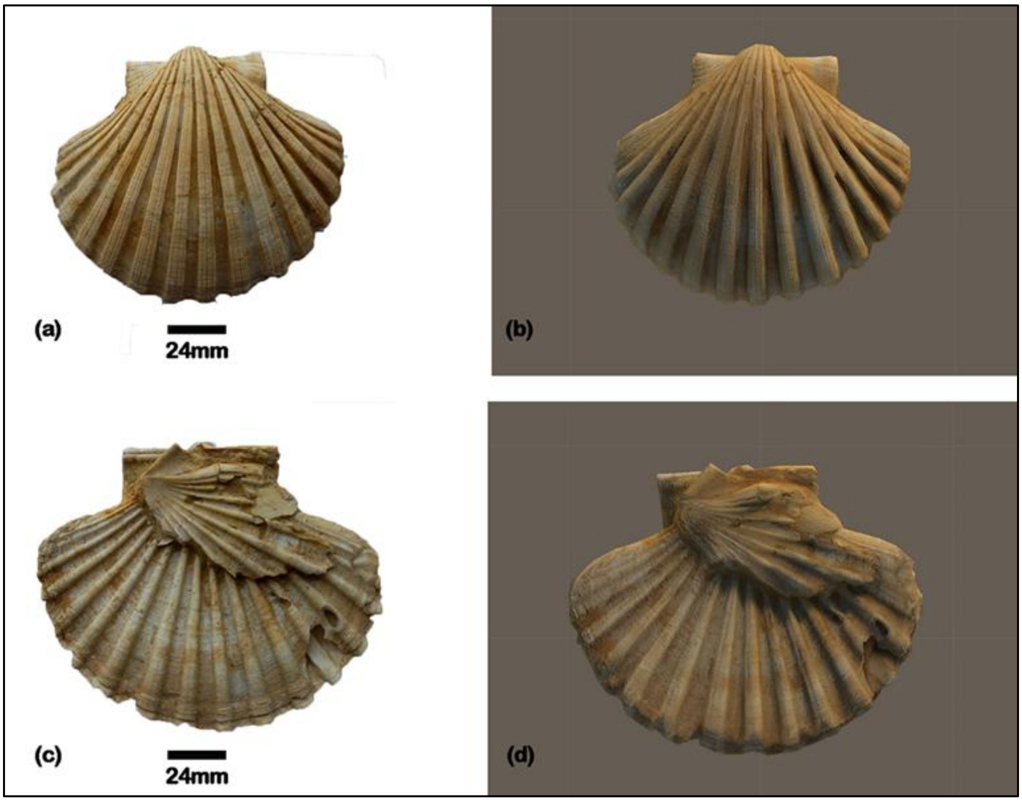

Fig. 6: External view of the right valve of the fossil *Pecten jacobaeus* in (a) and its three-dimensional representation in (b). External view of the left valve of *Pecten jacobaeus* in (c) and its three-dimensional representation in (d).

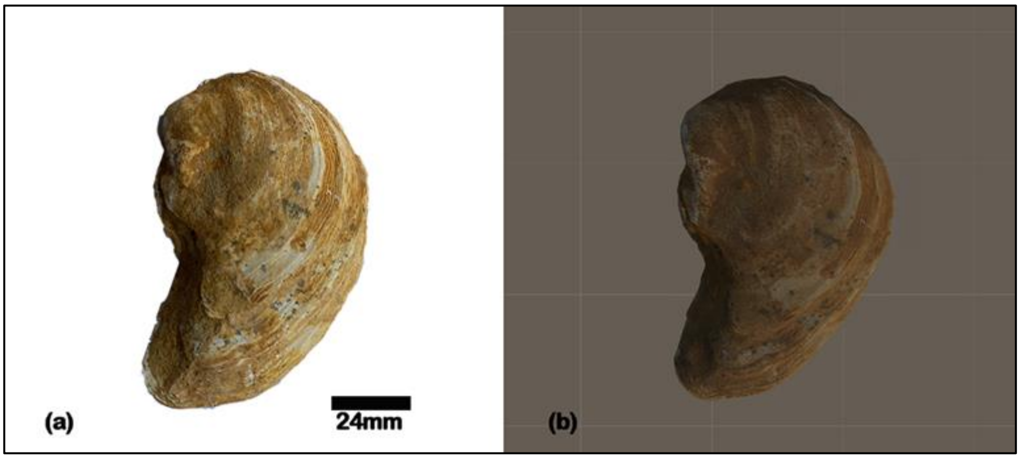

Fig. 7: Photograph of the fossil of *Ostrea* sp. in (a) and the created 3D model in (b).

In order to reconstruct the palaeo-environment of the two areas studied we had to identify and interpret palaeo-landscape features and to analyse climate conditions therefore, we used all geological and palaeontological information available, conducting also further research, as described in the following section. This resulted in the reconstruction of the seabed as illustrated in **Fig. 8**. The seabed of Aegina consists of sands with gravels sporadically scattered, while the seabed of Rafina consists solely of sands.

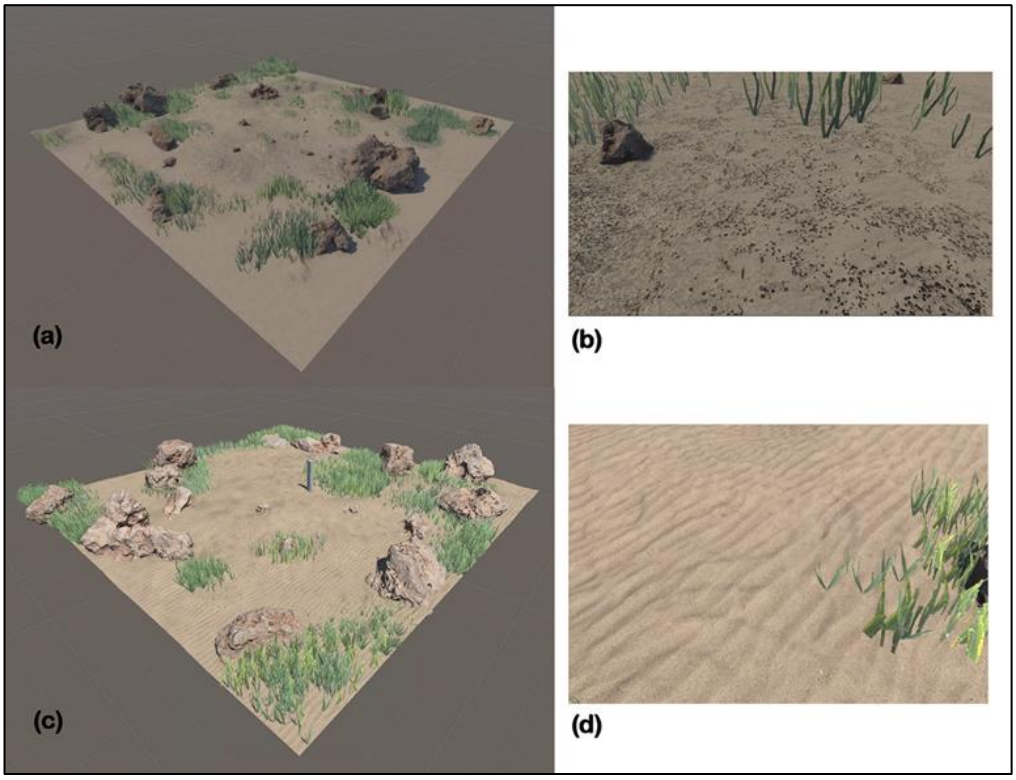

Fig. 8: The process of reconstructing the palaeo-environment of Aegina and Rafina sites. (a) The seabed of Aegina. (b) A close look of the seabed of Aegina. (c) The seabed of Rafina. (d) A close look of the seabed of Rafina.

3. Study area

3.1 Rafina

The first site is located at Avlaki in Rafina (Attiki peninsula), next to the municipal recreation park. It is on a cliffside coast located between the beach zones used by bathers (**Fig. 2**). The fossil layers are at sea level and can be accessed either through the municipal park or via the beach on Euboea Street. Geologically, the broader area mainly is comprised of alpine and post-alpine formations. The Alpine formations can be grouped into three primary stratigraphic units: the sub-Pelagonian unit, the autochthonous unit of Attiki, and the nappe of Lavrio-Attiki (Lepsius, 1893; Katsikatsos et al., 1976; 1986). The sub-Pelagonian unit consists of clastic formations, limestones, dolomites, ophiolithic formations, transgressive limestone, iron manganese ores, and flysch. The autochthonous unit of Attiki primarily includes schists, marbles, and limestones, while the nappe of Lavrio-Attiki is composed of phyllite, schist, and metalliferous ores. Neogene deposits are characterized by marls, clays, sandstone, conglomerates, and travertine limestone. Pleistocene continental deposits and Holocene deposits feature unconsolidated material such as sand and pebbles, alluvial sediments, debris cones, and lateral deposits (Lepsius, 1893; Katsikatsos et al., 1976, 1986).

The Rafina section (7 m) is primarily composed of conglomerates, silt to fine sand, and coarse sandstone. Studies on the area have presented the stratigraphic column with the encountered lithofacies, describing a total of 15 layers (Radwanska and Radwanski, 2008; Dermitzakis et al., 2009). At the base of this stratigraphic sequence, we find non-stratified silty sand, transitioning to a thin horizon of conglomerate, followed by a partially stratified silt layer. Above this, we encounter mollusk fossils and, more rarely, barnacles. Higher up, the sequence continues with subtidal layers, leading to the layer with a high concentration of barnacles (Radwanska and Radwanski, 2008; Dermitzakis et al., 2009). The layer bearing the barnacle assemblage (*Concavus concavus*) in the study area of the Rafina rock is characterized by a complex structure formed during sedimentation, which was likely slightly modified by diagenetic processes. The lower and thicker part includes almost bulbous to thick lenticular bodies and is characterized by the accumulation of barnacles (C. *concavus*) with sandy binding material, grading upwards into the finely stratified layer. C. *concavus* appears in almost all layers but with varying frequencies (Radwanska and Radwanski, 2008; Dermitzakis et al., 2009). The fossils in the study area of Rafina are dated between 5.3 and 3.6 million years old constituting the marine Pliocene succession (Mitzopoulos, 1948; Radwanska and Radwanski, 2008; Dermitzakis et al., 2009). This fauna primarily consists of shell fossils, including ostreids, pectinids, and balanids. This site is particularly known for its high concentration of balanids (**Fig. 2**b), which form a 2-metre-thick layer composed of thousands of shells. The fossils in Rafina were deposited in a shallow coastal area. Specifically, the balanid shells were transported post-mortem and accumulated together. Notable identified species include *C. concavus, Pecten biparditus, Aequipecten opercularis, Flabellipecten flabelliformis, Costellamussiopecten cristatus, Cerastoderma edule, Hinnites crispus*, and *Spondylus gaederopus.*

3.2 Agia Marina (Aegina)

The second site is located at Agia Marina in Aegina Island. It is a rocky coast located between the Panorama and Apollo hotels (**Fig. 9**). In Agia Marina, the fossils are aged between 5.3 and 2.5 million years old. Aegina Island provides a valuable opportunity to study benthic community dynamics, encompassing taphonomic, palaeoecological, and depositional conditions. This is made possible by the mollusc-rich sedimentary formations exposed in the northern part of the island (Kontakiotis et al., 2023).

Fig. 9: An overview of the fossil site of Agia Marina, Aegina.

Geologically, the island of Aegina is located in the Saronic Gulf and constitutes the northwestern part of the South Aegean Volcanic Arc. Three distinct types of sediments are observed on the island, the Alpine sediments, the Neogene marine clastics, and the volcanic deposits. The basement is primarily composed of limestone and chert, dating from the Permian System to the Maastrichtian Stage. The Neogene pre-volcanic sediments include transgressive conglomerates at their base, followed by shallow marly limestones and marls (specifically Pliocene marls), silty clays with diatomitic intercalations, and fluviolacustrine silts and sands (Müller et al., 1979; Fytikas et al., 1987; Morris, 2000). The volcanic sequence on Aegina includes two distinct phases: a dacitic phase starting in the early Pliocene (4.7 - 4.4 Ma) with rhyodacitic tuffs and andesitic dacite flows, and an andesitic phase from the late Pliocene to the Pleistocene (2.5 - 2.1 Ma) producing pyroclastics and basaltic andesite lavas. In the northern part of the island, Pleistocene "Poros" limestone, characterized by fluvio-lacustrine calcareous sandstones and marly limestones intercalated with volcanic material, are also present.

The sedimentary sequence in the Agia Marina section includes a coquina unit, preserved by volcanic capping. This unstructured, massive shell-accumulated layer consists of transported and poorly sorted fragments and/or entire mollusc shells, along with other bioclasts dispersed in a muddy matrix with tuff and conglomerate intercalations. There are no observed differences in the size or abundance of molluscan content throughout the section. The poorly sorted coquina is rich in both small and large bivalves, predominantly pectinids and ostreids (Kontakiotis et al., 2023). Key species include *Aequipecten scabrellus, P.biparditus, P. jacobaeus, Flabellipecten* sp., and *Manupecten pesfelis*, all belonging to the benthic epifaunal mobile group of pectinids. Aragonitic bivalves and gastropods are nearly absent, likely due to the extensive preferential dissolution of aragonitic shells during diagenesis. Most bivalve shells are disarticulated, with mixed concave-up and concave-down orientations, and are often fragmented. Barnacles are the second most common group, with *C. concavus* being the most prevalent species, some retaining their pinkish pigmentation. Echinoids, both regular and irregular taxa (tests and spines), are also present in some areas. Few brachiopods are observed, while some benthic foraminifera are quite common at the base of this bed. Fish remains and shark teeth (*Carcharhinus sp.*) are extremely rare. Preservation ranges from moderate to good, as evidenced by fragile skeletal elements like the external ornamentation of bivalves, delicate echinoderm tests, and fragments of pectinids and barnacles (Kontakiotis et al., 2023).

4. Discussion and Conclusions

Preserving and sharing knowledge about Earth's history can be accomplished in various ways, one of which is through the digital reproduction of natural history exhibits and sites, a practice that has become increasingly common recently. One of the key techniques used is photogrammetry, which involves capturing and analyzing multiple photographs to create 3D models of objects or sites (Mallison and Wings, 2014; Minaroviech, 2017; Cunningham, 2021). This technology has revolutionized the documentation and exploration of natural heritage by offering virtual access for research, education, and entertainment. Numerous projects have demonstrated the effectiveness of photogrammetry in digitizing natural history, showcasing their impact on enhancing our understanding and engagement with historical and scientific data, demonstrating in this way numerous possibilities and advancements in the field.

The article explores the potential unlocked by these techniques, with the AFT project serving as an exemplary model that can be adapted to various contexts. The integration of interactive technologies like virtual reality (VR) and augmented reality (AR) with multidimensional or multimodal representations represents a major innovation. User interaction enhances the experience by providing a broader perspective, increasing awareness of the palaeontological history of the studied areas, and positioning them at the center of the application. In this context, the user/ tourist can satisfy their curiosity by using their mobile devices to photograph fossil specimens, in the two piloted areas of Aegina and Rafina. The application then identifies the fossils and provides detailed information about the species, including photos and 3D representations of the fossil species that once inhabited the area. This interaction not only facilitates alternative scientific expression through virtual realities but also supports the storytelling of species that lived in these two sites with the use of virtual avatars (**Fig. 10**), enriching the narrative experience also by providing information about the palaeo-environment.

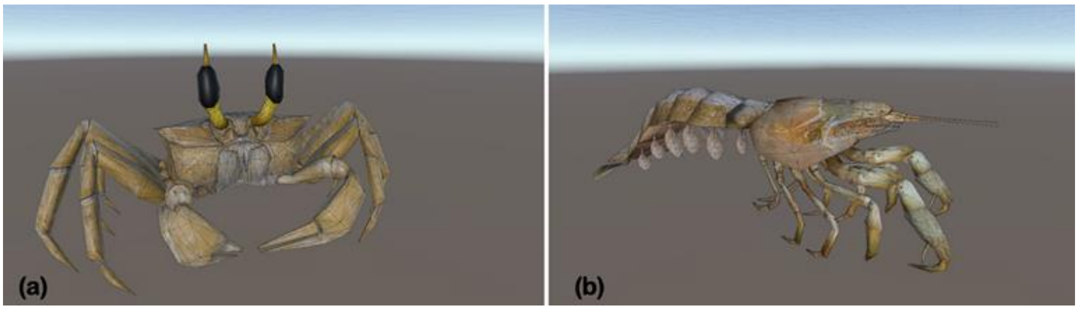

Fig. 10: (a) Virtual avatars of *Ocypode* species and (b) virtual avatar of *Upogebia* species.

This application represents a significant advancement in science communication and education, leveraging the power of mobile technology to create immersive and educational experiences that foster curiosity and understanding of palaeontology among users of all ages and backgrounds. Moreover, AFT brings attention to marine palaeo-environments that typically receive little attention, showcasing invertebrate species that are vital components of marine ecosystems. These invertebrates deserve greater recognition to raise awareness within the broader community.

The palaeo-reconstructions presented by AFT are crucial both educationally and scientifically, providing valuable insights and fostering a deeper understanding of ancient marine life and of our natural history. The application AFT is incorporating innovative Artificial Intelligence technologies that aim at the Automatic Recognition and Categorization of Fossils. The goal is to improve public understanding of palaeontological history and facilitate easy comprehension through mobile applications. This involves evaluating existing digital tools and assessing user feedback to make informed recommendations for designing digital experiences that effectively support scientific research, educational initiatives, and recreational activities. For this reason, extra 3D content is created and integrated into the application to provide an engaging user experience through access to augmented multimedia content. This project adds significant value by highlighting the geological and palaeontological heritage of the two pilot areas. The methodologies and findings developed through this project can be applied to future sites, enhancing our understanding and preservation of similar heritage areas.

Author Contributions

Conceptualization, G.L., G.K., and A.A.; methodology, D.L., C.G., E.G., P.K., N.K., A.I., K.P., E.B., E.S.; software, E.G., P.K., N.K., A.I., K.P.; validation, D.L., C.G., G.K., G.L., E.G., P.K., E.B., E.S., A.A.; formal analysis, D.L., C.G., G.K., G.L., E.G., P.K., N.K., A.I., K.P., E.B., E.S., A.A.; investigation, D.L., C.G., G.K., G.L., E.G., P.K., N.K., A.I., K.P., E.B., E.S., I.P.P., L.M., V.A., A.G., A.V., A.A.; resources, G.K., C.G., G.L., E.B., E.S., I.P.P., L.M., A.A.; data curation, D.L., C.G., E.G., P.K., N.K., A.I., K.P., E.B., E.S.; writing—original draft preparation, D.L.; writing—review and editing, D.L., C.G., G.K., G.L., E.G., P.K., E.B., E.S., I.P.P., L.M., V.A., A.G., A.V., A.A.; visualization, G.K., G.L., A.A.; supervision, A.A.; project administration, G.K., G.L., A.A.,; funding acquisition, A.A. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest.

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