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Tracing the origin of ancient building stones for monument preservation using Engineering Geology: insights from the Abdera quarries in Greece

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Abstract

Today, the development of ancient civilizations is reflected, among other things, in the important engineering works and monuments preserved, for the construction of which building stones from ancient quarries were used. Engineering geology can be engaged to identify and study such ancient quarries around ancient works, as well as to correlate the construction materials of the latter with the rocks found in these quarries. This paper presents the results of the engineering geological research studies conducted in the ancient quarries of Mandra and Petrolofos in Xanthi, Greece. The aim of the research was to interpret the parameters of the mining development in these quarries and the association of the excavated building stones with the walls and other structures of the adjacent city of Abdera. To determine the engineering-geological characteristics and tectonic structure of the quarry sites, field investigations were conducted, accompanied by laboratory examination of collected samples. The results highlight the significant influence of the geotectonic framework on the formation and accessibility of the quarry materials and reveal a satisfactory correlation between the stones from the quarries and those found in the archaeological remains of Abdera. The study highlights the importance of preserving and promoting these ancient quarries for scientific research, education, and geotourism.

Keywords: *ancient quarries; building stone; engineering geology; ancient Abdera; XRD; petrographic analysis.*

Περίληψη

Τα αρχαία λατομεία συνέβαλαν καθοριστικά στην ανάπτυξη ιστορικών πολιτισμών, ως πηγές κατάλληλων δομικών και διακοσμητικών υλικών. Παραδείγματα από την αρχαία

Αίγυπτο, την Περσία και τη Ρωμαϊκή αυτοκρατορία καταδεικνύουν την ποικιλομορφία των υλικών που χρησιμοποιήθηκαν, καθώς και τον ρόλο των αρχαίων λατομείων, ως κρίσιμα κέντρα παραγωγής. Επισημαίνεται το συνεχές επιστημονικό ενδιαφέρον για τα αρχαία υλικά και τις τεχνικές εξόρυξης, με ειδική αναφορά στις έρευνες του Ελλαδικού χώρου, όπου έχουν ήδη καταγραφεί περισσότερα από χίλια αρχαία λατομεία, ορισμένα εκ των οποίων, συνδέονται με εμβληματικά μνημεία όπως ο Παρθενώνας στην Αθήνα, το Ιερό των Δελφών, ο ναός του Δία στην Ολυμπία και του Ποσειδώνα στο Σούνιο. Τα αρχαία λατομεία αποτελούν δείγματα της Ελληνικής πολιτιστικής κληρονομιάς, μαρτυρώντας στοιχεία της αρχαίας τεχνολογίας, καθότι μεταξύ άλλων συνδέονται με την άσκηση της γλυπτικής και της λιθοξοϊκής. Η παρούσα εργασία αναφέρεται στην περιοχή της Ξάνθης, όπου δεσπόζει ο οικισμός των αρχαίων Αβδήρων, πατρίδας του φιλόσοφου Δημόκριτου (~460π.Χ.-370π.Χ.). Διερευνά τον βαθμό επίδρασης των τεχνικογεωλογικών παραγόντων στη δημιουργία και στον τρόπο λειτουργίας των αρχαίων λατομείων Πετρόλοφου και Μάνδρας, καθώς και την τροφοδοσία με κατάλληλα δομικά υλικά των τειχών και των κτισμάτων των Αρχαίων Αβδήρων. Τα αρχαία λατομεία Μάνδρας και Πετρόλοφου αποτελούν πολιτιστικό ορόσημο της περιοχής, με τη λειτουργία τους να χρονολογείται από τα τέλη του 6ου έως τις αρχές του 3ου αιώνα π.Χ., καλύπτοντας την περίοδο ακμής της πόλης. Η περιοχή χαρακτηρίζεται από σύνθετη γεωτεκτονική ιστορία, καθώς ανήκει στο νότιο τμήμα της μάζας της Ροδόπης, με παρουσία μεταμορφωμένων, ιζηματογενών και πυριγενών πετρωμάτων. Τα δύο λατομεία εντάσσονται στα μολασικά ιζήματα της Θράκης, εντός των οποίων κυριαρχούν ψαμμίτες και κροκαλοπαγή.

Η παρούσα εργασία βασίζεται στις εργασίες υπαίθρου για τον προσδιορισμό των τεχνικογεωλογικών χαρακτηριστικών και της τεκτονικής δομής στον χώρο των αρχαίων λατομείων, καθώς και τη λήψη δειγμάτων για την εκτέλεση κατάλληλων εργαστηριακών δοκιμών. Συγκεκριμένα, εκτελέστηκαν επιτόπιες γεωλογικές μετρήσεις (με χρήση γεωλογικής πυξίδας), μη καταστροφικές δοκιμές αντοχής με κρουστική σφύρα Schmidt, καθώς και συλλογή δειγμάτων για εργαστηριακές αναλύσεις (XRD, XRF, πολωτικό μικροσκόπιο). Τα δείγματα που εξετάστηκαν προέρχονται από αποκολλημένα τεμάχια βράχων των αρχαίων λατομείων Πετρόλοφου και Μάνδρας, καθώς και από τρία διαφορετικά αρχαία μνημεία εντός της αρχαίας πόλης των Αβδήρων (το Ιερό της Δήμητρας και Κόρης, τον Νεώσοικο και το νότιο τείχος της πόλης). Οι γεωλογικές χαρτογραφήσεις ανέδειξαν ότι και τα δύο λατομεία αποτελούνται κυρίως από παραοριζόντιες στρώσεις ψαμμίτη, ενώ η περιοχή του Πετρόλοφου παρουσιάζει αυξημένη τεκτονική καταπόνηση και συνδέεται άμεσα με την παρουσία κανονικού ρήγματος. Η σκληρότητα των ψαμμιτών και στα δύο λατομεία χαρακτηρίζεται χαμηλή έως μέτρια, έχοντας τιμές από 13MPa έως 28MPa, ενώ ο σχηματισμός του

κροκαλοπαγούς που απαντάται στον Πετρόλοφο εμφανίζει τιμές που κυμαίνονται από 19MPa έως 21MPa.

Οι ορυκτολογικές και χημικές αναλύσεις κατέδειξαν ότι τα κλαστικά αυτά πετρώματα είναι κυρίως αρκοζικοί ψαμμίτες και γραουβάκες, με σημαντικά ποσοστά χαλαζία (56–78%), αστρίων (17–34%), αργιλικών ορυκτών (κυρίως καολινίτη) και δευτερευόντως μαρμαρυγιών. Η παρουσία ασβεστίτη σε ορισμένα δείγματα από τα μνημεία των Αβδήρων αποδόθηκε είτε σε φυσική εξαλλοίωση είτε σε τεχνητές επεμβάσεις. Τα αποτελέσματα των XRF αναλύσεων χρησιμοποιήθηκαν για στατιστική σύγκριση με υπολογισμό 95% διαστημάτων εμπιστοσύνης, βασισμένη στα κύρια οξείδια SiO_2 και Al_2O_3. Μέσω της σύγκρισης της ορυκτολογικής - χημικής σύστασης των επιλεγμένων δειγμάτων, αναδείχθηκε η ικανοποιητική συσχέτιση μεταξύ των λατομικών υλικών και των υλικών των αρχαιολογικών ευρημάτων των αρχαίων Αβδήρων. Τα δείγματα από το Βόρειο Τείχος και τον Νεώσοικο παρουσιάζουν ισχυρή συσχέτιση χημικά και ορυκτολογικά με τα πετρώματα του αρχαίου λατομείου του Πετρόλοφου, ενώ το δείγμα από το Νότιο Τείχος μπορεί να συσχετιστεί με τα υλικά του αρχαίου λατομείου της Μάνδρας, τόσο ως προς το SiO_2 όσο και, έστω οριακά, ως προς το Al_2O_3. Επιπλέον, η έρευνα υπαίθρου καταδεικνύει ότι οι τεκτονικές δομές της περιοχής (π.χ. ρήγματα) διευκόλυναν τη δημιουργία εκμεταλλεύσιμων επιφανειών εξόρυξης, ειδικότερα στο αρχαίο λατομείο του Πετρόλοφου, όπου το κατακόρυφο μέτωπο εκτιμάται ότι ταυτίζεται με τεκτονική επιφάνεια κανονικού ρήγματος. Τα στοιχεία αυτά επιβεβαιώνουν ότι τα δύο λατομεία χρησιμοποιήθηκαν στην αρχαιότητα για την προμήθεια οικοδομικών λίθων για διάφορα οικοδομήματα της πόλης. Συμπεραίνεται ότι, ο συνδυασμός της τεχνικής γεωλογίας και της γεωχημείας αποτελεί ισχυρό εργαλείο για την κατανόηση των αρχαίων λατομικών πρακτικών και την τεκμηρίωση ιστορικών γεωτόπων. Η μελέτη αναδεικνύει τη σημασία της διατήρησης και της προώθησης αυτών των λατομείων για την επιστημονική έρευνα, την εκπαίδευση και τον γεωτουρισμό.

Λέξεις-κλειδιά: *αρχαία λατομεία, δομικός λίθος, τεχνική γεωλογία, XRD, πετρογραφική ανάλυση.*

1 Introduction

The earliest form of organized "industry" is stoneworking, developed by humans long before the advent of agriculture (Thomas, 2015). Comparable patterns can be observed all over the world in ancient civilizations, where the construction of monuments of global cultural significance, through extensive quarrying and the use of natural building materials, contributed decisively to the establishment and dissemination of these cultures. In Pharaonic Egypt, the main geological formations used in construction are soft and hard rock types. Limestone and sandstone, as soft rocks, were quarried until the 18th Dynasty (Fathy et al., 2008). After this period, limestone usage declined, whereas sandstone continued to be utilized throughout Egyptian history. Limestone was extracted from scattered quarries extending from the Mediterranean to the city of Esna, while sandstone quarries existed from Esna southward to Sudan. Granite and granodiorite, as hard rocks, were also key construction materials in ancient Egypt, with major quarry sites located in Aswan (Fathy et al., 2008). Similarly, in the temple of Anahita at Kangavar, western Iran, low-Mg and low-Si limestone sourced from nearby quarries was used as the primary building material (Shekofteh et al., 2020). In the case of the Flavian Amphitheatre (the Colosseum), the primary lithic materials employed in its construction were travertine and volcanic tuff. They were extracted from the quarries of Tivoli, located approximately 20 km east of Rome, as well as from neighboring extraction sites (Lancaster, 2005; Grawehr, 2021). Over the past decades, scholarly interest in locating and characterizing ancient quarries has intensified, with particular emphasis on raw material sources and technological practices in antiquity. Research on ancient quarries, encompassing the provenance and identification of building stones, quarrying and stone-working techniques, production costs, and associated transport networks, now constitutes a major field within archaeological and geo-scientific studies. This research is linked to the engineering-geological conditions that shaped the exploitation of stone resources.

Foundational contributions to the study of ancient stone materials were already made in the 18th and 19th centuries (Garofalo, De antiques marmoribus, 1743; Blümner, Technologie und Terminologie der Gewerbe und Künste bei Griechen und Römern, Vol. III, 1878–1912; Lepsius, Griechische Marmorstudien, 1890). In the 20th century, the systematic investigations of J.B. Ward-Perkins and A. Dworakowska further advanced the field and established the basis for modern quarry research (Kokkorou-Alevra et al., 2014). Building stones used in antiquity were selected not only on availability but also on their mechanical behavior, weathering resistance, and suitability for architectural and structural purposes (Hoek and Brown, 1980; Goodman, 1993; Thomas, 2015; Germinario and Török, 2020; Coletti et al., 2025). Within this context, engineering geological investigations contribute significantly to the understanding of lithological properties relevant to provenance studies, as they allow the evaluation of petrographic, geomechanical, and geochemical features that serve as diagnostic indicators of source quarries (Goodman, 1993; Price, 2007; Malfilâtre et al., 2012; Lisci et al., 2023). Studies have demonstrated that integrated geological, petrographic, and geochemical approaches can successfully trace the origin of building stones used in antiquity (Degryse and Cassar, 2015). These multidisciplinary methodologies are vital in regions where multiple lithological units of similar appearance occur, as is the case in northern Greece. Provenance research not only enhances archaeological interpretation but also provides essential knowledge for the restoration of monuments using compatible stones, ensuring structural integrity and long-term preservation (Bell, 2007; Malfilâtre et al., 2012).

The development of ancient Greek civilization is reflected, among other things, in a series of emblematic monuments, for the construction of which natural building materials were used, highlighting the need for the operation of ancient quarries. Anastasios Orlandos was a pioneer in the research of stones and quarrying-stone tools in Greece as early as the 1950s-60s with his unsurpassed monograph "*The Building Materials of the Ancient Greeks,* 1958", while by 2014 more than a thousand ancient quarries had been identified in Greece (Kokkorou-Alevra et al., 2014). Thus, according to relevant research using isotopic analyses (Pike, 2025), marbles from different quarry zones of Penteli Mountain were used for the construction of the Parthenon. Accordingly, a large part of the Sanctuary of Delphi was constructed from quarries near the area, with the main quarry material being the limestone of the Parnassus geotectonic unit, but also secondary materials such as sandstone, travertine, and slope breccia (de Vals et al., 2020). The Temple of Zeus in Olympia was constructed using ordinary shell conglomerate, quarried from the opposite side of the Alpheus River, in proximity to the temple site (Smith, 1924). The base, columns, and walls of the Temple of Poseidon on Cape Sounion were built from Agrylez marble, sourced from the quarries of Sounion (Orlandos, 1955-1960).

The ancient quarries of the Abdera region in Xanthi, northeastern Greece, represent a characteristic example where systematic engineering geological studies can contribute to the identification, documentation, and conservation of historical stone resources. Their diverse lithological assemblages and geomorphological settings present an opportunity for applying an integrated methodological framework combining field geology, laboratory analyses, and engineering geological testing. Such an approach aligns with broader international research trends that emphasize the constructive collaboration between geology and cultural heritage conservation (Price, 2007; Degryse and Cassar, 2015; Coletti et al., 2025). Ultimately, tracing the origin of stones used in ancient monuments through engineering geological methods not only enriches scientific understanding but also supports the sustainable management and rehabilitation of archaeological sites (Kósa and Török, 2020; Varró et al., 2025).

This paper examines the development and exploitation of the ancient quarries of Mandra and Petrolofos in Xanthi, in relation to the engineering geological context of the area. In addition, the correlation of the stones extracted from these quarries with the monuments in the city of Ancient Abdera was confirmed based on laboratory testing methods. The mechanical behavior of stones, assessed through parameters such as uniaxial compressive strength (UCS), tensile strength, and weathering susceptibility, is critical in both provenance studies and conservation practice (Hoek and Brown, 1997; Bell, 2007; Pappalardo et al., 2022; Lisci et al., 2023; Zomborácz et al., 2025). Engineering geological tests, including Schmidt hammer rebound values, point load index, and slake durability, support the quantification of stone performance and allow correlations with lithotypes found in nearby quarries. They also illuminate the effects of long-term weathering, salt crystallization, and environmental exposure on the degradation patterns commonly observed in ancient structures.

Within this context, the investigation of the engineering geological conditions at the sites of the ancient quarries under study involved extensive fieldwork. This included geological mapping, measurements of dip and direction of development of the sandstone rock mass, and in-situ rock strength measurements using a Schmidt rebound hammer (type L). Petrographic analysis, through thin sections, mineralogical identification, and fabric interpretation, remains fundamental in correlating ancient building stones with their geological origins (Degryse and Cassar, 2015). Microstructural and mineralogical signatures, such as grain size distribution, cementation, porosity, and accessory mineral assemblages, enable comparisons with known geological formations and documented quarrying sites (Fitzner and Heinrichs, 2004; Price, 2007; Pappalardo et al., 2022).

2 Materials and Methods

To correlate the materials from the two quarries with the building material of Abdera, a few rock samples were collected from various locations of the ancient quarries, as well as from three ancient monuments, which correspond to nine (9) representative sample groups, labeled S1–S9. Which was the mineralogical composition of the samples evaluated with X-ray Diffraction (XRD) on an automated PANalytical X'Pert Pro diffractometer equipped with a copper X-ray tube and a graphite monochromator. The chemical analysis of the major elements of the samples was conducted with X-ray Fluorescence (XRF) spectroscopy, using an automated S4 Pioneer spectrometer by Bruker AXS. Thin sections were prepared for samples, which were examined with a Zeiss Axioskop 40 polarizing transmitted-light microscope. The laboratory study took place at the Department of Mineralogy and Petrography of the Hellenic Authority for Geological & Mining Research (HSGME) in Athens.

The results of the lab measurements were studied statistically. The methodology followed was based on the calculation of the standard deviation for each analyzed element, as well as the determination of the 95% confidence level regions for each of the two ancient quarries. Subsequently, the corresponding wt.% values of the main oxides (SiO_2, Al_2O_3) of the three samples from ancient Abdera are graphically displayed in the diagrams depicting the range of values of the samples from the two quarries. This approach allowed the visual and statistical comparison of the data, with the aim of drawing safer conclusions regarding the possible origin relationships of the ancient building stones. The comparison should be based only on the chemical constituents' contents because they are more accurate, since the mineralogical analysis was semi-quantitative.

2.1 Introducing the study area

Ancient Abdera (Fig.1) founded around the seventh century BC in a privileged and strategic position with two natural harbors on the coast of Thrace and was one of the most important ancient cities of Thrace and the North Aegean (Kallintzi, 2011). The history of ancient Abdera is associated with great personalities such as Democritus, Hippocrates, Protagoras, Anaxarchus, and Bion the Abderite (Mousopoulos, 1998). The ancient quarries of Petrolofos and Mandra are an integral historical and cultural part of the settlement of ancient Abdera (Fig.1). Their operation extended from the late sixth to the early third century BC (Kallintzi et al., 2024).

Fig. 1. Study area location showing the archaeological site of ancient Abdera and the two nearby ancient quarries: (a) Archaeological site of Abdera (Kallintzi et al., 2022); (b) Ancient quarry of Petrolofos, with a near-vertical quarry face (Kallintzi et al., 2024); (c) The ancient horizontal quarry of Mandra (Kallintzi, 2020).

2.2 Geomorphological and Geological Setting

The ancient quarries are located on residual hilly outcrops that are a short distance from the sea (<10 km), as parts of larger hilly outcrops that follow the NW coastline of Vistonia Bay. Geomorphological structures that dominate the wider area are the Nestos River to the west and Lake Vistonida to the east. The geomorphological relief in the immediate area of the ancient quarries is hilly, while around them it is plain, with gentle to zero slopes decreasing towards the coastline. Geologically, the broader area of the region of Abdera belongs to the southern part of the Rhodope Massif. Its tectonic history is quite complex, having undergone multiple phases of folding and faulting. As a result, the area comprises a wide variety of rock types, including metamorphic and sedimentary, as well as igneous rocks and volcanic extrusions. The ancient quarries' rocks comprise conglomerate and sandstone (ol) masses, the thickness of which exceeds 150 metres in the Xanthi-Komotini plain (Xeidakis and Samaras, 1980), while the rocks' layers dip towards the northeast (Dimadis and Zachos, 1986). According to the geological map (Dimadis and Zachos, 1986) (Fig. 2), in the narrow area of the ancient quarries under study, Tertiary sandstones (ol) dominate, which were the main quarry product. In addition, normal faults with a general NE-SW direction were identified near the study area.

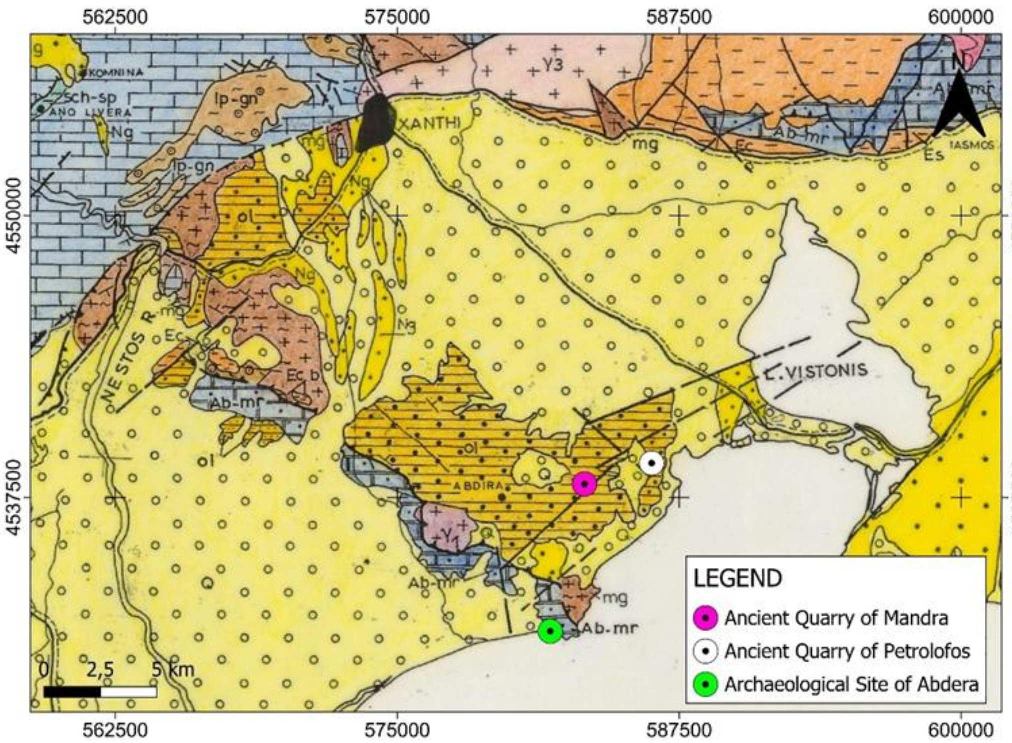

Fig. 2. Geological Map of the broader area of the ancient quarries (Dimadis and Zachos, 1986). Q: Terraces (river-marine), pebbles and cobbles, alluvial deposits and coastal sands; Ng: Conglomerate, sand, clay, marl and shale; Ol: Conglomerate and sandstone; Ec: flysch; sch-sp: Mica-schist and cipolline; mr: Massive marble-calcitic and dolomitic in its upper part and bituminous, graphitic with a banded structure at its base; lp-gn: Metavolcanic series of acid composition; Ab-mr: Variegated volcano-sedimentary series of mafic composition; mg: Granite-gneiss; γ3: Granodiorite; γ1: Granodiorite.

2.3 Presentation of the Ancient Quarries

The quarries are around Abdera, where the Abderiteon Laas, the stone of Abdera, is mined. The rock extracted was a sandstone, a very popular structural and decorative material in antiquity, due to the following factors: a) great availability; b) ease of extraction and processing; c) good mechanical characteristics (resistance to compression and cohesion) due to the high percentage of the contained quartz (>65%); d) resistance to erosion (many ancient monuments made of sandstone are preserved to this day); and e) high aesthetic characteristics. The use of sandstone as a building stone in ancient Abdera is estimated to be approximately 53% by volume, compared to the other local rocks found in the wider area, such as limestone (~42%), gneiss, slate (~2.5%) and marble (~2%) (Xidakis et al., 1990). The geomorphologies that occur in the formation of sandstone at the sites of the ancient quarries of Mandra and Petrolofos are characteristic, such as honeycomb weathering and salt weathering (Figs 3 and 4, respectively). The honeycombing phenomenon is a characteristic type of erosion of sandstones in coastal areas, which creates characteristic cavities (honeycombs) of various dimensions, which usually do not communicate with each other. The phenomenon of salinization characterizes the erosion of sandstones also in coastal environments where water containing salts (such as sodium chloride, sulfates and nitrates) evaporates, the salts crystallize and increase their volume, and they exert mechanical pressure on the pore walls that causes rupture and disintegration of the rock.

Fig. 3. Honeycombing phenomena in the ancient quarry of Mandra.

Fig. 4. Salt weathering of sandstone in the ancient quarry of Petrolofos.

On the contrary, limited occurrences of conglomerate were identified (only in the Petrolofos quarry), which was not appropriate as building material due to its inhomogeneous composition, low strength and cohesion, difficulty in processing (carving), its sensitivity to water and frost, and low load resistance.

2.3.1 The ancient quarry of Petrolofos

The quarry is estimated to have been active during the 4th and 3rd centuries BC and supplied building materials for the construction of the walls and buildings of ancient Abdera. It is located at an average altitude of about +30.00 m and is located 7.0 km and 7.6 km NE of the ancient city of Abdera of the Hellenistic and Roman periods, respectively. Its shape is "type Π", with current visible dimensions of 60 m in length, 20 m in width, and a maximum height of 10 m. Its height is greater, as it continues to be at least 3.70 m below the current natural ground level (Fig. 5). The quarry was created within a formation of sandstone of the Tertiary Age developed in the form of benches. On its facade, ancient quarrying traces are evident, with a tyko (ancient hammer) and a needle, while the detachment happened with various techniques (Fig. 6). Elements related to the rejection of rock fragments observed in the backfill. Among the movable finds are a small amount of post-Byzantine pottery and a tobacco syringe from the early 19th century. Two inscriptions appear on the front of the quarry. Lines, phallic symbols, and phrases engraved by quarrymen during the first period of use of the quarry, placed in the last quarter of the 5th or 4th century BC (Fig. 7). A technical-geological characteristic of the ancient quarry of Petrolofos is the vertical appearance of its front, which constitutes the “mirror” surface of a normal fault that essentially contributed to its creation and revelation, with a general strike of NE-SW that is identical to the general arrangement of the larger faults of the area (Fig. 5).

Fig. 5. Photographic impression of the front of the ancient quarry, with visible signs of quarrying throughout it.

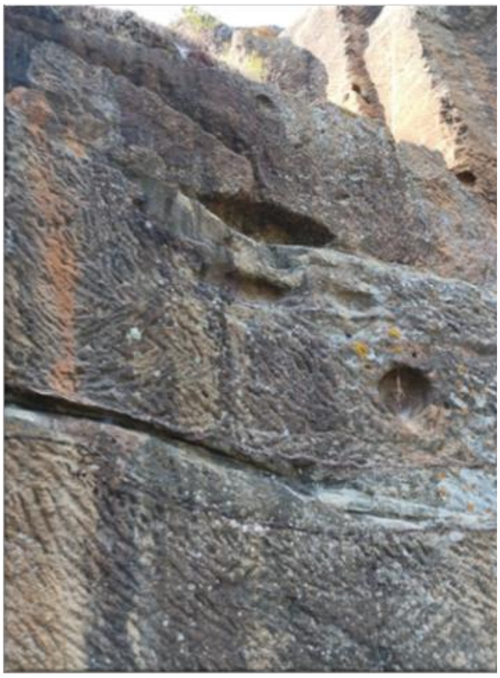

Fig. 6. Visible signs of quarrying and scattered impressions (from the placement of scaffolding) on the front of the quarry (Kallintzi et al., 2024).

Fig. 7. Ancient inscriptions on the front of the quarry (Kallintzi et al., 2024).

2.3.2 The ancient quarry of Mandra

It is an open-pit quarry and for the most part is horizontal. The rock is extracted in four-sided blocks, but there are also indications of circular-shaped carvings. The existence of a dense network of intersecting discontinuities is dominant, which facilitated the extraction of sandstone benches of various dimensions (Figs 8 and 9). The flat surface of the ground allowed the construction of a cart road with chariot tracks carved into the rocky ground. The stone transport road with a slightly curved course and general N-S direction marks the "core" of the quarry. Distinct tool marks testify to the use of the well-known mining technique of creating a perimeter groove around the block to be extracted. The fishbone pattern is common, while the pointillé technique (dense circular holes opened with a needle - ancient cutter) is also present. Larger grooves for the insertion of wooden wedges are present too (Figs 5, 6 and 10).

Fig. 8. Rock transport routes (main and secondary) towards the sea front and traces of intense quarrying. Strong tectonic stress and prevailing discontinuity systems are discernible (Kallintzi et al., 2024).

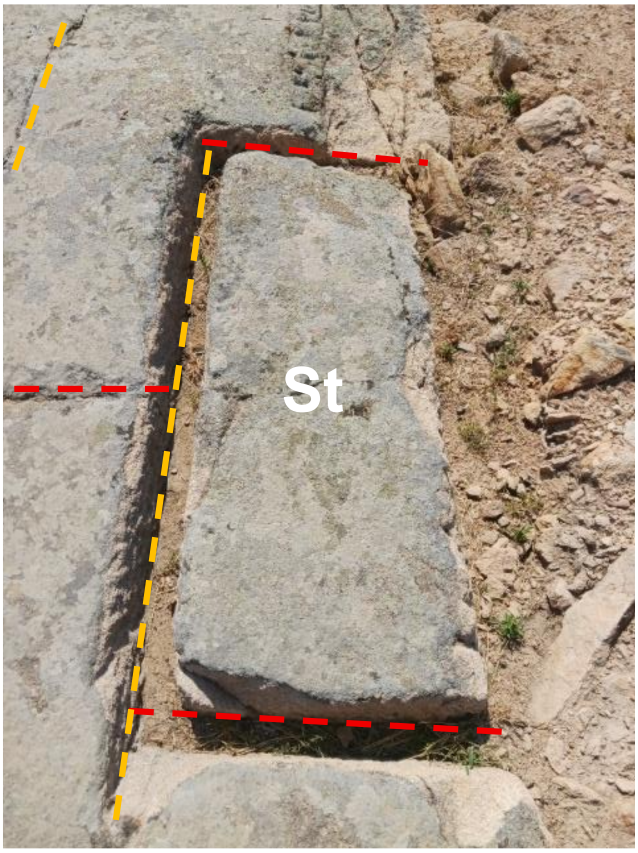

Fig. 9. Detached sandstone (St) rock block along the two main discontinuity systems.

Fig. 10. Various carving techniques: (a) Carving marks with the pointillé technique; (b) Four-sided block extraction with needle marks and wedge nests; and (c) Ichthyacanthus motif (a festoni) on the bench carving.

3 Results

3.1 Geological mapping

Both the Petrolofos and Mandra quarries were geologically mapped at a scale of 1:500 and an area of approximately 0.0285 km^2 each (Figs 11 and 12). According to the Engineering Geological Map of Greece, scale 1:500000, of the Institute of Geology and Mineral Exploration (Andronopoulos et al., 1993), the sandstone (St) and conglomerate (Cg) formations that prevail are included in the molassic sediments of Thrace (ol-e), of mixed phases (marine, lacustrine - lake deposits) that comprise clays, sands, marls, sandstones, conglomerates and marly limestones. During mapping, slopes and directions of maximum slopes of the sandstone layer were measured, as well as the tectonic discontinuities observed in the specific layer. The slopes of the layers in both quarries appear to be horizontal-parahorizontal, which is consistent with the presence of molassic sediments. Furthermore, the average value of persistence and the opening of the discontinuities were calculated, based on the records of the measurements of the discontinuities in the two ancient quarries under examination. In the Petrolofos quarry, the average persistence is 2.28 m, and the average opening is 0.48 cm, while in the Mandra quarry, the values are 1.21 m and 0.33 cm, respectively. Consequently, increased values were observed in the Petrolofos quarry compared to those in Mandra.

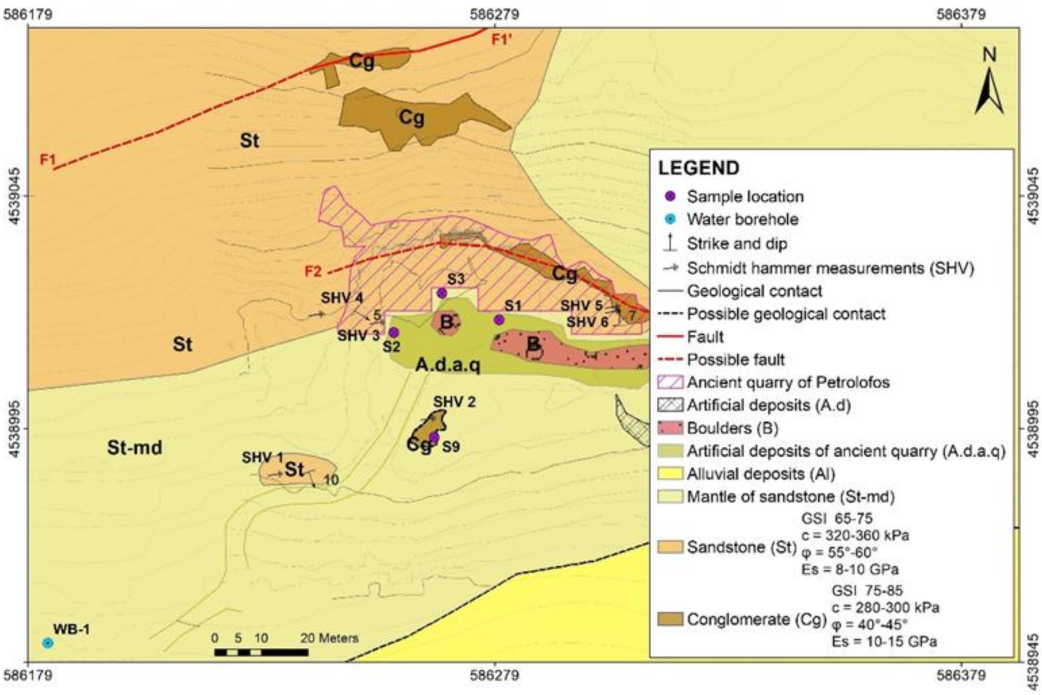

Fig. 11. Engineering geological map of the ancient quarry of Petrolofos, scale 1:500 (compiled by D. Tsagkas).

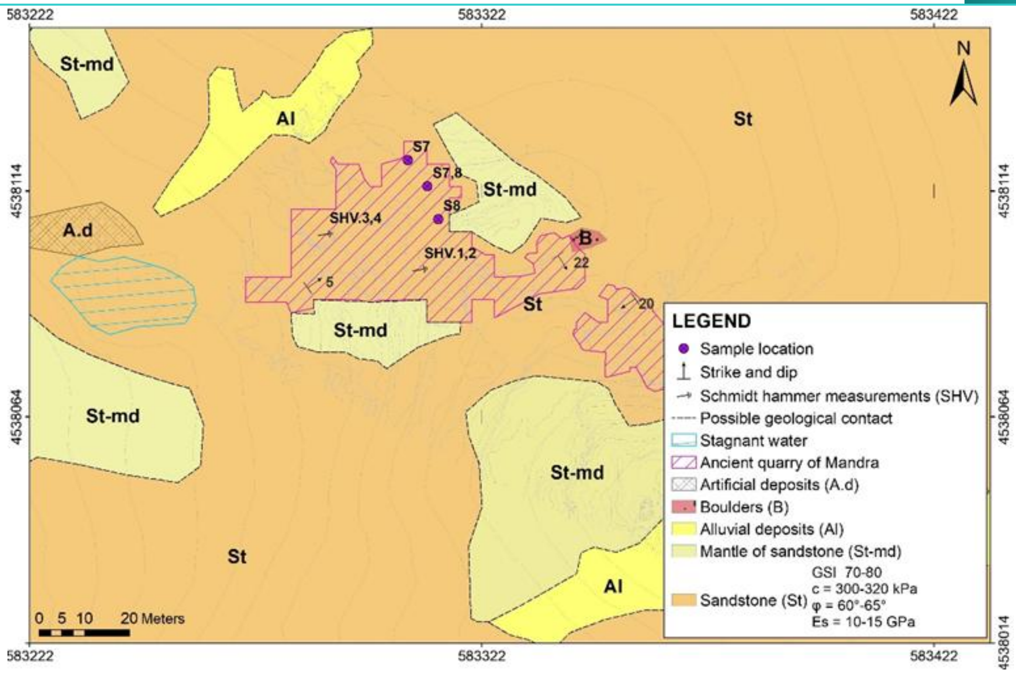

Fig. 12. Engineering geological map of the ancient quarry of Mandra, scale 1:500 (compiled by D. Tsagkas).

3.2 Hardness measurements

A series of hardness measurements using a Schmidt rebound hammer was conducted in the ancient quarries during the geological mapping at selected locations (Figs 11 and 12) to determine the strength of the rock mass (non-destructive test). The results show that the Petrolofos quarry exhibits strength values ranging from 14 MPa to 28 MPa, with an average of approximately 18 MPa, while the Mandra quarry shows values between 13 MPa and 25 MPa, averaging about 21 MPa. These measurements confirm that the sandstone has poor mechanical properties at both sites. The conglomerate displays slightly higher strength values, ranging from 19 MPa to 21 MPa, with an average of about 20 MPa. In-situ Schmidt hammer testing, in conjunction with analyses conducted using Rocscience Inc.'s RockLab software and the application of the Hoek–Brown failure criterion (Hoek et al., 2002), enabled the determination of the key geomechanical parameters of the rock masses depicted in Figs 11 and 12.

3.3 Mineralogical analysis

As mentioned above a number of rock samples were collected from different locations of the ancient quarries, as well as three ancient monuments, which were further mixed into nine representative samples, in order to correlate the materials from the two quarries with the building material in the ancient Abdera as follows: (a) Samples S1, S2, S3: Detached (fallen) stone fragments from the western face of the Petrolofos quarry; (b) Samples S7, S8: Detached surface fragments from the central area of the Mandra quarry; (c) Sample S9: In situ rock sample from an outcrop located east of the Petrolofos quarry entrance; (d) Sample S4: Detached surface fragment from a stone located on the steps of the Sanctuary of Demeter and Kore (Northern Enclosure); (e) Sample S5: Detached surface fragments from the pier of the Neosoikos (Northern Enclosure); and (f) Sample S6: Detached stone fragments from the inner side of the western arm of the wall, south of the area of the Western Gate (Southern Enclosure).

Based on both the macroscopic characteristics and microscopic observations of the samples, it was determined that these are sedimentary rocks belonging to the sandstone category. According to their grain size, sample S2 is a fine-grained sandstone, while samples S6 and S8 are coarse-grained sandstones. The grains appear subangular to round with moderate sorting. The main mass of all examined samples consists of silicate and clay material (porous beige phase), while the clastic grains consist of quartz, feldspars (both K-feldspars and plagioclasts), and micas (biotite). The feldspar crystals have begun to alter, forming kaolinite. It is worth noting that in sample S6, gneiss fragments were identified. Optical microscopy images of the mineralogical composition of the sandstone in samples S2, S6, and S8 are presented in Fig. 13.

The semi-quantitative mineralogical composition of the analyzed samples, based on XRD analysis, is presented in Table 1. The results show that SiO_2 is the dominant component in all samples, reflecting the high quartz content determined by XRD and petrographic analysis. The significant content of feldspars may not be ignored, either. The hardness and durability of quartz and feldspars also justify the limited impact of weathering and erosion on the hilly outcrops that morphologically prevail around the two ancient quarries.

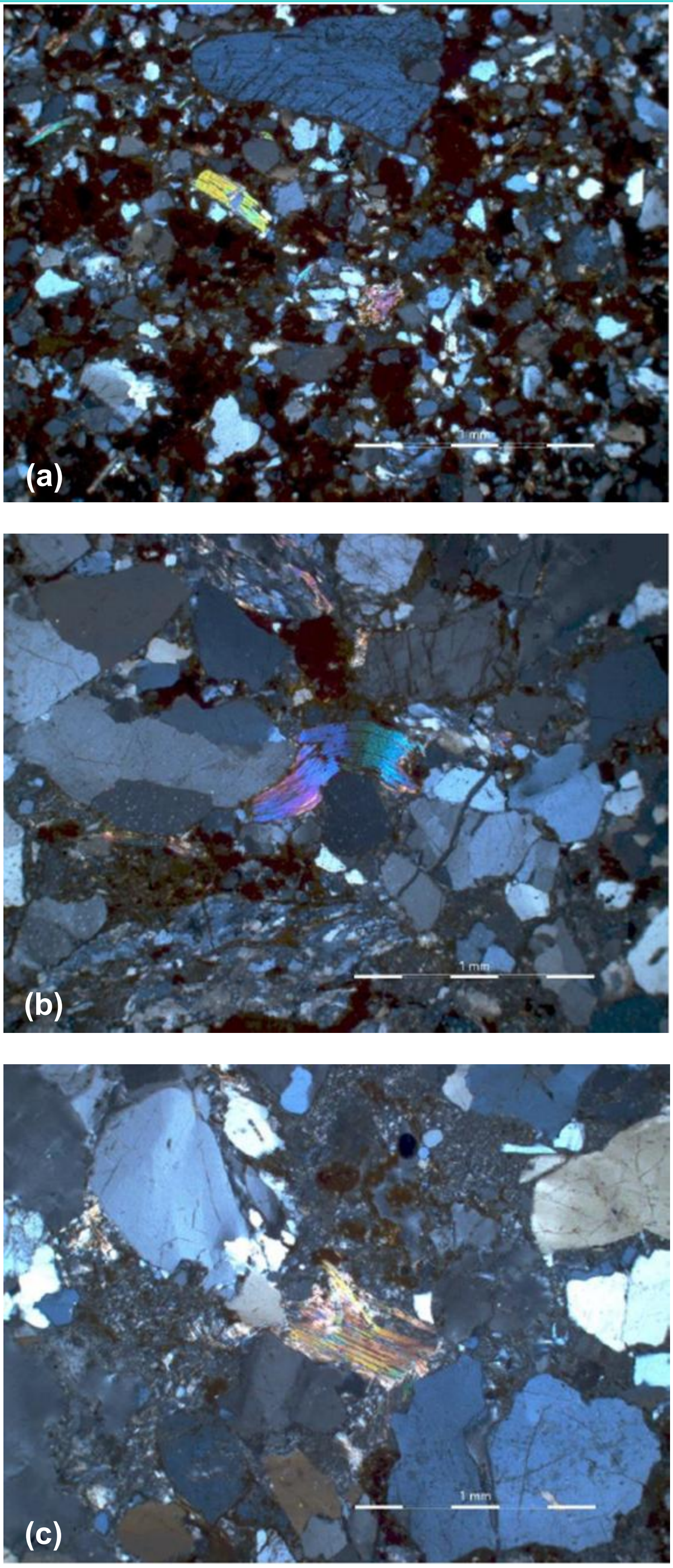

Fig. 13. Microphotographs of building material samples: (a) S2 – Quartz and mica grains cemented with siliceous-clay matrix and iron oxides; (b) S6 – Tectonically deformed mica crystal, along with biotite, quartz, feldspar crystals, and lithic gneiss fragments, all cemented with a siliceous-clay matrix; (c) S8 – Tectonically deformed mica crystal situated among quartz and feldspar crystals, cemented with siliceous-clay matrix (⊥Nicols, x5).

Table 1. Semi-quantitative mineralogical composition (wt. %) of the samples S1-S9.

Sample	Origin	Quartz	Feldpsar	Kaolinite	Mica	Calcite
S1	Petrolofos quarry	56	34	6	4	-
S2	Petrolofos quarry	62	30	5	2	-
S3	Petrolofos quarry	63	29	5	3	-
S4	Sanctuary of Demeter and Kore -Abdera	58	27	6	2	7
S5	Neosoikos (Northern Enclosure) -Abdera	66	22	7	3	2
S6	Southern enclosure - Western Gate -Abdera	78	17	4	1	-
S7	Mandra quarry	71	24	4	1	-
S7-8	Mandra quarry	75	20	3	2	-
S8	Mandra quarry	71	22	5	1	-
S9	Petrolofos quarry	68	25	4	3	-

The chemical composition of the same samples, obtained by XRF analysis, is presented in Table 2.

Table 2. Chemical composition (wt.%) of the samples S1-S9, based on XRF analysis.

Sample	Origin	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	K_2O
S1	Petrolofos quarry	70.57	0.73	22.12	1.83	1.13	0.28	3.02
S2	Petrolofos quarry	69.88	0.62	19.40	7.61	0.40	0.04	1.69
S3	Petrolofos quarry	76.73	0.38	18.05	1.87	0.15	0.01	2.54
S4	Sanctuary of Demeter and Kore -Abdera	73.80	0.37	18.03	1.64	0.13	3.78	2.02
S5	Neosoikos (Northern Enclosure) -Abdera	71.42	0.54	21.26	2.46	0.18	1.56	2.33
S6	Southern enclosure - Western Gate -Abdera	81.91	0.21	12.94	1.99	0.14	0.27	2.32
S7	Mandra quarry	79.69	0.20	16.12	1.28	0.07	0.02	2.45
S7-8	Mandra quarry	82.20	0.20	13.8	1.40	0.30	0.00	2.10
S8	Mandra quarry	80.77	0.20	15.27	1.18	0.03	0.00	2.37
S9	Petrolofos quarry	78.69	0.31	15.82	2.23	0.21	0.06	2.47

Al_2O_3 and alkalis ($Na_2O + K_2O$) are also present in significant amounts, correlated with the presence of feldspars and clay minerals. Fe_2O_3 is in lower concentrations, associated with secondary phases containing iron or oxide/hydroxide impurities. The high Fe_2O_3 content in sample S2 is attributed to the systematic presence of para-horizontal red veinlets, which separate the different sedimentary phases of the sandstone material in the ancient quarry of Petrolofos. The presence of CaO in samples S4 and S5, which were collected from the Northern enclosure of ancient Abdera, is attributed to the calcite phase, as confirmed by the XRD pattern evaluations. The presence of calcite may be related to the proximity of ancient Abdera to the sea, or the local presence of construction binder, or to mineralogically altered feldspars (calcareous plagioclase), a hypothesis that is consistent with the general nature and composition of the sandstone under consideration. Based on the comprehensive mineralogical and geochemical data, samples S1 and S2 correspond to ash-beige fine-grained sandstone. Samples S3, S6, S7, S7-8 and S8 correspond to beige coarse-grained sandstone. Sample S9 corresponds to a conglomerate with lithic gneiss fragments. Sample S9 was not taken into consideration during the statistical processing of the results since it differs from the other samples and does not represent the prevailing rock type, which is sandstone. Most of the sandstone rocks analyzed, due to their high percentage of feldspars (>25%) and the participation of clay minerals in their composition, are arkosic sandstones.

4 Discussion

Based on the overall fieldwork performed and the geological mapping, the two quarries studied do not differ significantly in terms of the clastic formations encountered. The Mandra quarry seems to lack the conglomerate (Cg) formations, which are part of the molasse formations, as well as the Excavation and Re-Embankment Materials (artificial deposits of an ancient quarry). As far as the petrographic, chemical, and mineralogical analyses results, the materials of the two quarries appear to differ in terms of the content of the main minerals and oxides. The samples from the ancient quarry of Petrolofos and from the Northern enclosure of ancient Abdera are clearly correlated. The samples of the ancient quarry of Mandra and of the Southern enclosure are clearly correlated, too. To verify the above claim, diagrams based on the contents of the samples in the main oxides (SiO_2 and Al_2O_3) were drawn up with the help of statistical processing (Figs 14 and 15, respectively). As observed in Figs 14 and 15, both in terms of SiO_2 and Al_2O_3 content, the samples taken from the North Wall (Samples S4 & S5) seem to be, indeed, related to the sandstones mined from the ancient quarry of Petrolofos. As for the sample taken from the Southern Wall (Sample S6), it seems quite likely that it comes from the ancient quarry of Mandra, as it is in the 95% confidence area as far as the SiO_2 content is concerned and marginally outside the confidence area of the said quarry as far as the Al_2O_3 content is concerned. Regarding the mechanical characteristics of the sandstone, the higher strength values (in MPa) recorded from the in-situ Schmidt hammer tests in the Mandra quarry, compared to those in the Petrolofos quarry, are attributed to the higher SiO_2 content. Furthermore, according to the records of the measurements of the tectonic discontinuities in the ancient quarry of Petrolofos, more unfavorable (increased) values were observed in terms of the persistence (length) and the opening of the discontinuities compared to those of the quarry of Mandra. The hardness and durability of quartz also justify the limited effect of weathering and erosion on the hilly outcrops that prevail morphologically in the immediate area of the two ancient quarries. Consequently, the geology of the area is linked to its morphology that influences the current image of the natural landscape around the ancient quarries.

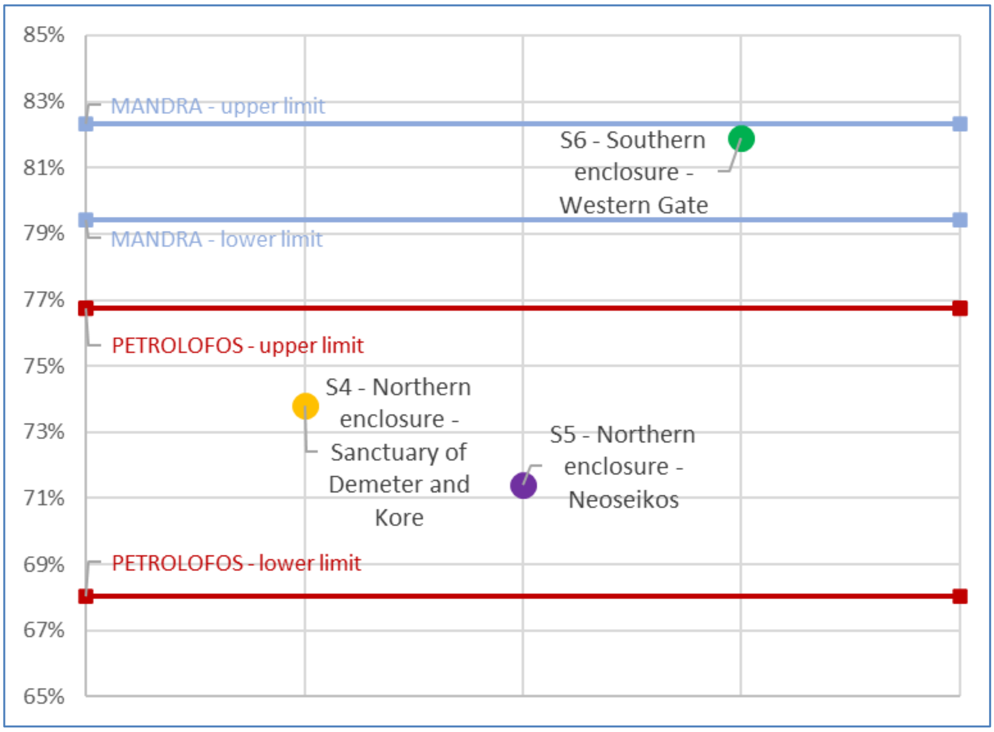

Fig. 14. Illustration of the content of SiO_2 in the samples from ancient Abdera, in relation to the corresponding zones (95% confidence level) of the two ancient quarries.

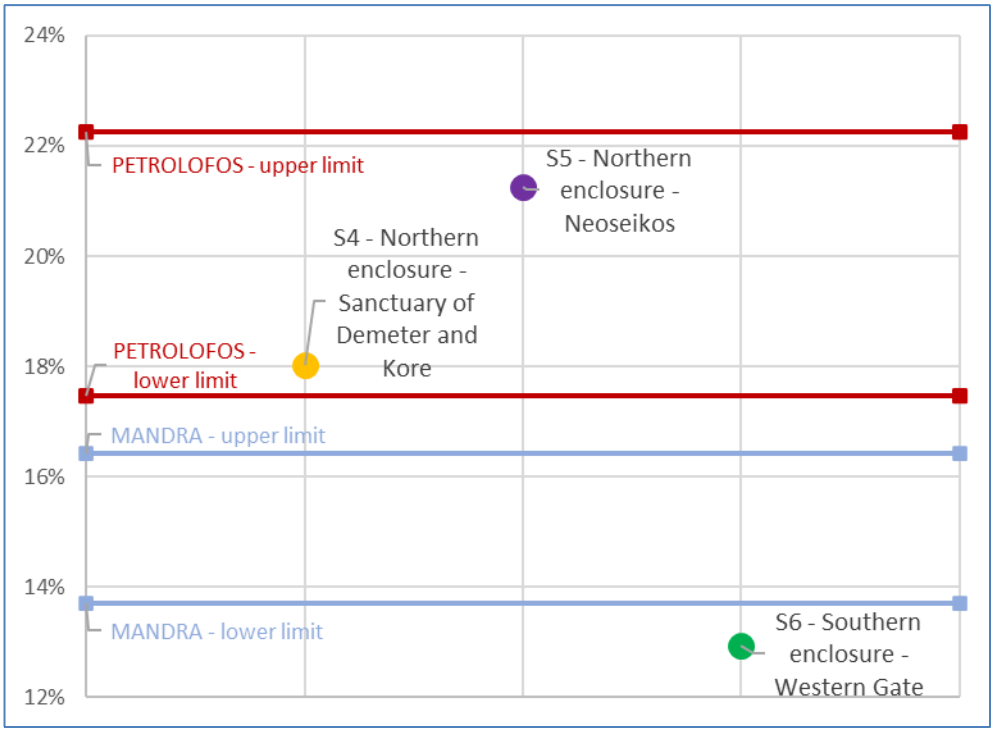

Fig. 15. Illustration of the content of Al_2O_3 in the samples from ancient Abdera, in relation to the corresponding zones (95% confidence level) of the two ancient quarries.

5 Conclusions

Based on all the data and findings from the geological research conducted in the ancient quarries of the Abdera region, I reached the following conclusions:

- At least part of the ancient monuments and works of the ancient city of Abdera were constructed from material extracted from the two adjacent ancient quarries of Petrolofos and Mandra.
- The main quarry product of the ancient quarry of Petrolofos is Tertiary sandstones. They appear para-horizontal, in benches, in places with iron oxides (hematite) that separate the various phases of sedimentation. They present poor mechanical characteristics, while a very sparse network of discontinuities develops in the sandstone rock mass. The extraction of the sandstone rock was conducted through vertical mining on a front about 50 m wide, with visible signs of ancient quarrying throughout the surface of the ancient quarry. The height of the quarrying face was approximately 8 m, while, according to observations, the base of the ancient quarry was located below the current floor, which filled in later. The vertical development of the ancient quarry is linked to the presence of a fault zone, which is part of the general intensive exploitation in the area.
- The ancient quarry of Mandra is a quarry with horizontal development structured by light brown to brown sandstone of Tertiary age. The dominant sandstone formation presents poor mechanical strength, has a visible layer, and has a dense network of intersecting discontinuities of long length. This sandstone was exploited during ancient times, quarrying significant volumes of sandstone benches of many sizes that were used both as building materials and as covers for funerary monuments.
- As shown by the mineralogical analysis of the materials, quartz has the largest percentage of participation in the composition of the sandstone rock, which in the Petrolofos quarry ranges from 56% to 63%, while in the Mandra quarry it ranges from 71% to 75%. The second most important mineral is feldspar, which ranges from 29% to 34% in Petrolofos, while in Mandra it is lower and ranges from 20% to 24%. Secondary minerals that occur are (in decreasing amounts) kaolinite (derived from the weathering of feldspars), micas, calcite, and hematite.
- According to the statistical processing based on the SiO_2 and Al_2O_3 contents, a particularly good correlation exists between the samples of the Northern enclosure of ancient Abdera with the ancient quarry of Petrolofos and the sample of the Southern enclosure with the ancient quarry of Mandra.

With the appropriate application of techniques and methods of Engineering Geology, it is possible to study the operation and development of ancient quarries and to trace the origin of the materials used to construct ancient monuments.

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