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GEOLOGICAL MAP OF ATHENS METROPOLITAN AREA, ATTICA (GREECE): A REVIEW BASED ON ATHENS METRO GROUND INVESTIGATION DATA

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Abstract

The ground investigations for the construction of Athens Metro –including over 60.000 m of sampling boreholes and geological mapping of the underground tunnel face–, planned and carried out under the supervision of ATTIKO METRO S.A., offer important geological data that enrich and locally modify our knowledge for the geology of Athens Metropolitan Area (AMA). On the basis of these data, this paper presents the Geological Map of AMA as well as a revised tectonostratigraphic scheme for the area and geological profiles along several sections of the Athens Metro lines. The geological map is a synthesis of the geological data obtained from the ground investigations with the already published geological maps and includes a Mesozoic rock assemblage as well as the Neogene-Quaternary Athens Basin. The following basic conclusions can be drawn from the interpretation of these data: (a) The Athens Unit, the basement of AMA, is divided into four formations (from bottom to top), the Lower Athens Schist, the Upper Athens Schist, the Athens Sandstone-Marl Series and the Crest Limestone. (b) Ultrabasic rocks (serpentinite) constitute the basement of Athens Unit. (c) Serpentinite bodies at the eastern border of Athens Basin, have undergone almost complete metasomatism to listwanite along their tectonic contacts with Alepovouni Marble on top and Kessariani Dolomite at their base. (d) The limestone outcrops at the western border of Athens Basin (e.g., Karavas hill) form tectonic windows of Pelagonian Upper Cretaceous limestone underneath the Athens Schist and not klippen of Crest Limestone

on top of it. The revised geological map also includes the Attica-Evia Fault, which is the dominant structure of the broader area, locally mapped by two sampling boreholes across the planned metro line 4.

Keywords: *Geological map of Athens Metropolitan Area, Athens Unit, Athens Schist, Athens Sandstone-Marl Series, listwanite, Attica-Evia Fault.*

Περίληψη

Οι έρευνες υπεδάφους για την κατασκευή του Μετρό Αθήνας, –με πάνω από 60.000 m δειγματοληπτικών γεωτρήσεων και γεωλογικές χαρτογραφήσεις σε μέτωπα εκσκαφής υπογείων σηράγγων–, που σχεδιάστηκαν και εκτελέσθηκαν υπό την επίβλεψη της ΑΤΤΙΚΟ ΜΕΤΡΟ Α.Ε., αποδίδουν σημαντικά γεωλογικά στοιχεία που εμπλουτίζουν και τροποποιούν τοπικά τη γνώση μας για τη γεωλογική δομή της μητροπολιτικής περιοχής της Αθήνας. Με βάση τα στοιχεία αυτά, στην εργασία αυτή παρουσιάζεται ο Γεωλογικός Χάρτης της Μητροπολιτικής Περιοχής Αθήνας καθώς επίσης μια αναθεωρημένη στρωματογραφία για την περιοχή και γεωλογικές τομές κατά μήκος τμημάτων των γραμμών του Μετρό Αθήνας. Ο γεωλογικός χάρτης είναι μια σύνθεση των γεωλογικών στοιχείων που συλλέχθηκαν στο πλαίσιο των ερευνών υπεδάφους και των δημοσιευμένων γεωλογικών χαρτών και περιλαμβάνει Μεσοζωικά πετρώματα καθώς και τη Νεογενή-Τεταρτογενή λεκάνη των Αθηνών. Τα παρακάτω βασικά συμπεράσματα προέκυψαν από την αξιολόγηση των στοιχείων αυτών: (α) Η Ενότητα των Αθηνών, το υπόβαθρο της μητροπολιτικής περιοχής της Αθήνας, διαχωρίζεται σε τέσσερις σχηματισμούς (από κάτω προς τα πάνω), τον Κατώτερο Αθηναϊκό Σχιστόλιθο, τον Ανώτερο Αθηναϊκό Σχιστόλιθο, την Αθηναϊκή Ψαμμιτική-Μαργαϊκή Σειρά και τον Ασβεστόλιθο Κορυφών. (β) Υπερβασικά πετρώματα (σερπεντινίτης) διαμορφώνουν το υπόβαθρο της Ενότητας των Αθηνών. (γ) Σώματα σερπεντινίτη στο ανατολικό περιθώριο της λεκάνης των Αθηνών, έχουν υποστεί σχεδόν ολοκληρωτική μετασωμάτωση σε λιστβανίτη κατά μήκος των τεκτονικών επαφών με το Μάρμαρο Αλεποβουνίου στην οροφή και το Δολομίτη Καισαριανής στη βάση τους. (δ) Οι εμφανίσεις ασβεστόλιθου στο δυτικό περιθώριο της λεκάνης των Αθηνών (π.χ. λόφος Καραβά) διαμορφώνουν τεκτονικά παράθυρα του Άνω Κρητιδικού ασβεστόλιθου της Πελαγονικής κάτω από τον Αθηναϊκό Σχιστόλιθο και όχι τεκτονικά ράκη του Ασβεστόλιθου Κορυφών πάνω σε αυτόν. Ο αναθεωρημένος γεωλογικός χάρτης περιλαμβάνει επίσης το Ρήγμα Αττικής-Εύβοιας, το οποίο είναι η κυρίαρχη δομή της ευρύτερης περιοχής, που χαρτογραφήθηκε τοπικά από δύο δειγματοληπτικές γεωτρήσεις, εγκάρσια στη μελλοντική γραμμή 4 του Μετρό Αθήνας.

Λέξεις κλειδιά: *Γεωλογικός Χάρτης Μητροπολιτικής Περιοχής Αθήνας, Ενότητα Αθηνών, Αθηναϊκός Σχιστόλιθος, Αθηναϊκή Ψαμμιτική-Μαργαϊκή Σειρά, Λιστβανίτης, Ρήγμα Αττικής-Εύβοιας.*

1. INTRODUCTION

From 1991 onwards, ATTIKO METRO S.A. has been conducting extensive ground investigations at a significant part of the Athens Metropolitan Area (AMA), in order to determine the geological and geotechnical conditions along the underground works of the Athens Metro. Due to the underground works in an urban environment, ground investigations have incorporated the drilling of more than 2300 sampling boreholes and the execution of numerous in situ tests as well as laboratory tests on borehole core samples. Furthermore, over than 60000 m of core run have been engineering geologically logged and more than 3000 engineering geological mappings have been performed on faces of tunnels excavated by conventional mechanical means and open-face Tunnel Boring Machines (TBMs). Regrettably, in closed-face TBM tunnelling, the obtainment of geological data is extremely limited. As such, since closed-face TBM tunnelling has been the primary method for the construction of Athens Metro during the last decades, no substantial geological data have been retrieved during the excavation of these tunnels. Athens Metro ground investigations provided a vast amount of geological data that concern the upper 25 to 50 m of the AMA subsurface. These geological data would be of a lesser importance, had the geological structure and stratigraphy of the AMA been either simpler or agreed upon. However, the exact opposite applies, giving the ground investigations' data of the Athens Metro a scientific value that far exceeds the purpose for which they were collected.

The complexity of the geology of the AMA arises from: (a) the coexistence at the area of both sedimentary and rocky bedrock formations; (b) stratigraphic and lithological heterogeneity; (c) the existence of similar lithological types in different formations, e.g. limestone within almost all geological formations of AMA (Athens Schist, Athens Sandstone-Marl Series and Crest Limestone of Athens Unit, Upper Cretaceous limestone at the foothills of Egaleo Mt.); (d) the strong tectonic deformation; and (e) the locally significant rock alteration due to fluid circulation. An additional factor that contributes to the difficulty in understanding the geology of AMA, is the fact that the four different map sheets of the Geological Map of Greece 1:50000 of the Hellenic Survey of Geology and Mineral Exploration (HSGME) (former Institute of Geology and Mineral Exploration) –map sheets Athinai-Piraiefs (Gaitanakis, 1982), Athinai-

Elefsis (Katsikatsos et al., 1986), Koropi-Plaka (Latsoudas, 2003) and Kifissia (Katsikatsos, 2002), exhibit some inconsistencies in the description of the same formations which are present in all maps. In 2002, the publishing of Geological Tectonic Map of the Athens Basin in the framework of a joint research programme conducted by the National and Kapodistrian University of Athens, the Earthquake Planning and Protection Organization and the National Technical University of Athens (Papanikolaou et al., 2002), eliminated this problem of the different descriptions of the formations and presented a coherent tectonostratigraphic scheme.

Apart from the above-mentioned issues regarding the geological data in literature, the basic scope of the present paper is the exploitation of all available geological data from the ground investigations of Athens Metro. These data modify in places the published geological structure of Athens as they provide new geological information for significant sections of AMA. All these data were used to compile a revised Geological Map of AMA. Besides, the evaluation and correlation of this vast amount of borehole logs, gave rise to modifications of Athens Unit stratigraphy.

2. GEOLOGICAL SETTING

AMA is spread over the Athens Basin, a Neogene-Quaternary, narrow, wedge-shaped basin on the Attica peninsula, confined to the west, north and east by Egaleo, Parnitha, Pentelikon and Hymettus Mts. respectively, whereas to the southwest it opens up to the Saronic gulf. The Athens Basin is formed along the contact of Pelagonian (or Subpelagonian) lithotectonic unit to the northwest, with the Attic-Cycladic Complex (cited as ACC hereafter) to the southeast (Fig. 1). The Pelagonian is the remnants of a microcontinent, consisting of Paleozoic basement with Paleozoic-Mesozoic (mostly Triassic) carbonate cover. On top of this carbonate platform, Triassic-Jurassic west Vardar ophiolites were obducted during Upper Jurassic to Lower Cretaceous (Doutsos et al. 1993). During Upper Cretaceous, transgressive carbonates were deposited (Upper Cretaceous limestone of Fig. 1); sedimentation locally continued during Paleocene-Eocene, with the deposition of flysch (for Pelagonian stratigraphy see Auboin, 1959; Clement and Guernet, 1971; Bonneau, 1984; Jacobshagen, 1986; Doutsos et al., 1993; Coleman et al., 2020). The basement of the Athens Basin mainly consists of the Athens Unit (*sensu* Papanikolaou et al., 2004) (Fig. 1), a local unit of Pelagonian affinity that crops out only in this area. It is an Upper Cretaceous (Turonian-Maastrichtian), few hundred meters thick, lithologically heterogeneous, meta-clastic sequence with intercalations and alternations of carbonates and locally basic and ultrabasic magmatic rocks (Marinos et al., 1971 and 1974 and references therein).

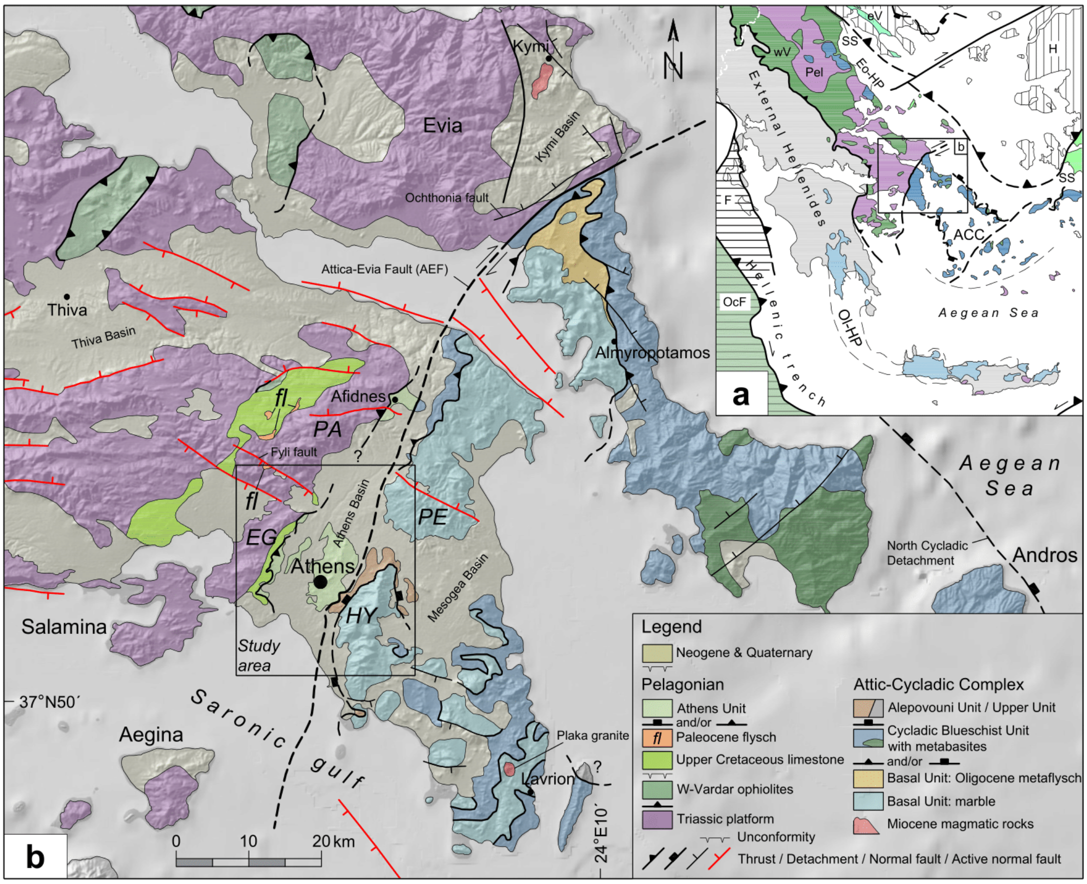


Fig. 1: Geological setting of Attica peninsula and south Evia (Euboea). a) Simplified overview and main tectonic characteristics of the Hellenides (Schmidt et al., 2020 with modifications). H: Hinterland, eV: obducted E-Vardar ophiolites, SS: Sava-Vardar-Izmir-Ankara-Erzincan suture zone, wV: obducted W-Vardar ophiolites, Pel: Pelagonian, Eo-HP: Eocene HP metamorphosed External Hellenides, the major part of which is Attic-Cycladic Complex (ACC), Ol-HP: Oligocene HP metamorphosed External Hellenides, F: Foreland, OcF: oceanic Foreland. b) Simplified geological and tectonic map of the broader area of Attica peninsula (from geological map of Greece of HSGME; Xypolias et al., 2003; Spanos, 2012; Ring et al., 2007a; Deligiannakis et al., 2018; Tsodoulos et al., 2008; Coleman et al., 2020 with modifications). PA: Parnitha Mt., PE: Pentelikon Mt., EG: Egaleo Mt., HY: Hymettus Mt. Topographic background made with GeoMapApp (www.geomapapp.org).

The ACC consists almost entirely of metamorphic rocks and is subdivided into the following four nappes (from bottom to top) (Boronkay and Doutsos, 1994; Jolivet et al., 2010 and references therein): (a) The Basal Unit, which constitutes a carbonate platform succession of Upper Triassic to Eocene age, locally covered by Oligocene meta-flysch, metamorphosed at HP/LT metamorphic conditions during Early Miocene (Ring et al., 2007b). Given the similar lithostratigraphy and age, the Basal Unit is considered by most researchers to be a lateral equivalent of the Gavrovo-Tripolitza lithotectonic unit (van Hinsbergen and Schmid, 2012) (b) The Cycladic Basement Unit, a polymetamorphic terrane comprising pre-Carboniferous schist intruded by Carboniferous granites (Reischmann, 1998; Flansburg et al., 2019; Poulaki et al., 2019) (not exposed in Attica peninsula) (c) The Cycladic Blueschist Unit, which constitutes a complex unit consisting widely of meta-pelitic schist and marble alternations with local intercalations of ultrabasic rocks (Blake et al., 1981; Avigad and Garfunkel, 1991), metamorphosed at HP/LT conditions in Eocene-Early Oligocene times (Jolivet et al., 2010 and references therein) (d) On top, the Upper Unit (or Upper Cycladic Nappe of Jolivet et al., 2010) comprises a heterogeneous nappe pile, which has partially suffered Late Cretaceous HT metamorphism, and has a Pelagonian affinity. During Miocene, granitoids (e.g., Plaka granite, Fig. 1) and locally subvolcanic rocks intruded ACC.

In Attica and south Evia (Euboea), over 1000 m of thick-bedded marble with schist intercalations, of Upper Paleozoic-Mesozoic protolith age (Katsikatsos, 1976; Liati et al., 2013), crop out at several tectonic windows, forming Pentelikon and Hymettus Mts., the hills at southern Attica between Hymettus Mt. and Lavrion as well as Almyropotamos window in Evia (Fig. 1). The HP/LT metamorphic conditions defined for these formations (Shaked et al., 2000; Baziotis and Mposkos, 2011; Coleman et al., 2020) together with the absence of reliable geochronological data (Coleman et al., 2020), lead to dispute regarding the provenance of these rocks: Some researchers suggest that they belong to the Basal Unit (Jolivet and Brun, 2010; Krohe et al., 2010; Spanos et al., 2015; Scheffer et al., 2016), whereas others suggest that at least some of these outcrops at Attica belong to the Cycladic Blueschist Unit (Baziotis et al., 2009; Baziotis and Mposkos, 2011; Coleman et al., 2020). In this paper, we presume that marble and schist, cropping out at Hymettus tectonic window –which borders the study area to the east–, belong to the Basal Unit (Fig. 1).

Between the Athens Unit and the ACC, along the western and northern flanks of Hymettus Mt., the few hundred meters thick Alepovouni Unit (*sensu* Papanikolaou et al., 2004) intervenes (Fig. 1). Recent research has revealed low-grade metamorphic conditions for the unit (burial temperatures ~130 °C, Coleman et al., 2020). According to Katsikatsos et al. (1986), Katsikatsos (2002), Papanikolaou et al. (2004) and Krohe et al. (2010), the phyllite of the Alepovouni Unit corresponds to the SE Attica Phyllite of Marinos et al. (1971), which is considered to be part of the Cycladic Blueschist Unit of ACC. Yet, recent petrographic, structural and geochronological data support the assumption that the Alepovouni Unit is equivalent to the Upper Unit of ACC (Coleman et al., 2020).

The contact of the overlain Pelagonian with ACC is a curved, NNE to NE-trending, crustal scale fault (Fig. 1), which is considered to be responsible for at least the later stages of the exhumation of HP/LT ACC at the area (van Hinsbergen and Schmid, 2012 and references therein). It is referred in literature as Pelagonian Fault (Xypolias et al., 2003; Ring et al., 2007a; Spanos et al., 2015; Scheffer et al., 2016; Faucher et al., 2021), Southern Evia-Northern Attica Detachment (Papanikolaou and Royden, 2007; Bradley, 2012), Attica Detachment (Krohe et al., 2010), Pindos Suture Zone (Philippon et al., 2012), Evia-Attica Fault or Attica-Evia Transfer Fault (van Hinsbergen and Schmid, 2012) and Attica-Evia Detachment (Schmid et al., 2020). In Evia, the fault is well exposed, it is sub-vertical, it exhibits a dextral strike-slip kinematic character and was active from Early to Middle Miocene times (Xypolias et al., 2003; Faucher et al., 2021). In Attica on the other hand, the exact trace of the fault is obscured as it is covered by Pliocene and Quaternary sediments. Most researchers interpret this fault in Attica peninsula as a normal detachment (Papanikolaou et al., 2004; Papanikolaou and Papanikolaou, 2007; Papanikolaou and Royden, 2007; Krohe et al., 2010). Stratigraphical data reveal that it was active from Upper Miocene to Lower Pliocene (Papanikolaou and Papanikolaou, 2007). In this paper we adopt the name Attica-Evia Fault (cited as AEF hereafter) for this fault, since its kinematics is still a matter of debate.

Active tectonics of Attica peninsula was marked by the recent seismic activity of Fyli Fault at Parnitha Mt., a NW-SE trending and SW dipping normal fault (Fig. 1), that hosted the recent seismicity of the 7th September 1999, $M_W = 6.0$ (Papadopoulos et al., 2000; Ganas et al., 2001; Pavlides et al., 2002; Papadopoulos et al., 2002; Pomonis, 2002; Louis et al., 2002; Ganas et al., 2004), which caused huge social and economic consequences. Besides Fyli Fault, all around AMA –at the northern part of Attica, at the Thiva basin to the NW, as well as at western Attica toward the gulf of Corinth, a number of active, NW–SE trending or E–W to ENE–WSW trending normal faults (Fig. 1) were reported and investigated (Ganas et al., 2004; Papanikolaou and Papanikolaou, 2007; Tsodoulos et al. 2008; Deligiannakis et al. 2018; Konstantinou et al. 2020 and references therein), which are consistent with the modern NNE-SSW extension of the area.

3. METHODOLOGY

3.1. Available Data and Their Presentation

The approximately 2300 sampling boreholes –with depths generally ranging from 25 to 50 m, which were executed in the framework of the ground investigations of the Athens Metro, retrieved over 60.000 m of core run and thus valuable geological information regarding the ground conditions of AMA. On the map of Fig. 2, the lines of Athens Metro (both constructed and planned) as well as the locations of the sampling boreholes, define the extent of the ground investigations' data. Moreover, petrographic and mineralogical analyses were performed on approximately 200 specimens from borehole core samples. These analyses provided the mineral assemblages of several lithological units –mostly from Athens Schist– and assisted in their accurate identification and description. Core photos of characteristic lithological types from the various geological formations encountered at the AMA are shown in the figures presented in this paper to visualize their mesoscopic characteristics. Selected photos of tunnel excavation faces or open excavation faces, accompanied by borehole core photos and optical microscope images (when available), for each of the major geological formations encountered during Athens Metro construction, are presented in Appendix A of this paper.

The major stratigraphic and structural data deriving from the sampling boreholes and the geological mapping are presented in geological longitudinal sections. Two types of geological sections were compiled: (a) detailed geological sections that derive primarily from geological mapping of tunnel faces excavated with conventional mechanical means and secondarily from sampling boreholes (Figs 5 and 15); and (b) geological sections based solely on the correlation of sampling boreholes (Figs 7, 8, 9, 10 and 14). The former case refers to projects that have already been constructed with conventional mechanical means or open-face TBMs and as such, mapping of the excavation face was possible. The latter refers to projects that have either been constructed with closed-face TBM tunnelling –a method that does not allow for systematic mapping of the tunnel excavation face (extension of Line 3 to Piraeus, Fig. 8), or that are designed but not yet constructed or completed (e.g., Athens Metro Line 4, Figs 7, 9 and 10, extension of Line 2 to Anthoupoli, Fig. 14).

The compilation of the geological longitudinal sections presented in Figs 9, 10, 14 and 15, was based on data drawn from the following drawings:

- "Section 4, Egaleo station, section 3 K.P. 1+194 - 1+314,50 - Geological section - Geological mapping at TOR level" (dwg No 3TW5CW180A401A), issued by "PANTECHNIKI S.A." (2005).
- "Geotechnical longitudinal section, location Line 4" (dwg No 4GE0EN180R410A), issued by "EDAFOMICHANIKI S.A. -

GEOTECHNICAL INVESTIGATIONS S.A. - ANESTIS PANAGOPOULOS - HARA ALEXIADOU" (2009).

- "Monitoring final report - Longitudinal geological section - Data of encountered geological & engineering geological conditions - As built" (dwg No 3GW0CW415C1511), issued by "J/V ALPINE BAU GmbH - TERNA S.A. - PANTECHNIKI S.A. - POWELL ELECTRICAL SYSTEMS Inc" (2012).
- "Geological and hydrogeological longitudinal section - section 'Evangelismos - Vyronas - Ilioupoli' from K.P. 17+300 to K.P. 21+289" (dwg No 4G00PW180S403B), issued by "EDAFOMICHANIKI S.A. - ISTRIA GENERAL CONSULTANTS - ANESTIS PANAGOPOULOS" (2017).
- "Geological sections" (dwg No 2G00PW180S301B), issued by "N. LOUKATOS & ASSOCIATES S.A. - STYLIANOS MAVROGEORGIS" (2019).

In addition to the above, field geological surveys were carried out focusing on areas of geological interest (Attiko Alsos, Alepotrypa hill and Ano Kypseli at Tourkovounia hill area, Kessariani, Karavas hill) in order to gather additional structural and stratigraphic data.

3.2. Compilation of Geological Map of AMA

The Geological Map of AMA is a 1:25000 scale, geological map (see supplementary map) compiled from published geological maps and geological data from Athens Metro ground investigation.

The available geological maps of the study area which were used are the following:

- The 1:50000 HSGME geological map sheets of the area: "Athinai – Piraiefs Sheet", Gaitanakis (1982), "Athinai – Elefsis Sheet", Katsikatsos et al. (1986), "Kifissia Sheet", Katsikatsos (2002) and "Koropi – Plaka Sheet", Latsoudas (2003).
- "Geological Tectonic Map" of the Athens Basin, Papanikolaou et al. (2002).
- For Hymettus Mt., Coleman et al. (2020).

Recently, ground investigation incorporated geological mapping of zones along metro line under investigation, which were also used for the compilation of the geological map of this paper. These where the following:

- For the area between Vyronas and Ilioupoli districts: “Geological map view - section ‘Evangelismos - Vyronas - Ilioupoli’ from K.P. 17+300 to K.P. 21+289” (dwg No 4G00PW180S102B), issued by “EDAFOMICHANIKI S.A. - ISTRIA GENERAL CONSULTANTS - ANESTIS PANAGOPOULOS” (2017).
- For Anthoupoli area: “Geological map” (dwg No 2G00PW180S101B), issued by “N. LOUKATOS & ASSOCIATES S.A. - STYLIANOS MAVROGEORGIS” (2019).

Since there are differences regarding the stratigraphic scheme between each of the four HSGME geological map sheets and the geological map of Papanikolaou et al. (2002), a synthetic scheme was adopted, taking also into account available geological data from the ground investigations. This scheme is analytically presented in section 4. All map lines of the Geological Map of AMA, i.e., the geological contacts, faults etc., were edited as follows: A first synthetic digital map was compiled using the available geological maps –the one from the compilation of the four HSGME sheets and the one of Papanikolaou et al. (2002). For each map line, differences between the two base maps were treated one by one, and the map line was chosen according to the adopted stratigraphic scheme and the relevant literature. After the first synthetic map was created, a layer of all available sampling boreholes was added and the uppermost recorded formation at the borehole log was compared to that on map at the same location. Exceptions to the above rule were the cases where the uppermost formation of the borehole was anthropogenic or Quaternary, with thickness less than ~1.5 m. In such cases, the next formation was taken into account. If the two formations –from borehole log and map– did not coincide, the map line was corrected accordingly to match the boreholes’ data. The main differences between the compiled map and the original ones are discussed throughout the next section.

In the following sections, the geological structure and the main formations of the AMA are described, focusing on lithological and structural characteristics deriving from the Athens Metro ground investigations. Additionally, the major modifications proposed in the Geological Map of AMA are discussed.

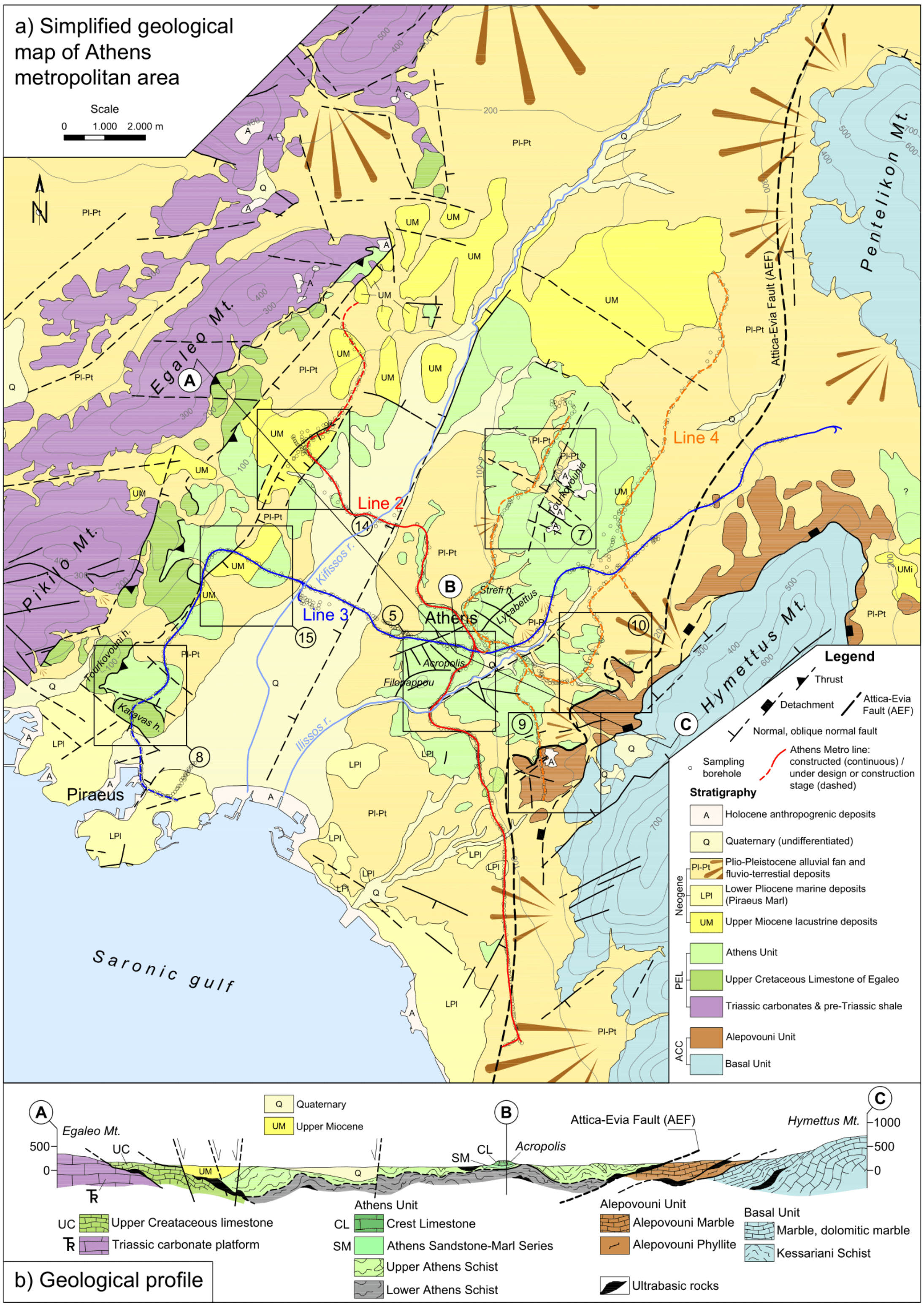


Fig. 2: a) Simplified version of the "Geological Map of AMA" of the Supplementary material, with Athens Metro lines (constructed sections and under construction or design sections) and sampling boreholes from ground investigation for Athens Metro. Squares indicate the location of the geological maps of the corresponding Figures. b) Simplified geological profile across the Athens Basin (from Marinos et al., 1971, Papanikolaou et al., 2004, Coleman et al., 2020, with modifications).

4. GEOLOGICAL FORMATIONS AND STRUCTURE PROPOSED IN THE GEOLOGICAL MAP OF AMA

4.1. Geology and structure of AMA

Fig. 2 provides a simplified version of the Geological Map of AMA, where the geological units and the major structural characters show an overall NE-SW structural trend. A simplified geological section is drawn perpendicular to this trend, to show the main contacts between the different geological units.

The Quaternary fluvio-torrential deposits of Kifissos River mark the major NE-SW structural trend. Thick Pleistocene (Papanikolaou and Papanikolaou, 2007) or Plio-Pleistocene (Krohe et al., 2010) alluvial fan deposits –near the source– and fluvio-terrestrial deposits –on the flat planes– descend from Parnitha, Pentelikon and Hymettus Mts. Lower Pliocene marine sediments (Papp, 1947; Charalambakis, 1951) crop out at the southern suburbs of Athens, parallel to the coastline of Saronic gulf. Older, Upper Miocene lacustrine deposits (Freyberg, 1951; Ioakim et al., 2005) crop out at the northern part of Athens Basin as well as along the eastern foothills of Egaleo Mt., and are bordered from the basement with predominantly NE-SW and secondarily WNW-ESE trending faults.

The basement of Athens Basin mostly consists of the Upper Cretaceous Athens Unit, which forms the central hills of Athens. The unit is traditionally divided into a series of meta-clastic and calcareous formations. Several stratigraphic schemes have been proposed for this unit over the years, the classical being the following (from bottom to top): a) the Athens Schist, b) the intermediate formation, consisting of limestone, sandstone, marl and conglomerate and c) the upper Crest Limestone (*sensu* Marinos and Petrascheck (1956) and Marinos et al. (1971), for other nomenclature of Athens Unit stratigraphy, see Fig. 3). As deduced from paleontological and lithological data, the Athens Unit was considered to be a flysch-like sequence (Marinos et al., 1971). Later on, Papanikolaou et al. (2004) divided the Athens Unit into a neritic formation and a pelagic one (Fig. 3, column 5). According to these authors, these two formations show no specific stratigraphic correlation between them, as they constantly alternate, their contacts with the adjacent formations are always tectonic, and there is no stratigraphic continuity between them. From the above observations, Papanikolaou et al. (2004) concluded that the Athens Unit resembles an Upper Cretaceous ophiolitic mélange. The unit is generally not metamorphosed (Marinos et al., 1971; Papanikolaou et al., 2004) but in several areas of the AMA, phyllite, sericite-chlorite schist, mica schist with well-defined schistosity and green chlorite phyllite can be observed (Marinos et al., 1971), which correspond probably to low-grade metamorphism.

Lithostratigraphic affinity of Athens Unit is still in debate. Some researchers consider the Athens Unit as part of Pelagonian (e.g., Krohe et al., 2010; Spanos, 2012), whereas others assume that it comprises a local unit developed between Pelagonian and ACC (Papanikolaou et al., 2004; Afidnai-Tourkovounia Unit of Katsikatsos et al., 1986; Katsikatsos, 2002, column 4 of Fig. 3). However, all authors agree that the Athens Unit overlies the ACC metamorphics, which indicates that it correlates –to some extent– to Pelagonian unit. The ACC at Hymettus Mt., consists of the following six formations from top to bottom (Coleman et al., 2020, column 6 of Fig. 3): the Kessariani Marble, the Kessariani Schist (or Kessariani Unit), a meta-clastic sequence with marble intercalations, the Kessariani Dolomite, the Lower Marble, the Pirnari Marble and the Cheroma Unit (not depicted in the Geological Map of AMA). At Pentelikon Mt., common stratigraphy of the Basal Unit encounters three formations (from top to bottom): The Upper Marble, the Kessariani Schist and the Lower Marble (Marinos and Petrascheck, 1956, see column 3 of Fig. 3; Spanos et al., 2015). Other authors suggest that stratigraphy at Pentelikon Mt. is more complex and encounters continental basement lithological types (orthogneiss and meta-migmatite, Pentelikon Gneiss after Kober (1929a), see column 2 of Fig. 3) (Baziotis, 2008; Baziotis et al., 2019), which are considered remnants of the Hercynian basement of the ACC (Liati et al., 2013), possibly correlated to Cycladic Basement Unit. The same conclusion was reached by Lozios (1993) from tectonic analysis and mapping at Pentelikon Mt., which revealed that the tectonostratigraphic deeper formation is the above mentioned orthogneiss and meta-migmatite rather than the Lower Marble.

Two faults mark the eastern border of the Athens Unit with ACC at Hymettus Mt. (Fig. 2b): (a) The fault separating the Athens Unit from the underlying Alepovouni Unit, –which probably corresponds to AEF–, and (b) the fault separating the Alepovouni Unit from the underlying HP/LT metamorphics of ACC. To the west, Athens Unit is situated upon the Upper Cretaceous limestone of Pelagonian, and the contact between the units is again a fault (Fig. 2b).

1 Lepsius (1893)			2 Kober (1929a & 1929b)			3 Marinos & Petrascheck (1956), Marinos et al. (1971)			4 Katsikatsos (2002)			5 Papanikolaou et al. (2002, 2004)			6 Coleman et al. (2020) (for Hymettus Mt. only)		
a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
UK	*Up. Limest. Stage*	Lycabettus Limestone (C_3)	**UK**	*Lower Boeotic Series*	Tourkovounia Limestone & marl	**UK**	*Schists of Athens System*	Crest Limestone	**UK**	*Afidnai - Tourkovounia Unit*	Tourkovounia Limestone	**UK**	*Athens Unit*	Neritic limestone			
	Athens Schist Stage	Marly horizon (C_{2b})	**J**		Lycabettus Limestone			Platy limestone, sandstone, marl, conglomerate	**UK**		Marly horizon						
UK?		Athens Schist (C_2)	**K**	*Upper Attica Series*	Athens Schist			Athens Schist			Athens Schist			Pelagic sediments ("Schists of Athens")			
J-LK	*Lower Limestone Stage*	Limestone (C_1)	**?**		Alepovouni & Ardettus Limestone	**?**		Alepovouni Limestone	**?**	*Neo-Hellenic Tectonic Nappe*	Schist with marble intercalations	**Tr?**	*Alepovouni Unit*	Alepovouni crystalline limestone		*Upper Unit*	Alepovouni Marble
		Marl, schist (C_{1a})	**?**	*Lower Attica Series*	Karas Beds	**UK**		SE Attica Phyllite				**?**		Phyllite, schist and marl beds			Alepovouni Phyllite
pC?	*Autochthonous System*	Upper Marble	**LJ?**		Kessariani Schist	**UTr-J**	*Autochthonous System*	Upper Marble	**Mz**	*Almyropotamos - Attica Autochthonous Unit (Pentelikon area) = Tripolitza lithotectonic umit*	NE Attica Marble	**UTr**	*Attica Unit*	Dolomite & marble		*Middle Unit*	Kessariani Marble
		Kessariani Schist						Kessariani Schist	**LTr-MTr**		NE Attica Schist	**Mz**		Kessariani Schist (Hymettus), Pentelikon Schist			Kessariani Schist
		Lower Marble	**Tr-J?**		Marble & dolomite			Lower Marble, dolomite, schist	**LTr-MTr**		Pentelikon Marble	**Mz**		Marble			Kessariani Dolomite
		Dolomite & Pirnari calcareous schist															Lower Marble
		Vari Schist	**Pz-Tr?**		Vari Schist											*Lower Unit*	Pyrnari Marble
			?		Pentelikon Gneiss												Cheroma Unit

Fig. 3: Schematic stratigraphy of Attica and nomenclature of units and formations according to basic literature references: column 1 after Lepsius (1893), column 2 after Kober (1929a and 1929b), column 3 after Marinos and Petraschek (1956) and Marinos et al. (1971), column 4 after Katsikatsos (2002), column 5 after Papanikolaou et al (2002 and 2004) and column 6 after Coleman et al. (2020). Column a: age, column b: lithostratigraphic group (unit), column c: lithostratigraphic formation. Abbreviations: pC: pre-Cambrian, Pz: Paleozoic, Mz: Mesozoic, LTr, MTr, UTr: Lower, Middle, Upper Triassic, J, LJ: Jurassic, Lower Jurassic, K, UK: Cretaceous, Upper Cretaceous. Dashed line: unconformity, thick black line: tectonic contact, thick green line: tectonic contact with serpentinite. Note that columns are not stratigraphic columns per se, since lithostratigraphic units correspond to different lithotectonic units (Pelagonian, ACC).

According to relatively recent literature, the two faults at the eastern border of Athens Unit are detachments. In particular, Papanikolaou et al. (2004) as well as Krohe et al. (2010), consider these two faults as a single, main detachment system, with top-NNW sense of movement. Furthermore, Papanikolaou et al. (2004) consider the fault bounding the Athens Unit to the west as the conjugate to the main detachment. Coleman et al. (2020) also describes the fault bounding the Alepovouni Unit to the underlying Basal Unit as a detachment, (namely the 'Upper Detachment'), but with opposite, top-S sense of movement. Yet in earlier research, Marinos et al. (1971) describe all major contacts of the Athens Unit as well as the Alepovouni Unit as alpine thrusts accompanied by systematic folding. No major active faults –i.e., which can generate earthquake with moment magnitude $M_W \geq 6$– are found within Athens Basin (Konstantinou et al. 2020; see also Fig. 1).

4.2. Athens Schist

The Athens Schist (cited as AS hereafter) is the main formation of the Athens Unit with an estimated thickness of a few hundred meters. Based on lithological and also on geotechnical characteristics, the AS is divided into an upper formation, namely the Upper Athens Schist, and a lower one, the Lower Athens Schist.

The Upper Athens Schist is a meta-clastic, heterogeneous formation, consisting predominantly of alternations of greyish-green, brownish-green metasandstone and brown, brownish-green metasiltstone. Other lithological types encountered include limestone or crystalline limestone, commonly as alternations with calcareous phyllite or calcareous schist (Pagrati district, Ardettus hill, see supplementary map), phyllite, sericite or muscovite schist (Syntagma Square area), alternations of chlorite-epidote schist and karstic limestone (Academia area) and brownish green, thickly-foliated epidote-chlorite schist (Egaleo district, see geological profile B–C of Fig. 15). The Lower Athens Schist exhibits a more confined lithology, as it is composed of alternations of metasiltstone (often calcareous), clayey shale and metasandstone (often calcareous) (Fig. 4e), locally with intercalations of crystalline limestone or thin talc schist. A key feature of the Lower AS is its grey to black-grey colour due to the participation of the clayey shale in this meta-clastic series (Fig. 4b). The contact of the two formations is either sharp or a transition zone. The transitional formation of the latter case, is a few meters thick with lithological characteristics of both Upper and Lower AS (e.g., brownish-green metasandstone and metasiltstone alternations with black shale intercalations) (Fig. 5, detail of geological section A–B) indicating a gradual change in primary depositional conditions of the two formations. Within the AS, altered volcanic bodies of the albitic spilitic and diabase-type have been locally found. Microscopic analyses (Marinos et al., 1971) have shown mineral assemblage of secondary calcite-chlorite-epidote-green hornblende-quartz ± magnetite ± leucoxene. The presence of augite and feldspar as primary minerals is also estimated. According to Marinos et al. (1971), these bodies are considered contemporary with the sedimentation, but no relevant dating tests have been performed so far to verify this assumption. Such altered volcanic bodies were found along Metro Line 2, near Larissis station.

In all lithological types of AS, but mainly within the Lower AS, decimetre scale quartz lenses, wrapped around by foliation, are often encountered. At some areas, these quartz lenses are widespread, characterizing and differentiating the lithology itself (Fig. 4b). Thin veins of calcite and/or quartz are also very common within almost all lithological types (Fig. 4c and d). In the clayey shale and metasiltstone of the Lower AS, euhedral pyrite crystals, that sometimes exceed 5 mm in length, are often found, a characteristic mineral that determines reductive depositional conditions during sedimentation of the formation. An important differentiation in the lithological types between the Upper and Lower AS is the almost systematic presence of Fe-oxide and hydroxide impregnations (hematite, gaitite, limonite) in the lithological types of the Upper AS and their almost complete absence in the Lower AS, a characteristic that indicates significant infiltration of fluids of possibly hydrothermal origin (see also section 4.6).

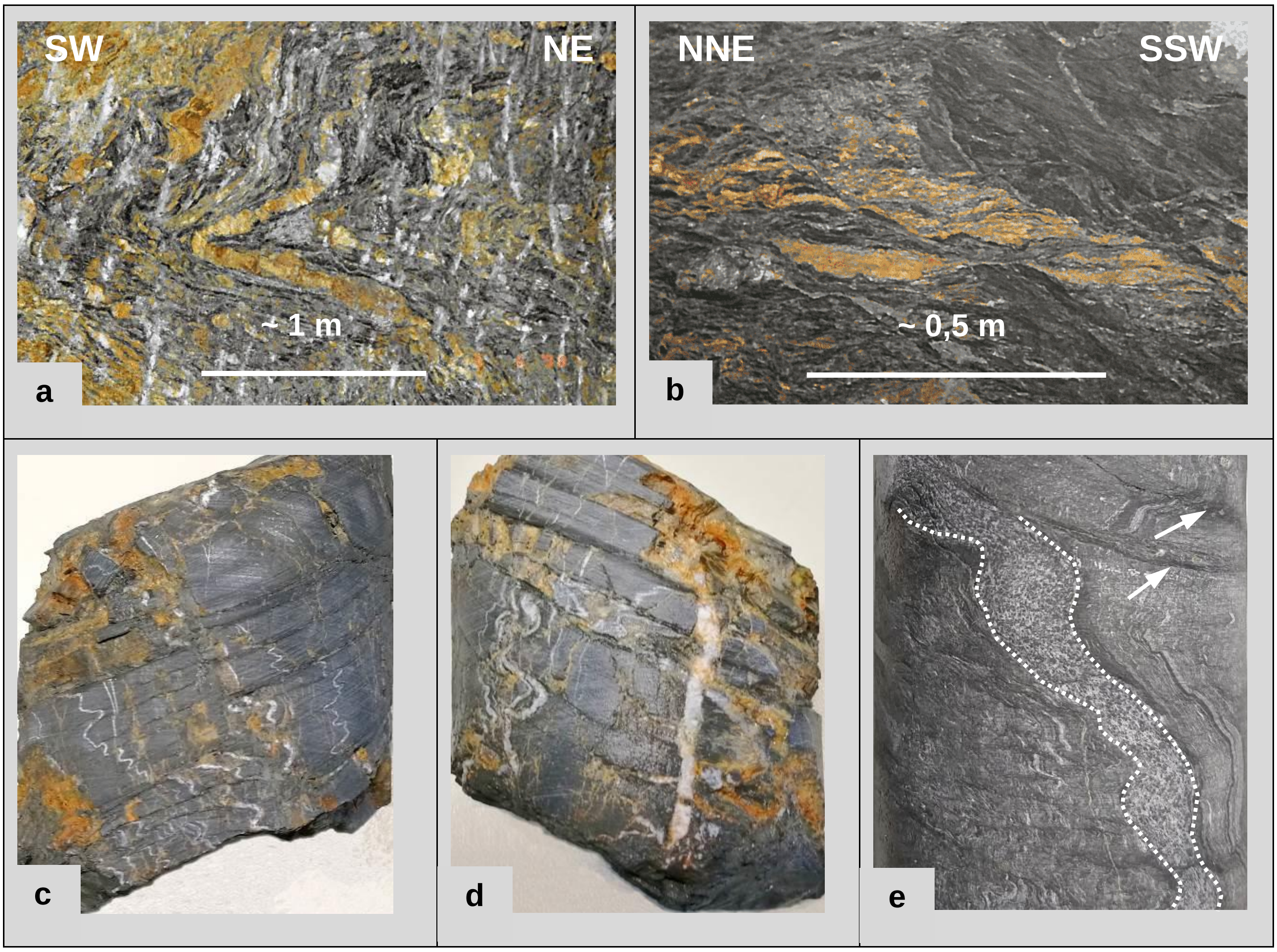


Fig. 4: Mesoscopic features of Athens Schist. a) Folded metasandstone and metasiltstone alternations (brownish grey) within dark grey to black clayey shale (Lower Athens Schist). Detail photo from excavation face, Metro Line 2 pilot tunnel towards Sygrou-Fix station, K.P. 6+632. b) Extensional shear bands in black clayey shale, intersecting and displacing light orange quartz lenses (Lower Athens Schist). Detail from excavation face of heading, Metro Line 2 pilot tunnel towards Ag. Ioannis station, K.P. 7+711. c) Plastic folds within metasiltstone and foliation-parallel displacement towards the left of the photo, as defined from the relevant displacements of the thin, folded veins. d) Back view of the same sample of photo (c), in which a 2 mm wide undeformed second-generation calcite vein crosscuts the foliation and the older and folded veins. e) Folded and sheared grey metasiltstone with coarser-grained metasandstone (in-between doted lines) and very thin black shale intercalations. Note the concentration of black shale along shear planes, indicated by arrows. Core samples (c), (d) and (e) derive from ground investigation for extension of planned Metro Line 4 toward Vyronas district.

From the elaboration of the results of 88 petrographic and mineralogical analyses, which were performed in the framework of the ground investigations of Athens Metro, the following average mineral composition emerged, for the meta-clastic rocks (metasandstone, metasiltstone, phyllite, schist) of the Upper AS: 46,6 % quartz, 19,9 % white mica (e.g. sericite, muscovite), 18,1 % calcite, 4,8 % chlorite, 4,4 % feldspar (e.g. albite, K-feldspar usually sericitized) and 3,3 % opaque minerals, mainly oxides' impregnations (hematite), Fe-hydroxides (limonite, goethite) and euhedral pyrite. Secondary minerals include biotite, dolomite, epidote, tourmaline and clay minerals. Microscopic analysis showed that most of the metamorphic minerals (muscovite, biotite, feldspar, tourmaline) are detrital. The rock texture defined from these microscopic analyses is mostly cataclastic and secondarily fibroblastic, lepidoblastic or sparitic (for the calcareous rocks). The more abundant quartz grains appear fine-grained, with crystal sizes approximately 0,05 to 1 mm, they often exhibit undulose extinction and are in an extensive degree re-crystallized. The very thin bands that appears in the mesoscopic scale, in the form of alternations of very thin layers of different colour tone (Fig. 4e), is directly related to the alternation of quartz-rich and mica-rich bands and/or opaque minerals. In these cases, folding is intense even in the microscopic scale. A principal tectonic structure that characterizes AS is the contact between the Lower and the Upper AS. It is a low-angle fault separating the relatively brittle Upper AS (metasandstone, metasandstone and metasiltstone alternations) from the ductile Lower AS –metasiltstone, clayey shale– which resembles a shear zone. This shear zone was systematically observed in almost all Athens Metro projects (see geological profiles in Figs 2, 5, 7, 10, 14 and 15). The deformation of the AS is intense and is characterized, on a macroscopic scale, by several contraction structures –shear zones with cataclasite and fault gouge up to 3 m thick, anticlines (geological profile B–C of Fig. 15) and synclines. Faulting is also widespread. The main directions of the faults are NW-SE and NE-SW, but their kinematics remains obscured, since no tectonic analysis has yet been performed. A few measurements of striations on fault planes, together with fault planes recovered from borehole cores of AS, show sub-horizontal to dip-directed striations. In the mesoscopic and microscopic scales, most AS rocks exhibit a pervasive foliation, tightly to isoclinally folded (Figs 4a, c, d and e) which is, in many cases, accompanied by a pervasive axial plane cleavage which forms successive foliation (Fig. 4e) and also rootless folds. These rocks often exhibit striations on almost all foliation planes, a characteristic that implies the severe shearing that took place. The described quartz lenses and quartz / calcite veins are systematically co-folded (Fig. 4c), indicating that quartz and calcite veining is syn-tectonic and syn-metamorphic. Besides, a generation of younger calcite veins that crosscut the folded foliation and veins can be observed (Fig. 4d). Even though contractional structures prevail, extensional structures can also be found, which sometimes characterize locally the deformation of AS. These structures are mainly closely-spaced extensional shear bands (Fig. 4b), mostly within clayey shale and metasiltstone of the Lower AS, that crosscut and displace foliation and sub-parallel to foliation quartz lenses. In map scale, the Upper AS crops out in most of the Athens hills, while the Lower AS is not generally exposed on the surface, even though it is found in almost all Athens Metro lines. The only cases that the Lower AS crops out on the surface, are in Monastiraki and Koukaki districts as shown in this paper's geological map (see supplementary map; Fig. 5).

4.3. Athens Sandstone-Marl Series and Crest Limestone

The second more abundant formation of the Athens Unit is the Athens Sandstone-Marl Series (cited as SM hereafter). The formation's name is a slight modification of Sandstone-Marl Phase of the Geological Map of Metro Area (Katsikatsos et al., 1981; Kounis, 1981). The SM comprises alternations of thinly bedded, greyish-white or brownish-yellow, locally karstic, marly limestone, thinly bedded greyish-white, locally intraclastic limestone (Fig. 6d), reddish-brown or brown coarse to fine grained, often calcareous, sandstone (Fig. 6c and d), variable-coloured claystone (Fig. 6e) and grey calcareous conglomerate. The absence of metamorphic rocks in SM together, with the fact that it is always found on top of AS, leads to the conclusion that the formation has escaped the low-grade metamorphism that is locally observed in the AS.

The formation overlies the AS. Its thickness varies from a few tens of meters at Lycabettus, Acropolis and Filopappou hills (Fig. 5) to a few hundred meters at Tourkovounia hills area, where the main outcrop of the SM exists (Fig. 7). It exhibits the same deformation at mesoscopic (Fig. 6c) and map scale as AS, including abundant folds and densely spaced low-angle shear zones (Fig. 6d). Faults exhibit mainly NW–SE and secondarily NE–SW directions. Striations and kinematic indicators such as drag-folds indicate horizontal or normal / oblique-normal (Fig. 6e) kinematic character of the faults. Geological data from ground investigation along Metro Line 4, revealed thick marly limestone of the SM underneath thin Plio-Pleistocene fluvio-terrestrial deposits along Veikou Avenue. This marly limestone bed crops out at the surface in-between kilometric positions (K.P.) 10+000-10+500, 11+000-11+200 and 13+100-13+350 –just above the contact with AS– of the Metro Line 4 (see geological section of Fig. 7). The uppermost Athens Unit formation is the Crest Limestone that crops out at the top of most of the hills of Athens Basin (Acropolis, Filopappou, Lycabettus, Tourkovounia; see supplementary map). Crest Limestone either directly overlies SM or a tens of meters thick transition bed between the two formations intervenes

(Andronopoulos and Koukis, 1976). It consists of massive, grey to white, locally intraclastic and karstic limestone. Almost in all occurrences, fragments and complete *Rudists*, fragments of *Corals* and *Echinoderms*, *Gasteropods*, *Crustaceans*, *Shellfish*, micro-fossils etc. indicate Cenomanian to Turonian and Upper Senonian age (Marinos et al., 1971).

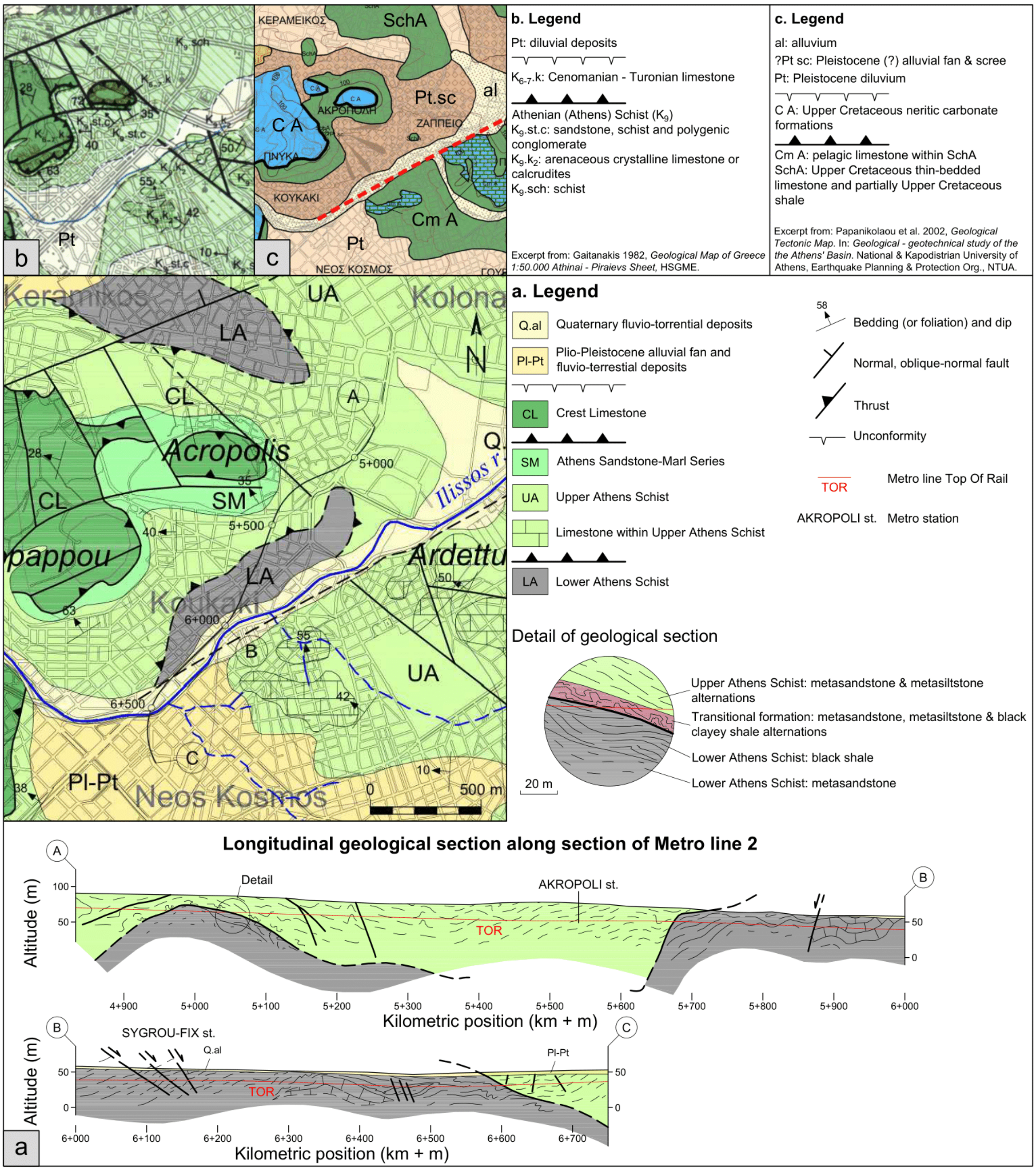


Fig. 5: a) Excerpt from the Geological Map of AMA at the Acropolis area. Longitudinal geological section A–B–C is drawn along the Athens Metro line 2, approx. from Syntagma station to Neos Kosmos station. (b) and (c) show the excerpts from HSGME and Papanikolaou et al. (2002) geological maps respectively, of the same area, for comparison. Scale of (b) and (c) maps is half the scale of (a) map.

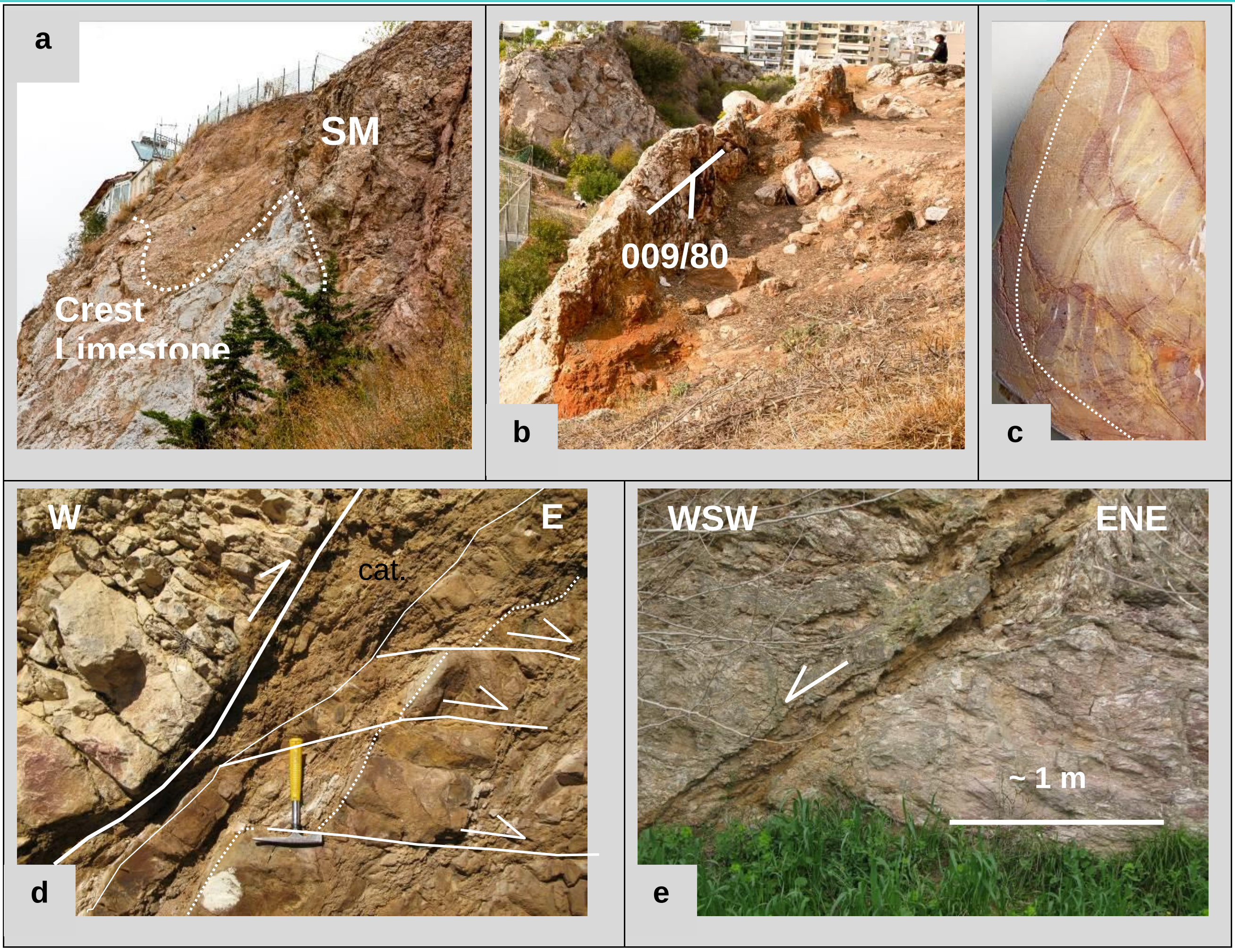


Fig. 6: Mesoscopic structures of SM and relationships between SM and Crest Limestone. a) Contact between SM and Crest Limestone at the abandoned quarry of Alepotrypa hill, Tourkovounia (for location see Fig. 7, Athens Metro Line 4, K.P. 12+800 to K.P. 12+900). In the side view of the quarry slope, the sub-vertical contact (dashed line) can be traced. b) Same contact as in (a), at a neighbouring site: the limestone block rises up to 1 m from the ground surface due to the differential erosion of limestone and adjacent sandstone. The shadowed surface is the contact between limestone of Crest Limestone to the left and sandstone of SM to the right. The white symbol shows the dip direction of the contact (for scale see the person at the top right corner). The limestone constitutes part of the short limb of the eroded fold shown in geological profile B–C of Fig. 7 c) Folded, reddish grey sandstone of SM (see dotted line indicating bedding). Note the thin quartz veinlets, the oxidized joints and the concentric altered rings (liesegang rings) due to infiltration of oxide-rich fluids in sandstone. Core sample from ground investigation of planned Metro Line 4, Tourkovounia hills area. d) Top-E, bedding parallel thrust with ~ 30 cm thick cataclasite, which brings the light grey limestone (left side of photo) over reddish brown sandstone. The thrust is accompanied by three sub-horizontal shear bands, with top-E sense of shear, which cut and displace a thick sandstone bed. Armonias and Astypalaia strs., Alepotrypa hill, Tourkovounia hills. e) Normal fault cutting calcareous claystone with sparse sandstone alternations. The fault exhibits a 40 cm thick cataclastic zone. Attikou Alsous Av. and Ellinikou str., Tourkovounia hills.

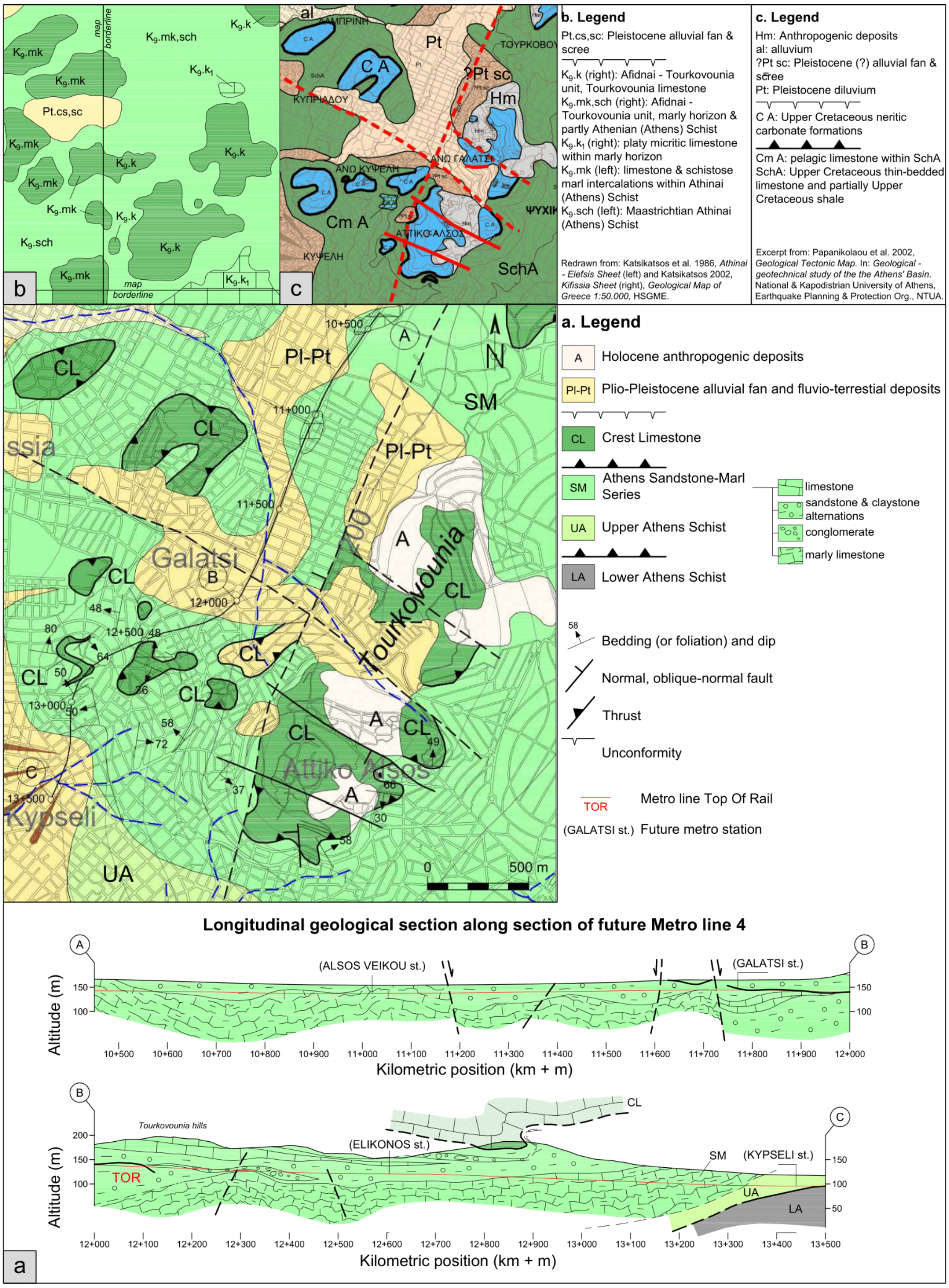


Fig. 7: a) Excerpt from the Geological Map of AMA at Tourkovounia hills. Longitudinal geological section A–B–C is drawn along part of the planned Athens Metro Line 4. (b) and (c) show the excerpts from HSGME and Papanikolaou et al. (2002) geological maps respectively, of the same area, for comparison. Scale of (b) and (c) maps is half the scale of (a) map.

The contact of the Crest Limestone with the underlying SM is often a folded shear zone, as is the case at the area of Alepotrypa hill at Ano Kypseli (Fig. 7, K.P. 12+800 –

12+900). There, the shear zone, separating the two formations, is characterized by a 1 m thick cataclasite and is folded, forming a mesoscopic-scale anticline with an inverted short limb and axis trending almost parallel to the direction of the quarry slope. The geometry and direction of the anticline with respect to the direction of the quarry slope is such that, the exposure of the Crest Limestone –forming the short limb of the anticline– is underneath the exposure of SM –forming the crest of the anticline– on the wall of the quarry slope, whereas stratigraphically the opposite occurs (Fig. 6a and b). The deformation of the Crest Limestone is characterized by ENE-WSW to NW-SE trending faults and dense joints that favour the development of karstic features (Andronopoulos and Koukis, 1976; Karfakis and Loupasakis, 2006). The existence of several limestone occurrences throughout the Athens Unit –within the AS (e.g., limestone at Ardettus hill), within SM, Crest Limestone itself, their identical lithological characteristics and the significant dispersion of limestone outcrops, predominantly at Tourkovounia hills area, makes it difficult to distinguish which limestone corresponds to which formation. As a safe criterion, the thickness of the formation combined with stratigraphy was considered. Thus, where the thickness of a limestone bed is significant (over 30 m) and no other bed is identified above, this bed is considered to belong to the Crest Limestone. On the contrary, where the limestone is within other formations of the Athens Unit, it is usually in the order of a few meters to a few tens of meters thick.

4.4. Serpentinite and Upper Cretaceous limestone at Karavas hill area (western border of Athens Unit)

Extension of Athens Metro line 3 towards Piraeus, runs parallel to the western border of Athens Basin and crosscuts Karavas hill, 1.5 km to the north of Piraeus port (Fig. 2). The section from K.P. 4+400 up to K.P. 6+600 was proved to be very important geologically, because, during the execution of the ground investigation, extensive serpentinite bodies were revealed, not only at the foothills of Karavas hill as expected, but also some 700 m to the northeast (geological profile D–E, Fig. 8). Serpentinite lithology is discussed separately in section 4.6. The contact between the AS and the underlying serpentinite is not always tectonic, whereas serpentinite bodies are always in tectonic contact with underlain limestone (geological profiles A–B–C and D–E of Fig. 8). This contact is well documented by numerous sampling boreholes, as well as excavations (Fig. 12d), cutting both serpentinite and subjacent limestone. The contact is always marked by complete alteration of serpentinite as well as karstic features within the underlying limestone, probably due to circulation of underground water along this contact (Fig. 12d).

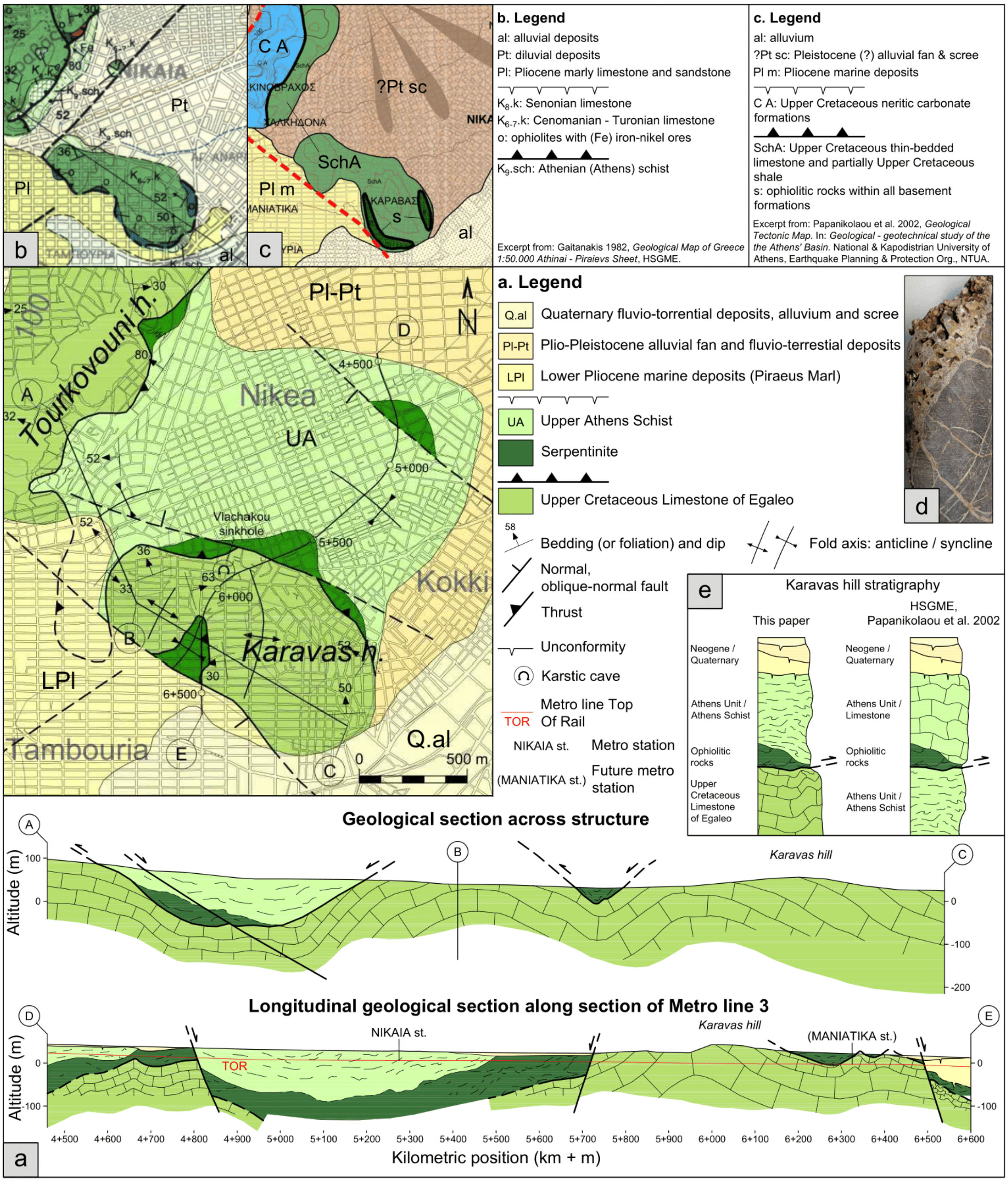


Fig. 8: a) Excerpt from the Geological Map of AMA at the western margin of Athens Basin, around Karavas hill. Geological profile A–B–C is drawn perpendicular to the structural trend whereas geological longitudinal section D–E is drawn along part of the extension Ag. Varvara - Piraeus of Athens Metro Line 3 (b) and (c) show excerpts from HSGME and Papanikolaou et al. (2002) geological maps respectively, of the same area, for comparison. Scale of (b) and (c) maps is half the scale of (a) map d) Core photo of massive, grey, karstic limestone, typical lithological type of the Upper Cretaceous limestone from Karavas hill e) Simplified and comparative stratigraphic columns that show the difference in stratigraphy of Karavas hill area described in this paper and in HSGME and Papanikolaou et al. (2002) geological maps.

Limestone underneath the AS and serpentinite, that crops out at Karavas hill, is medium-bedded to massive, bluish grey to brownish grey –when it is ferrous–, locally karstic and crystalline (Fig. 8d). The above tectonostratigraphic relation, the large thickness of the limestone –no other formation was found underneath– together with its lithological characteristics, led to the conclusion that it belongs to the Pelagonian Upper Cretaceous limestone described by Marinos et al. (1971) and not to a carbonate lithology of Athens Unit. The Upper Cretaceous limestone crops out along the foothills of Egaleo and Pikilo Mts., south of Kamatero up the bay of Keratsini, between the Athens Unit and the Triassic platform carbonates of the Pelagonian (Fig. 2). Within the limestone, numerous fossils (fragments and complete sections of *Rudists*, fragments of *Corals* and *Echinoderms*, *Gasteropods*, *Crustaceans*, *Shellfish*, micro-fossils, etc.) have been identified that indicate stratigraphic age from Cenomanian to Turonian and Upper Senonian (Marinos et al., 1971 and references therein).

All formations of the area appear folded in mesoscopic and map scales with large, open to closed anticlines and synclines (geological profiles of Fig. 8). Locally, numerous joints and faults have favoured the development of karstic features. The most characteristic karstic feature recorded is the Vlachakou sinkhole (for location see Fig. 8), a helical, high-slope hole more than 20 m deep (data from http://urbanspeleology.blogspot.com). Karavas hill is a horst, bounded by two sub-parallel NW to WNW-trending, normal –or oblique normal– faults (Fig. 8). The southern one coincides with the probable fault shown in geological map of Papanikolaou et al. (2002). Another parallel normal or oblique-normal fault further north bounds the Upper AS syncline (Fig. 8). The considered tectonostratigraphy of Karavas hill area, as deduced from our data, is the opposite of that described in the so far published maps (see comparative stratigraphic columns of Fig. 8e).

4.5. Alepovouni Unit and AEF at the eastern margin of Athens Basin

At the western foothills of Hymettus Mt., the Alepovouni Unit crops out (Figs 2, 9 and 10). The unit consists of the predominant Alepovouni Marble and the underlying Alepovouni Phyllite. The Alepovouni Marble consists of thick-bedded to massive, locally karstic, pink or greyish-white, often ankeritic and locally dolomitic marble (Fig. 9d) with local intercalations of brownish grey calcareous schist. Calcite veins are locally very common as well as euhedral pyrite crystals up to a few cm long. In many cases, karstic voids are secondarily filled with ferrous and/or manganese material. Characteristic are the karstic features, like the 'Nikos Margiolis' cave at Vyronas district, a cave with two chambers of maximum width 10-25 m and a depth of ~22 m (see Fig. 9 for location, data from http://urbanspeleology.blogspot.com). The Alepovouni Phyllite is a thin formation, underlying the Alepovouni Marble and consists of severely deformed, calcareous phyllite and phyllite mixed with beds of thin-bedded, ankeritic, silicified marble, quartz lenses and greenstone (Marinos et al., 1971; Papanikolaou et al., 2004; Coleman et al., 2020). Mineral assemblage for phyllite is calcite-sericite-chlorite-white mica-quartz-plagioclase ± tourmaline ± epidote (Coleman et al., 2020). Mesoscopic structures of the unit are primarily contractional, analogous to Athens Unit. In particular, excellent exposure of marble with calcareous schist intercalations (Alepovouni Marble) at Vyronas municipal stadium, have revealed plastic folding accompanied by foliation-parallel thrusting (Fig. 11a).

The data from the ground investigation of the extension of Line 4 to Vyronas and Ilioupoli, showed that Alepovouni Marble is placed on top of serpentinite and that they are together tectonically placed over the Kessariani Dolomite of the ACC (Fig. 9). The tectonic contact is a low-angle folded fault, as is suggested from borehole data (geological section of Fig. 9, K.P. 20+400 to 21+300). According to Coleman et al. (2020) this fault is a normal character detachment –namely the ‘Upper Detachment’– as it brings the low grade metamorphosed Alepovouni Unit over the HP/LT metamorphics of ACC. The contact of the Alepovouni Marble with the overlying Athens Unit is considered as part of the AEF. Ground investigation data and field data from a road cut outcrop (Fig. 11b) revealed that AEF at this area is an intermediate to high-angle fault zone which is also characterized by the existence of serpentinite lenses (geological profile of Fig. 9, K.P. 19+850 to 19+950). As deduced from the geological map and from few dip-direction measurements (Fig. 11b), the direction of AEF is changing, showing that its surface is characterized by complex and probably long structural history, however, its detailed description is out of the scope of this work. The AS and the serpentinite of the hanging wall of the AEF are characterized by strong cataclasis (Fig. 11b). Correspondingly, the Alepovouni Marble at the footwall of the fault is characterized by a dense network of joints, oxide impregnation and karstification. AEF is also detected from sampling boreholes for the future Metro Line 4 at Zografou district. In this case, a ~40 m thick serpentinite body is located between the overlying AS and the underlying Alepovouni Marble (geological profile A–B of Fig. 10). It is obvious that the sampling borehole data are not sufficient to identify more features of the AEF, such as the direction and dip of the fault zone, its kinematics etc.

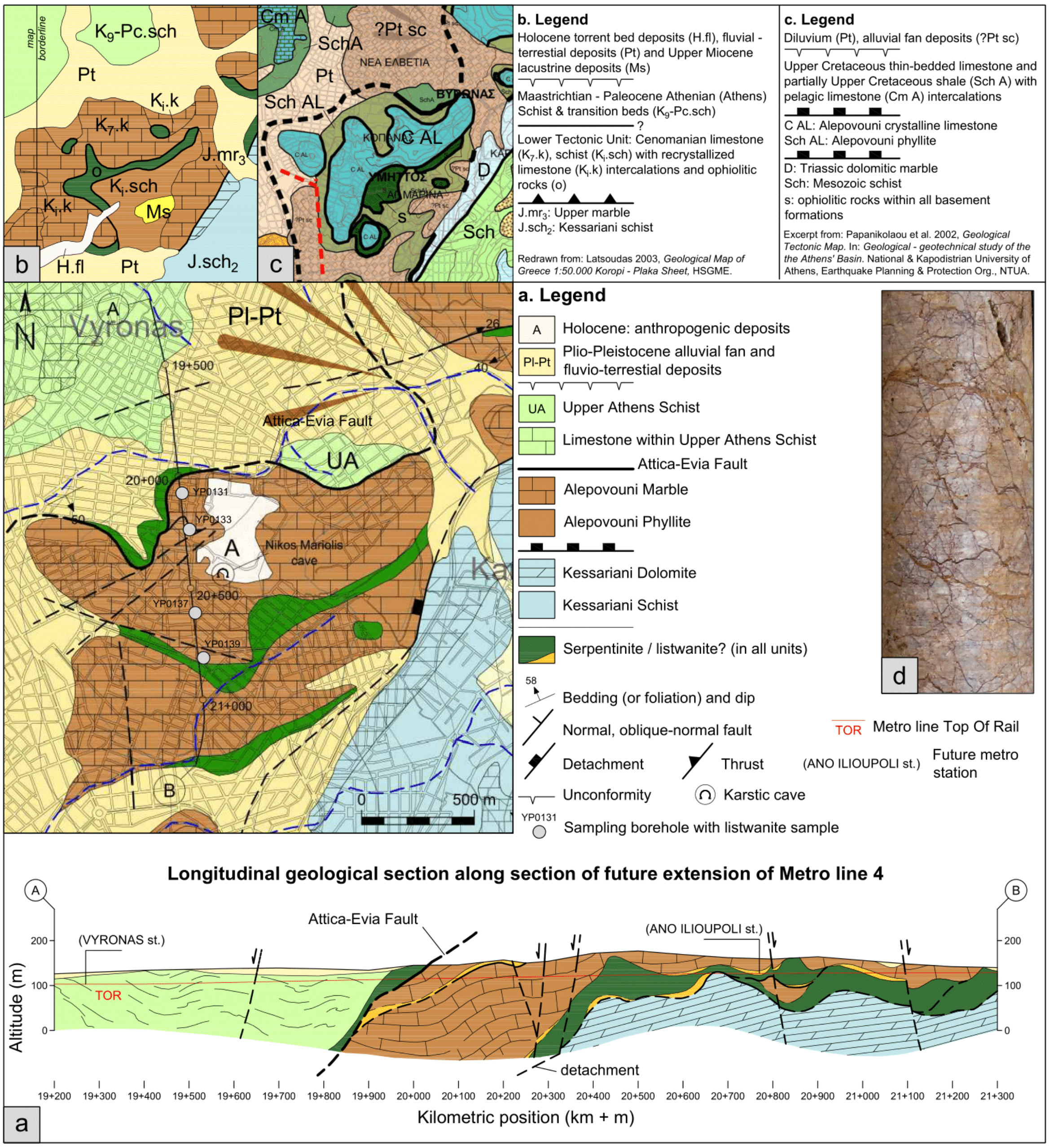


Fig. 9: a) Excerpt from the Geological Map of AMA at Vyronas and Ano Ilioupoli districts, based on "Geological map view - section 'Evangelismos - Vyronas - Ilioupoli' from K.P. 17+300 to K.P. 21+289" (dwg No 4G00PW180S102B), issued by "EDAFOMICHANIKI S.A. - ISTRIA GENERAL CONSULTANTS - ANESTIS PANAGOPOULOS" (2017). Longitudinal geological section A–B is based on "Geological and hydrogeological longitudinal section - section 'Evangelismos - Vyronas - Ilioupoli' from K.P. 17+300 to K.P. 21+289" (dwg No 4G00PW180S403B), issued by "EDAFOMICHANIKI S.A. - ISTRIA GENERAL CONSULTANTS - ANESTIS PANAGOPOULOS" (2017) (b) and (c) show the excerpts from HSGME and Papanikolaou et al. (2002) geological maps respectively, of the same area, for comparison. Scale of (b) and (c) maps is half the scale of (a) map d) Core of pink, fractured, massive, fine grained marble, Alepovouni Marble, Vyronas district.

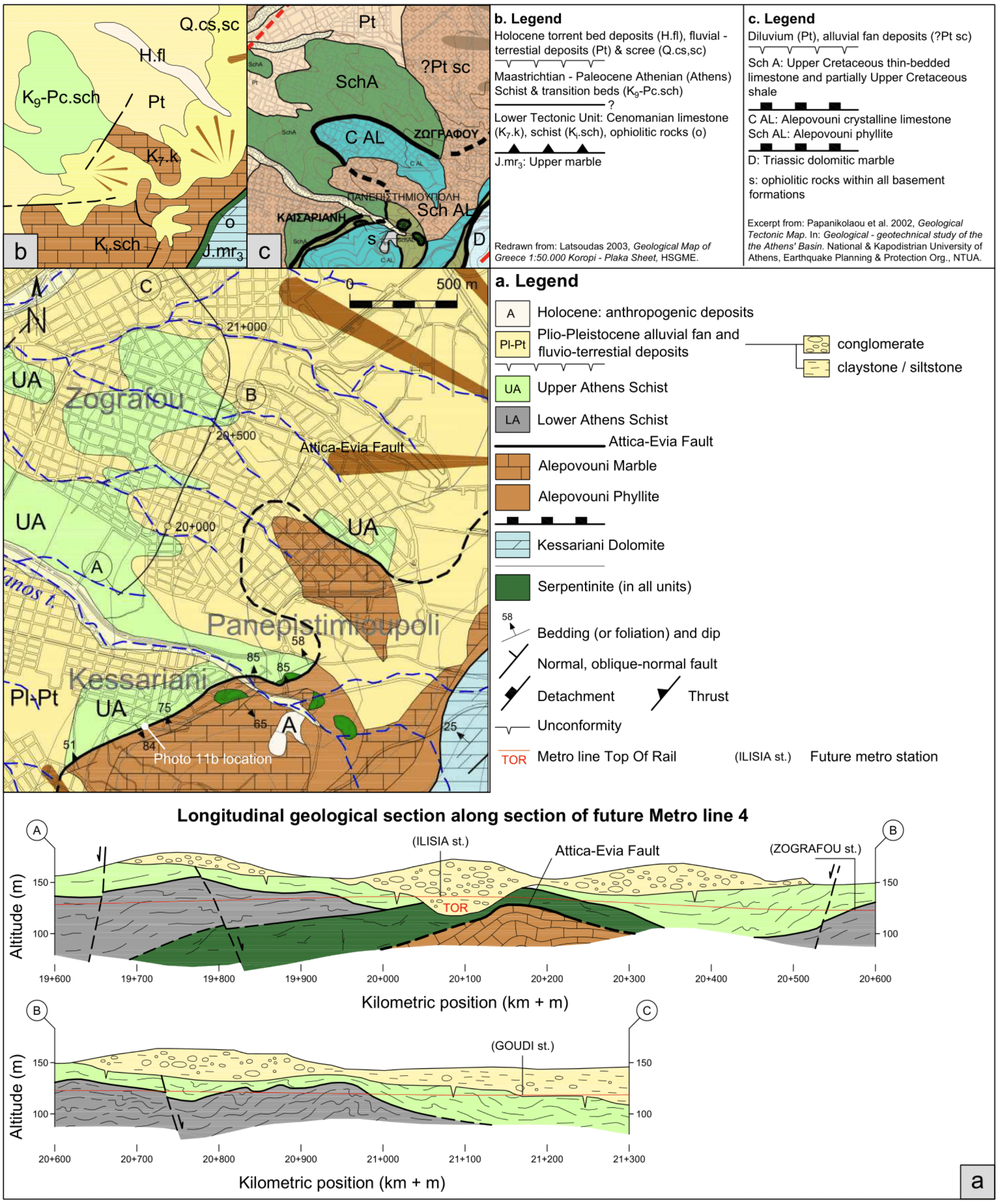


Fig. 10: a) Excerpt from the Geological Map of AMA at Zografou district and Panepistimioupoli area. Longitudinal geological section A–B–C is based on "Geotechnical longitudinal section, location line 4" (dwg No 4GE0EN180R410A), issued by "EDAFOMICHANIKI S.A. - GEOTECHNICAL INVESTIGATIONS S.A. - ANESTIS PANAGOPOULOS - HARA ALEXIADOU" (2009) (b) and (c) show the excerpts from HSGME and Papanikolaou et al. (2002) geological maps respectively, of the same area, for comparison. Scale of (b) and (c) maps is half the scale of (a) map.

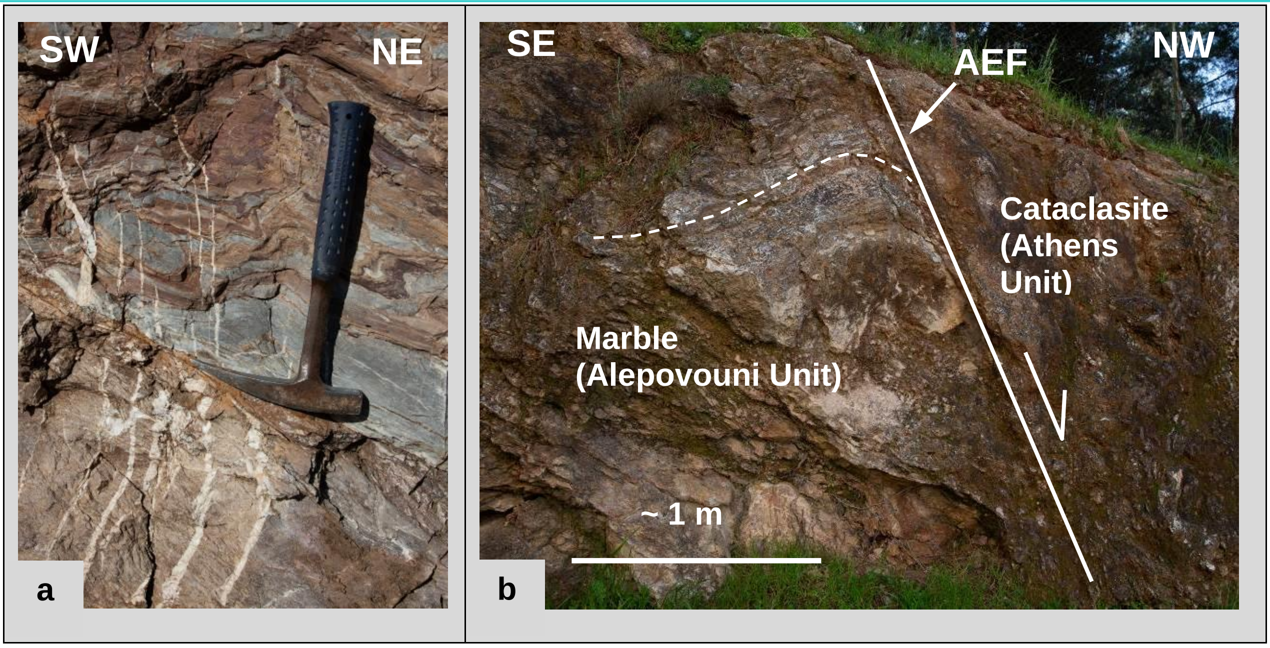


Fig. 11: Characteristic photos of Alepovouni Unit and AEF. a) Foliation parallel, top-SW, thrust, within plastically folded, thin bedded grey marble and reddish-brown calcareous schist alternations of Alepovouni Marble. Sense of shear derives from displacement of a set of centimetre-thick quartz veins. Note the asymmetry of s-shaped plastic folds, at the right and left of geologic hammer, indicating the same, top-SW, sense of shear. Northwest slope of Vyronas municipal stadium. b) Outcrop of the AEF (dip direction: 304/65). Note the drag fold of marble foliation (white dashed line), indicating a normal relative displacement of the fault and the thick cataclasite (~ 2 m) formed at the hanging wall phyllite of the Athens Unit. Road cut at Dervenakion and Kasamba strs., Kessariani.

Fig. 12: Mesoscopic characteristics of ultrabasic rocks. a) Serpentinite core with talc-rich shears and dense, thin calcite veins. Karavas hill area (b) and (c) Rusty orange-brown, massive listwanite (?) cores. Note the small scale karstic joint and the extremely thin veins in sample (b) and the calcite crusts on sub-horizontal karstic features in sample (c). Both cores derive from Vyronas district d) Tectonic contact (solid white line) of serpentinite with underlain Upper Cretaceous limestone, as exposed on excavation face from building pit of Maniatika station, Karavas hill. The limestone exhibits alteration (yellow, orange colours) and intense karstification. Serpentinite is highly sheared, completely altered (note the striking green and orange colours) into clayey soil (note the marks from excavating machinery on excavation face) and alternated with thin, crimson mudstone.

At the western foothills of Hymettus Mt., on top of the Athens and Alepovouni Units, Plio-Pleistocene alluvial fans descend, consisting of well-cemented conglomerate with claystone intercalations. Four of these alluvial fans are crosscut by the future Metro Line 4 at Zografou district, at an area where they were not previously mapped, thus slightly modifying the geological map of the area (see maps and geological longitudinal section of Fig. 10).

4.6. Ultra-basic rocks

As already discussed in sections 4.4 and 4.5, along the tectonic contact of the Athens Unit with the underlain formations of Pelagonian Upper Cretaceous limestone to the west and Alepovouni Unit to the east, bodies of ultrabasic rocks occur, mainly consisting of serpentinite. Equivalent ultrabasic rocks have also been described along the contact of Alepovouni Unit with the underlying Kessariani dolomitic marble of the Basal Unit of ACC (section 4.5). Almost all serpentinite cores from sampling boreholes are highly deformed and altered –in some cases, completely weathered to clay, see Fig. 12d and exhibit an anastomosed, talc-rich slickenfibre veins and a dense network of thin calcite veins (Fig. 12a). In Karavas hill area (Fig. 8), serpentinite is locally accompanied by thin, irregular beds of dark crimson mudstone (Fig. 12d).

At the tectonic contacts of serpentinite with carbonate rocks, especially at the eastern border of Athens Basin (Fig. 9), serpentinite develops a few meters thick rusty orange-brown rock, the mineral composition of which (almost complete metasomatism of serpentine to carbonates and/or quartz, Fig. 13) were interpreted as alterations to listwanite (Figs 12b and c). Besides mineral composition, another argument for this assumption is that this metasomatism of serpentinite is directly related to the tectonic contacts of the ultrabasic rocks with the neighbour carbonate rocks. This relationship is apparent at the geological profile of Fig. 9, and is in full agreement with the relevant literature (Hansen et al., 2004; Tsikouras et al., 2006 and references therein). Besides, all boreholes that penetrate the base of AS –the lowest formation of Athens Unit–, have revealed serpentinite underneath. Since the contact of the AS with the underlying serpentinite is not always tectonic, it is estimated that the bedrock of the Athens Unit is the Ultrabasic Rocks, and thus it can be suggested that Athens Unit was originally deposited onto oceanic or continental-oceanic transition crust.

<table>
<tr><th rowspan="2">Borehole</th><th colspan="2">Sample</th><th rowspan="2">Type of listwanite (?)</th><th rowspan="2">cc</th><th rowspan="2">dol</th><th rowspan="2">ms</th><th rowspan="2">qz</th><th rowspan="2">serp</th><th rowspan="2">tc</th><th rowspan="2">opaque</th><th rowspan="2">Minor minerals</th></tr>
<tr><th>No</th><th>Depth (m)</th></tr>
<tr><td rowspan="2">YP0133</td><td>Δ1</td><td>2,2-2,4</td><td rowspan="8">Carbonate-rich</td><td>10%</td><td>55%</td><td>–</td><td>25%</td><td>–</td><td>–</td><td>10%</td><td>Fe-oxides</td></tr>
<tr><td>Δ5</td><td>5,5-5,6</td><td>5%</td><td>80%</td><td>–</td><td>10%</td><td>3%</td><td>–</td><td>2%</td><td>Fe-oxides</td></tr>
<tr><td rowspan="2">YP0137</td><td>Δ27</td><td>41,8-41,9</td><td>80%</td><td>–</td><td>–</td><td>15%</td><td>–</td><td>–</td><td>5%</td><td>Fe-oxides</td></tr>
<tr><td>Δ35</td><td>49,7-49,9</td><td>95%</td><td>–</td><td>–</td><td>–</td><td>2%</td><td>–</td><td>3%</td><td>Fe-oxides</td></tr>
<tr><td>YP0139</td><td>Δ22</td><td>34,2-34,3</td><td>65%</td><td>5%</td><td>–</td><td>17%</td><td>10%</td><td>–</td><td>3%</td><td>Fe-oxides</td></tr>
<tr><td rowspan="4">YP0131</td><td>Δ26</td><td>28,4-28,5</td><td colspan="3">60%</td><td>23%</td><td>10%</td><td>5%</td><td>2%</td><td>Fe-oxides, chl</td></tr>
<tr><td>Δ27</td><td>32,0-32,1</td><td colspan="3">55%</td><td>10%</td><td>30%</td><td>5%</td><td>–</td><td>Fe-oxides, chl</td></tr>
<tr><td>Δ28</td><td>33,0-33,1</td><td colspan="3">55%</td><td>25%</td><td>15%</td><td>5%</td><td>?</td><td>Fe-oxides, chl</td></tr>
<tr><td>Δ29</td><td>36,0-36,1</td><td>Silica-rich</td><td>10%</td><td>15%</td><td>–</td><td>65%</td><td>7%</td><td>3%</td><td>–</td><td>Fe-oxides, chl</td></tr>
</table>

Fig. 13: Mineral composition of listwanite (?) samples from boreholes. Abbreviations: cc: calcite, chl: chlorite, dol: dolomite, ms: magnesite, qz: quartz, serp: serpentine, tc: talc. Borehole locations are shown on Fig. 9. Note that the serpentine is almost completely replaced by either carbonate minerals (carbonate-rich listwanite (?)) or quartz (quartz-rich listwanite (?)). Data from "Geological study - Engineering geological report - Line 4, section 'Evangelismos - Vyronas - Ilioupoli' (Ch. 17+300 - Ch. 21+289)" (report No 4G00PW180S923B), issued by "EDAFOMICHANIKI S.A. - ISTRIA GENERAL CONSULTANTS - ANESTIS PANAGOPOULOS" (2017).

4.7. Neogene lacustrine deposits

Lacustrine marly deposits were encountered during the construction of several projects of Athens Metro, the most distinctive cases being the extension of Metro Line 2 towards Anthoupoli (Figs 2 and 14) and the extension of Metro Line 3 towards Ag. Varvara (Figs 2 and 15). The ground investigation for the planned extension of Athens Metro line 2 at Anthoupoli area, incorporated a large number of boreholes spread throughout the area (Fig. 2) and reaching depths sometimes exceeding 100 m –which is more than double the depth of ordinary sampling boreholes for other Athens Metro projects– as well as other geological and geophysical investigation techniques. The goal was to design the extension towards Anthoupoli avoiding the underground lignite mining area (for details on lignite mining see Voreadis (1940); Trikkalinos and Mousoulos (1949); De Pian (1950) and Rozos et al. (1999)). Based on data from all the above-mentioned boreholes, the stratigraphy of the area is well known and the geological map and geological sections A–B (across the basin) and C–D (along a section of the planned metro extension to Ilion) have been drawn (Fig. 14).

Due to the widespread underground data, it was possible to draw more accurately the extent of Peristeri-Anthoupoli lacustrine basin at the geological map (Fig. 14). The stratigraphic column of the area consists –from bottom to top– of a lower formation, over 100 m thick, of bluish-grey, locally laminated, siltstone (Fig. 14d) and sandy siltstone with sand and lignite intercalations and a 40 m thick, upper formation consisting of marl and calcareous siltstone alternations with marly limestone intercalations lenses (see geological profile of Fig. 14). Locally, within the upper marly formation, coarse-grained, probably deltaic deposits can be detected.

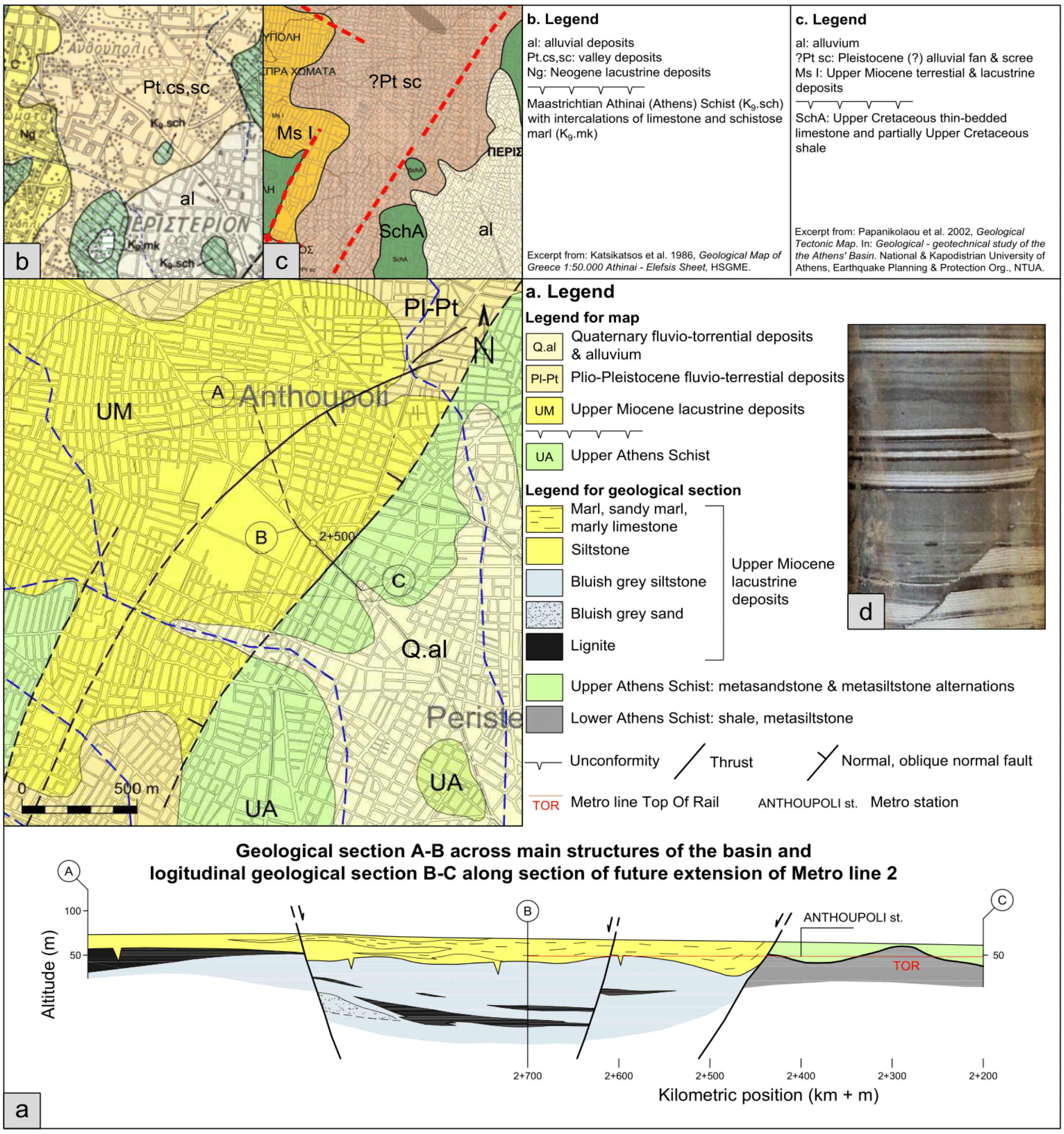


Fig. 14: a) Excerpt from the Geological Map of AMA at Anthoupoli district. Longitudinal geological section B–C is based on "Geological sections" (dwg No 2G00PW180S301B), issued by "N. LOUKATOS & ASSOCIATES S.A. - STYLIANOS MAVROGEORGIS" (2019) (b) and (c) show the excerpts from HSGME and Papanikolaou et al. (2002) geological maps respectively, of the same area, for comparison. Scale of (b) and (c) maps is half the scale of (a) map d) Core of grey, laminated, siltstone with syn-sedimentary compaction normal faults (Upper Miocene, lower formation) from Anthoupoli area.

Toward the SE, the basin’s margin is defined by a fault running approximately along the Thivon str. As resulted from the excavation of ‘Anthoupoli’ station, this marginal fault is NE–SW trending and NW-dipping, with the marl’s bedding at the hanging wall dipping toward NW, almost parallel to the fault surface (Fig. 14, geological profile B–C). Another NE-trending, SE-dipping normal fault could be traced from borehole data, taking into account the downthrown upper lignite horizon of the lower formation (Fig. 14, map and geological section A–B). This fault is conjugate to the basin’s marginal fault. The case of extension of Metro Line 3 ‘*Egaleo – Chaidari*’ is indicative of underground tunnelling with conventional mechanical means across the southern tip of the lacustrine basin, underneath the Iera Odos. The basin at this area exhibits a width of 700 m (Fig. 15, geological section A–B). The facies of the western basin’s border consist of reddish-green clayey breccia with red Fe-infiltrations. The stratigraphy at this section of the basin is similar to Peristeri and Anthoupoli areas: The lower formation consists of grey siltstone with sparse, thin lignite intercalations at deeper levels and the upper formation consists of marl, marly limestone and siltstone alternations.

As shown at geological section A–B of Fig. 15, the basin at Ag. Varvara area is an asymmetric half-graben created by a NE-SW trending and SE-dipping, syn-depositional, normal or oblique-normal fault. Reddish-green clayey breccia along the marginal fault is probably related to the fault’s colluvial deposits. Sediment accumulation at the base of the fault shows that the marginal fault’s displacement is probably larger than 100 m, so a considerable fault length should be accounted for. It is noted that 3 km to the northeast of this fault, at the centre of the lacustrine basin at Anthoupoli district, the conjugate fault of Thivon Str. fault is located. This fault exhibits the same geometrical characteristics and kinematics with the Ag. Varvara marginal fault (see geological profile A–B of Fig. 14). The latter also displays a similar displacement of approximately 50-70 m, as deduced from the lignite bed displacement across the fault. From the above geometrical and kinematic characteristics, it can be assumed that the lacustrine basin’s marginal fault at Ag. Varvara district extends to the northeast and probably coincides with the fault at the middle of the basin at Anthoupoli area (see supplementary map).

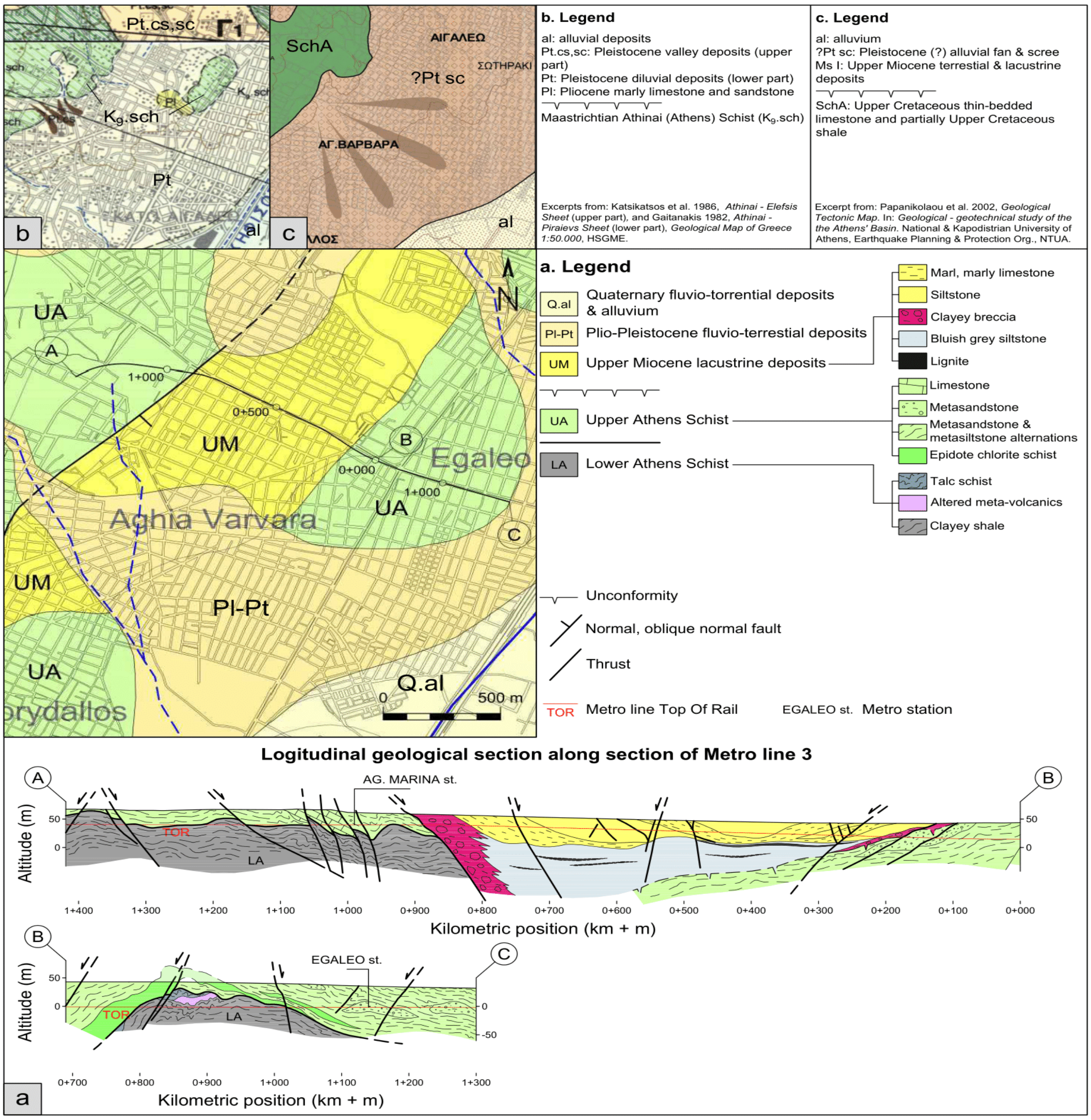


Fig. 15: a) Excerpt from the Geological Map of AMA at Ag. Varvara and Egaleo districts. Longitudinal geological sections A–B based on "Monitoring final report - Longitudinal geological section - Data of encountered geological & engineering geological conditions - As built" (dwg No 3GW0CW415C1511), issued by "J/V ALPINE BAU GmbH - TERNA S.A. - PANTECHNIKI S.A. - POWELL ELECTRICAL SYSTEMS Inc" (2012) and B-C based on "Section 4, Egaleo station, section 3 K.P. 1+194 - 1+314,50 - Geological section - Geological mapping at TOR level" (dwg No 3TW5CW180A401A), issued by "PANTECHNIKI S.A." (2005) (b) and (c) show the excerpts from HSGME and Papanikolaou et al. (2002) geological maps respectively, of the same area, for comparison. Scale of (b) and (c) maps is half the scale of (a) map.

The deformation of Upper Miocene deposits is characterized by strike-slip, oblique-slip and normal faulting, which has locally caused significant bedding offset and tilting (geological profile A–B of Fig. 15). Bed rotations and strike-parallel displacements were also detected during lignite mining at Peristeri and Anthoupoli areas (Voreadis, 1940; Trikkalinos and Mousoulos, 1949; De Pian, 1950). Horizontal and oblique striations were observed frequently on slickensided minor fault surfaces, discovered in borehole cores from Upper Miocene sediments. Since the tunnel excavation is perpendicular to the southern margin of the Upper Miocene lacustrine basin, at Ag. Varvara area, the accurate description of the stratigraphy and structure and the revision of the geological map at this area was possible (Fig. 15a).

5. CONCLUSIONS

An extensive amount of geological data, regarding the AMA, were obtained from the ground investigation campaigns for the construction of the Athens Metro. With the use of these data, the Geological Map of AMA was compiled. Furthermore, this paper proposes an updated and slightly revised stratigraphy for the Athens Unit, which corresponds to the basement of the AMA. The Athens Unit, in AMA, consists of four formations, namely (from bottom to top) the Lower Athens Schist, the Upper Athens Schist, the Athens Sandstone-Marl Series and on top, the Crest Limestone. The subdivision of the main formation, the Athens Schist, into two sub-formations is primarily based on lithological and engineering geological criteria. Namely Lower Athens Schist's lithology is more confined and it consists of alternations of dark grey to black metasiltstone, metasandstone and clayey shale with sparse intercalations of limestone. The Upper Athens Schist mainly consists of alternations of metasandstone and metasiltstone but it is very heterogeneous and locally many other lithological types prevail, such as limestone and calcareous phyllite, sericite or muscovite schist, chlorite-epidote schist, etc.

From sampling boreholes' data, both at the western and eastern margin of the Athens Basin, it is evident that the direct basement of the Athens Unit is ultra-basic rocks, mostly serpentinite and, given its lithology and structure, it is suggested that the Athens Unit was probably originally deposited onto an oceanic or continental-oceanic transition crust. Serpentinite is also found underneath Alepovouni Marble, where partial metasomatism altered it to listwanite (?).

Stratigraphic data were also obtained from the numerous sampling boreholes and tunnel excavations across Upper Miocene lacustrine deposits. Two formations were distinguished in these sediments: The lower >100 m thick grey siltstone with lignite intercalations and the upper, 40 m thick, marly formation (Figs 14 and 15).

NE-SW trending faults, parallel to the Athens Basin and the AEF trend, seem to be important for the formation of the Upper Miocene lacustrine basins. At Ag. Varvara district, the NE-SW trending and SE-dipping, syn-depositional normal / oblique-normal, marginal fault, with probably over 100 m displacement, forms a half-graben at the southern end of the basin (Fig. 15). This marginal fault probably extends up to Anthoupoli district, where a similar fault was detected –in this case in the middle of the basin–, at a distance of 3 km to the northeast, along the direction of the marginal fault (Fig. 14). Sense of movement data for the NE-SW trending faults are not available, nevertheless recent research has revealed that such direction faults within analogous Miocene sediments show a dextral strike-slip kinematic character (Faucher et al., 2021).

The ground investigation geological data were spread in a large section of the AMA, where the Athens Metro is being constructed. These data were sufficient for the compilation of the Geological Map of AMA, as they revealed major and minor differences in the geology that was perceived for certain areas in the relevant HSGME geological map sheet and the Geological and Tectonic map of Papanikolaou et al. (2002). These major differences are the following:

a) At Karavas hill, the revealed tectonostratigraphy was the opposite of that recorded in published maps: limestone at Karavas hill is the lower formation, correlated to the Upper Cretaceous limestone of Pelagonian, whereas the serpentinite and Athens Schist are tectonically on top of it (Fig. 8). Summarizing, the Karavas hill limestone forms a tectonic window through Athens Schist and serpentinite and not a klippen on top of them.

b) Even though the Lower Athens Schist has been found at depths 20-40 m at almost all Metro Lines, it only crops out to the north and south of Acropolis area (Fig. 5).

c) At Zografou district, four alluvial fan lobs were revealed at an area where Athens Schist was depicted on published maps (Fig. 10).

d) Three limestone outcrops within Athens Sandstone-Marl Series were revealed along Veikou Str. (Fig. 7).

e) At Peristeri and Ag. Varvara districts, the southern margin of the Upper Miocene lacustrine basin was revealed and mapped (Figs 14 and 15).

The compilation of the Geological Map of AMA also posed geological concerns, far beyond the scope of Athens Metro ground investigation but relative to editing a correct geological map: Firstly, there are no low-temperature geochronological data (apatite fission-track) for Athens Unit, in order to confine its geodynamic evolution. Secondly the exact location, kinematics and age of the AEF, the fundamental structural feature of Attica peninsula, juxtaposing Pelagonian to ACC, is still obscured. This fault is found from sampling borehole data along the route of Line 4, at two locations in Vyronas and Zografou districts (Figs 9 and 10).

6. ACKNOWLEDGMENTS

The extensive ground investigation for the construction of the Athens Metro, which is taking place since 1991, has employed so far, a lot of scientists of various disciplines: geologists, engineering geologists, geotechnical engineers, mining engineers, civil engineers etc., together with numerous specialized personnel, originating from all companies that have participated in the construction of Athens Metro –design companies, construction companies, from ATTIKO METRO S.A. itself and its consultants. Their contribution in the collection and interpretation of ground investigations' data, as well as in the high quality of these data, is truly invaluable. The number of these people is so large that makes it impossible to provide a complete list of their names. We are grateful to all the above-mentioned personnel, without the contribution of which, this paper would not be feasible and to ATTIKO METRO S.A. for allowing and encouraging the publication of this paper. Thanks are also extended to our colleague D. Panagiotakopoulos for providing technical solutions in preparing the final maps, Prof. Ioannis Koukouvelas for his valuable comments, which greatly improved an early version of the paper, as well as the reviewers for their insightful suggestions.

This paper represents the opinions of the authors, and it is not meant to represent the position or opinions of ATTIKO METRO S.A.

7. REFERENCES

Andronopoulos, B., Koukis, G., 1976. Engineering geology study in the Acropolis area – Athens (with 7 photos and 8 maps). Hellenic Survey of Geology and Mining Exploration, Engineering Geology Investigation No 1, 1–49.

Auboin, J., 1959. Contribution a l'étude géologique de la Grèce septentrionale. Les confins de l'Epire de la Thessalie. *Annales Géologiques des Pays Helléniques*, 10, p. 525.

Avigad, D., Garfunkel, Z., 1991. Uplift and exhumation of high-pressure metamorphic terrains: the example of the Cycladic blueschist belt (Aegean Sea). *Tectonophysics*, 188, 357–372. https://doi.org/10.1016/0040-1951(91)90464-4

Baziotis, I., 2008. Petrology and geochemistry of the metamorphic formations of Attica. Ph.D. Thesis, National Technical University of Athens, Athens (in Greek).

Baziotis, I., Proyer, A., Mposkos, E., 2009. High-pressure / low temperature metamorphism of metabasites in Lavrion area (SE Attica, Greece): Implications for the preservation of peak metamorphic assemblages in blueschists and greenschists. *European Journal of Mineralogy*, 21, 133–148. https://doi.org/10.1127/0935-1221/2008/0020-1853

Baziotis, I., Mposkos, E., 2011. Origin of metabasites from upper tectonic unit of the Lavrion area (SE Attica, Greece): geochemical implications for dual origin with distinct provenance of blueschist and greenschist's protoliths. *Lithos*, 126, 161–173. https://doi.org/10.1016/j.lithos.2011.07.014.

Baziotis, I., Proyer, A., Mposkos, E., Windley, B., Boukouvala I., 2019. Exhumation of the high-pressure northwestern Cyclades, Aegean: New P-T constraints, and geodynamic evolution. *Lithos*, 324–325, 439–453. https://doi.org/10.1016/j.lithos.2018.11.027

Blake, M.C., Bonneau, M., Geyssant, J., Kienast, J.R., Lepvier, C., Maluski, H., Papanikolaou, D., 1981. A geological reconnaissance of the Cycladic blueschist belt, Greece. *Bulletin of the Geological Society of America*, 92, 247–254.

Bonneau, M., 1984. Correlation of the Hellenide nappes in the south-east Aegean and their tectonic reconstruction. In. Dixon, J.E. and Robertson, A.H.F. (Eds.), *The geological evolution of the Eastern Mediterranean*, Geological Society of London Special Publication, 17, 517–527.

Boronkay, K., Doutsos, T., 1994. Transpression and transtension within different structural layers in the central Aegean region. *Journal of Structural Geology*, 16, 1555–1573. https://doi.org/10.1016/0191-8141(94)90033-7

Bradley, K.E., 2012. The roof of the Cyclades: A structural, stratigraphic, and paleomagnetic study of Neogene extensional tectonics in Central Greece. Ph.D. Thesis, Massachusetts Institute of Technology, Cambridge, Massachusetts.

Charalambakis, S., 1951. Contribution to the knowledge of Neogene of Attica. *Annales Géologiques des Pays Helléniques*, 4, 1–156 (in Greek).

Clement, B., Guernet, C., 1971. Données nouvelles sur le Carbonifère et le Permien du Mont Beletsi en Attique (Grèce). *Bulletin de Société Géologique de France*, 7, 795–799.

Coleman, M.J., Schneider, D.A., Grasemann, B., Soukis, K., Lozios, S., Hollinetz, M.S., 2020. Lateral Termination of a Cycladic-Style Detachment System (Hymittos, Greece). *Tectonics*, 39, 1–30. https://doi.org/10.1029/2020TC006128

De Pian, A., 1950. Aperçue de la mine de Peristeri. Hellenic Survey of Geological and Mineral Exploration, Athens (in French).

Deligiannakis, G., Papanikolaou, I.D., Roberts, G., 2018. Fault specific GIS based seismic hazard maps for the Attica region, Greece. *Geomorphology*, 306, 264–282. https://doi.org/10.1016/j.geomorph.2016.12.005

Doutsos, T., Pe-Piper, G., Boronkay, K., Koukouvelas, I., 1993. Kinematics of the central Hellenides. *Tectonics*, 12, 936–953 https://doi.org/10.1029/93TC00108 .

Faucher, A., Gueydan, F., Jolivet, M., Alsaf, M., Célérier, B., 2021. Dextral strike-slip and normal faulting during middle Miocene back-arc extension and westward Anatolia extrusion in Central Greece. *Tectonics*, 40, https://doi.org/10.1029/2020TC006615 .

Flansburg, M.E., Stockli, D.F., Poulaki, E.M., Soukis, K., 2019. Tectonomagmatic and stratigraphic evolution of the Cycladic basement, Ios Island, Greece. *Tectonics*, 38, 2291–2316 https://doi.org/10.1029/2018TC005436 .

Freyberg, B., 1951. Die Pikermi fauna von tour la reine (Attika). *Annales Géologiques des Pays Helléniques*, 5(3), 7–10.

Gaitanakis, P., 1982. Geological Map of Greece 1:50.000 Athinai – Piraievs Sheet. Hellenic Survey of Geology and Mineral Exploration, Athens, Greece.

Ganas, A., Papadopoulos, G.A., Pavlides, S., 2001. The 7 September 1999 Athens 5.9 Ms earthquake: Remote sensing and digital elevation model inputs towards identifying the seismic fault. *International Journal of Remote Sensing*, 22, 191–196. https://doi.org/10.1080/014311601750038938

Ganas, A., Pavlides, S.B., Sboras, S., Valkaniotis, S., Papaioannou, S., Alexandris, G.A., Plessa, A., Papadopoulos, G.A., 2004. Active fault geometry and kinematics in Parnitha Mountain, Attica, Greece. *Journal of Structural Geology*, 26, 2103–2118 https://doi.org/10.1016/j.jsg.2004.02.015 .

Hansen, L.D., Anderson, R.G., Dipple, G.M., Nakano, K., 2004. Geological setting of listwanite (carbonated serpentinite) at Atlin, British Columbia: implications for CO_2 sequestration and lode-gold mineralization. *Geological Survey of Canada, Current Research*, 2004–A5, 12p.

Ioakim, Ch., Rondoyanni, Th., Mettos, A., 2005. The Miocene Basins of Greece (Eastern Mediterranean) from a paleoclimatic perspective. *Revue de Paléobiologie*, 24, 735–748.

Jacobshagen, V., 1986. Geologie von Griechenland. Gebrueder Borntraeger, West Berlin, p. 363.

Jolivet, L., Brun, J.P., 2010. Cenozoic geodynamic evolution of the Aegean. *International Journal of Earth Sciences*, 99, 109–138. https://doi.org/10.1007/s00531-008-0366-4.

Jolivet, L., Lecomte, Em., Huet, B., Denèle, Y., Lacombe, O., Labrousse, L., Le Pourhiet, L., Mehl, C., 2010. The North Cycladic Detachment System. *Earth and Planetary Science Letters*, 289, 87–104. https://doi.org/10.1016/j.epsl.2009.10.032

Karfakis, J., Loupasakis, C., 2006. Geotechnical characteristics of the formation of “Tourkovounia” Limestones and their influence on urban construction – City of Athens, Greece. In: *10th Congress of the International Association of Engineering Geology and the Environment (IAEG) 2006*, Paper number 794, 1–8.

Katsikatsos, G., 1976. La structure tectonique de l' Attique et de l' ile de Eubée. *Bulletin de Société Géologique de France*, 19, 75–80.

Katsikatsos, G., 2002. Geological Map of Greece 1:50.000 Kifissia Sheet. Hellenic Survey of Geology and Mineral Exploration, Athens.

Katsikatsos, G., Kounis, G., Antoniades, P., Mettos, A., Papadopoulos, P., Gakis, Ach., 1981. Geological Map of Metro Area (summary). In: Kounis, G., (1981) *Hydrogeological investigation for Athens Metro*. Hellenic Survey of Geology and Mineral Exploration, Athens.

Katsikatsos, G., Mettos, A., Vidakis, M., Dounas, A. 1986. Geological Map of Greece 1:50.000 Athinai – Elefsis Sheet. Hellenic Survey of Geology and Mineral Exploration, Athens.

Kober, L., 1929a. Beiträge zur Geologie von Attika. *Sitz. Ber. Ak. Wsch., math-natw. Kl., Wien* 138/7, 299–327.

Kober, L., 1929b. Neue geologische Forschungen in Attika. *Forsch. & Fortschr.*, 5, 271.

Konstantinou, K., Mouslopoulou, V., Saltogianni, V., 2020. Seismicity and Active Faulting around the Metropolitan Area of Athens, Greece. *Bulletin of the Seismological Society of America*, 110, 1924–1941 https://doi.org/10.1785/0120200039 .

Kounis, G., 1981. Hydrogeological investigation for Athens Metro. Hellenic Survey of Geology and Mineral Exploration, Athens.

Krohe, A., Mposkos, E., Diamantopoulos, A., Kaouras, G., 2010. Formation of basins and mountain ranges in Attica (Greece): The role of Miocene to Recent low-angle normal detachment faults. *Earth Science Reviews*, 98, 81–104. https://doi.org/10.1016/j.earscirev.2009.10.005

Latsoudas, Ch., 2003. Geological Map of Greece 1:50.000 Koropi – Plaka Sheet. Hellenic Survey of Geology and Mineral Exploration, Athens.

Lepsius, R., 1893. Geologie von Attika. Ein breitag zur lehre von metamorphismus der gesteine (mit einem titelbild, 29 profilen im text, 8 tafeln und einem atlas von 9 geologischen karten). Dietrich Reimer, Berlin (in German).

Liati, A., Skarpelis, N., Fanning, C.M., 2013. Late Permian – Early Triassic igneous activity in the Attic Cycladic Belt (Attica): New geochronological data and geodynamic implications. *Tectonophysics*, 595–596, 140–174. https://doi.org/10.1016/j.tecto.2012.05.009

Louis, I.F., Raftopoulos, D., Goulis, I., Lois, F.I., 2002. Geophysical imaging of faults and fault zones in the urban complex of Ano Liosia Neogene basin, Greece: synthetic simulation approach and field investigations. In: *International Conference on Earth Sciences and Electronics – 2002 (ICESE-2002)*, 269–285.

Lozios, S., 1993. Tectonic analysis of the metamorphic formations of northeastern Attica. Ph.D. Thesis, National and Kapodistrian University of Athens, Athens, (in Greek).

Marinos, G., Petrascheck, W.E., 1956. Lavrium. Geological and Geophysical studies, Hellenic Survey of Geology and Mineral Exploration, Athens, Greece (in Greek).

Marinos, G., Katsikatsos, G., Georgiades – Dikeoulia, E., Mirkou, R., 1971. The Athens' Schists Formation, I. Stratigraphy and Structure. *Annales Géologiques des Pays Helléniques*, 23, 183–216 (in Greek).

Marinos, G., Katsikatsos, G., Mirkou - Peripopoulou, R.M., 1974. The Athens' Schists Formation, II. Stratigraphy and Structure. *Annales Géologiques des Pays Helléniques*, 25, 439–444 (in Greek).

Papadopoulos, G.A., Drakatos, G., Papanastassiou, D., Kalogeras, I., Stavrakakis, G., 2000. Preliminary results about the catastrophic earthquake of 7 September 1999 in Athens, Greece. *Seismological Research Letters*, 71, 318–329. https://doi.org/10.1785/gssrl.71.3.318

Papadopoulos, G.A., Ganas, A., Pavlides, S., 2002. The problem of seismic potential assessment: case study of the unexpected earthquake of 7 September 1999 in Athens, Greece. *Earth Planets Space*, 54, 9–18. https://doi.org/10.1186/BF03352417

Papanikolaou, D., Lozios, S., Sideris, Ch., Kranis, Ch., Danamos, G., Skourtsos, Em., Soukis, K., Bassi, E.K., 2002. Geological Tectonic Map. In: Geological – Geotechnical study of the Athens' basin. National and Kapodistrian University of Athens, Earthquake Planning and Protection Organization, National Technical University of Athens, Athens (in Greek).

Papanikolaou, D., Lozios, S., Soukis, K., Skourtsos, Em., 2004. The geological structure of the allochthonous "Athens Schists". *Bulletin of the Geological Society of Greece*, 36, 1550–1559 (in Greek).

Papanikolaou, D., Royden, L.H., 2007. Disruption of the Hellenic arc: Late Miocene extensional detachment faults and steep Pliocene-Quaternary normal faults – Or what happened at Corinth? *Tectonics*, 26, TC5003, 1–16. https://doi.org/10.1029/2006TC002007

Papanikolaou, D., Papanikolaou, I., 2007. Geological, geomorphological and tectonic structure of NE Attica and seismic hazard implications for the northern edge of the Athens plain. *Bulletin of the Geological Society of Greece*, 40, 425–438.

Papp, A., 1947. Über die Alterrsstellung der Congerienschichten von Trachones, Piräus und Perama in der Umbenung von Athen. *Annales Géologiques des Pays Helléniques*, 4, 104–111 (in German).

Pavlides, S.B., Ganas, A., Papadopoulos, G.A., 2002. The fault that caused the Athens September 1999 Ms = 5.9 earthquake: field observations. *Natural Hazards*, 27, 61–84.

Philippon, M., Brun, J.P., Gueydan, F., 2012. Deciphering subduction from exhumation in the segmented Cycladic Blueschist Unit (Central Aegean, Greece). *Tectonophysics*, 524–525, 116–134. https://doi.org/10.1016/j.tecto.2011.12.025

Pomonis, A., 2002. The mount Parnitha (Athens) earthquake of September 7, 1999: a disaster management perspective. *Natural Hazards*, 27, 171–199.

Poulaki, E.M., Stockli, D.F., Flansburg, M.E., Soukis, K. 2019. Zircon U-Pb chronostratigraphy and provenance of the Cycladic blueschist unit and the nature of the contact with the Cycladic basement on Sikinos and Ios Islands, Greece. *Tectonics*, 38(10), 3586–3613. https://doi.org/10.1029/2018TC005403

Reischmann, T., 1998. Pre-Alpine origin of tectonic units from the metamorphic core complex of Naxos, Greece, identified by single zircon Pb/Pb dating. *Bulletin of the Geological Society of Greece*, 32, 101–111.

Ring, U., Glodny, J., Will, T., Thompson, S., 2007a. An Oligocene extrusion wedge of blueschist-facies nappes on Evia, Aegean Sea, Greece: implications for the early exhumation of high-pressure rocks. *Journal of the Geological Society*, 164, 637–652. https://doi.org/10.1144/0016-76492006-041

Ring, U., Will, Th., Glodny, J., Kumerics, Ch., Gessner, K., Thomson, S., Güngör, T., Monié, P., Okrusch, M., Drüppel, K., 2007b. Early exhumation of high-pressure rocks in extrusion wedges: Cycladic blueschist unit in the eastern Aegean, Greece, and Turkey. *Tectonics*, 26, doi: 10.1029/2005TC001872, 1–23.

Rozos, D., Vakondios, I., Kynigilaki, M., Argyris, Ch., 1999. Geological investigation of surface subsidence at Anthoupoli – Peristeri. Hellenic Survey of Geology and Mineral Exploration, Athens, Greece (in Greek).

Scheffer, C., Vanderhaeghe, O., Lanari, P., Tarantola, A., Ponthus, L., Photiades, A., France, L., 2016. Syn- to post-orogenic exhumation of metamorphic nappes: Structure and thermobarometry of the western Attic-Cycladic metamorphic complex (Lavrion, Greece). *Journal of Geodynamics*, 96, 174–193. https://doi.org/10.1016/j.jog.2015.08.005

Schmid, S.M., Fügenschuh, B., Kounov, A., Maţenco, L., Nievergelt, P., Oberhänsli, R., Pleuger, J., Schefer, S., Schuster, R., Tomljenović, B., Ustaszowski, K., van Hinsbergen, D.J.J., 2020. Tectonic units of the Alpine collision zone between Eastern Alps and Western Turkey. *Gondwana Research*, 78, 308–374. https://doi.org/10.1016/j.gr.2019.07.005

Shaked, Y., Avigad, D., Garfunkel, Z., 2000. Alpine high-pressure metamorphism at the Almyropotamos window (southern Evia, Greece). *Geological Magazine*, 137, 367–380. https://doi.org/10.1017/S001675680000426X

Spanos, D., 2012. Geodynamic evolution of Attica. Ph.D. Thesis, University of Patras, Patras (in Greek).

Spanos, D., Xypolias, P., Koukouvelas, I., 2015. Vorticity analysis in calcite tectonites: An example from the Attico-Cycladic massif (Attica, Greece). *Journal of Structural Geology*, 80, 120–132. https://doi.org/10.1016/j.jsg.2015.08.014.

Trikkalinos, I., Moussoulos, A., 1949. Lignite mines of Peristeri, stratigraphical and tectonic study of the lignite bearing deposit. Hellenic Survey of Geology and Mineral Exploration, Athens, Greece (in Greek).

Tsikouras, B., Karipi, S., Grammatikopoulos, T.A., Hatzipanagiotou, K., 2006. Listwaenite evolution in the ophiolite mélange of Iti Mountain (continental Central Greece). *European Journal of Mineralogy*, 18, 243–255. *Chem. Erde*, 53, 315–329. https://doi.org/10.1127/0935-1221/2006/0018-0243

Tsodoulos, I.M., Koukouvelas, I.K., Pavlides, S., 2008. Tectonic geomorphology of the easternmost extension of the Gulf of Corinth (Beotia, Central Greece). *Tectonophysics*, 453, 211–232, doi: 10.1016/j.tecto.2007.06.015.

van Hinsbergen, D.J.J., Schmid, S.M., 2012. Map view restoration of Aegean – West Anatolian accretion and extension since the Eocene. *Tectonics*, 31, TC5005, 1–40 https://doi.org/10.1029/2012TC003132 .

Voreadis, Ch., 1940. The lignite mines of the 'Attica Lignite Mines S.A.' at the Athens Basin. Ministry of National Economy, Geological Service, Athens, Greece (in Greek).

Xypolias, P., Kokkalas, S., Skourlis, K., 2003. Upward extrusion and subsequent transpression as a possible mechanism for the exhumation of HP/LT rocks in Evia Island (Aegean Sea, Greece). *Journal of Geodynamics*, 35, 303–332. https://doi.org/10.1016/S0264-3707(02)00131-X

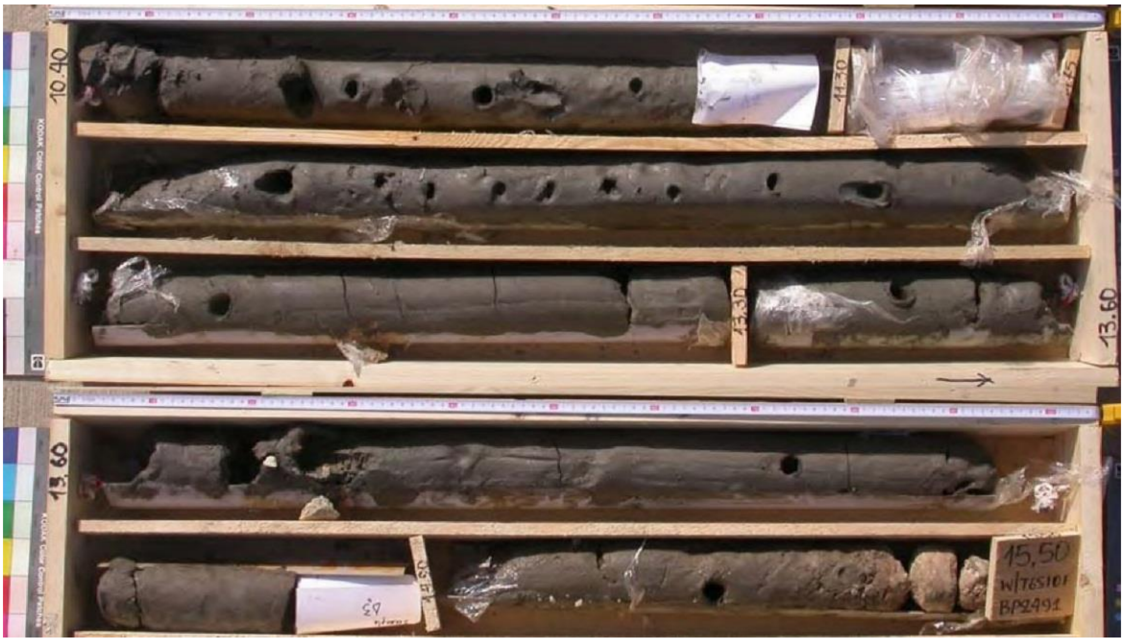
Supplementary material

Appendix A: Photographic documentation of geological formations.

Geological formation: Alluvium

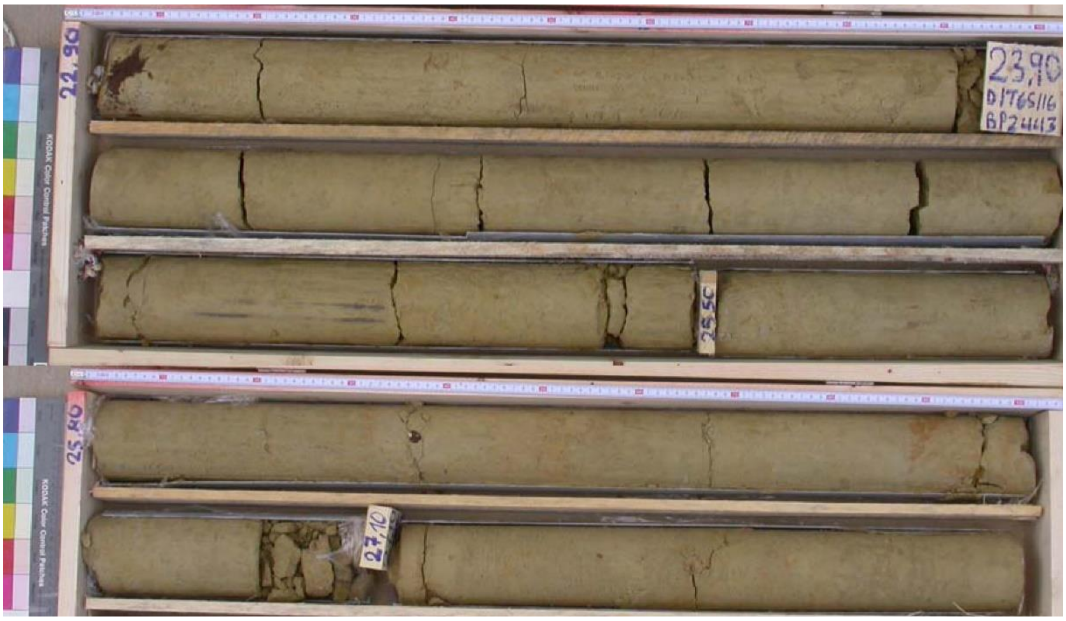
A.1 Conglomerate of Kifissos River bed. Double-track tunnel (10 m dia.) excavation face – Line 3, “Keramikos” - “Eleonas” interstation.


Geological formation: Marsh deposits

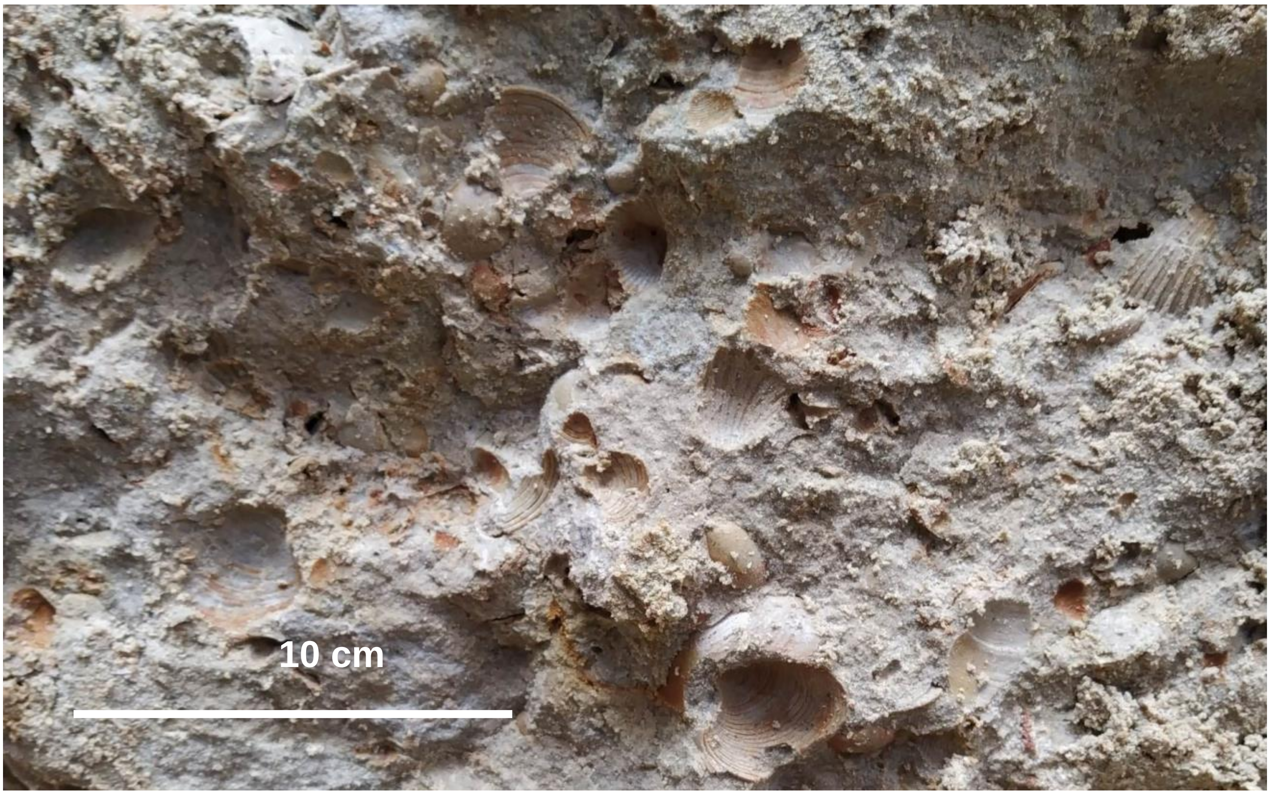
A.2 Soft silt and clay at ‘Alipedon’. Borehole: BP2491 – Depth: 10,40 - 15,60 m – Pireaus, Mikras Asias and Lambraki str. (from ground investigation for an extension of line 3 not constructed due to re-routing).


Geological formation: Coastal deposits

A.3 Silty sand and sandy silt.
Borehole: BP2443 – Depth: 22,90 - 27,70 m – Line 3, “Piraeus” station.



A.4 Close-up view of fossiliferous calcareous sandstone.
Top-down, open excavation – Line 3, “Piraeus” station.



Geological formations: Fluvio-terrestrial deposits and alluvial fan deposits

A.5 Fluvio-terrestrial deposits: red claystone and conglomerates.
Access tunnel (~ 3 m dia.) excavation face – Line 3, "Aghia Paraskevi" station.

A.6 Alluvial fan deposits: red claystone with conglomerate intercalations.
Borehole: NP2683 – Depth: 2,80 - 8,50 m – Line 4, future interstation "Goudi" - "Katehaki"

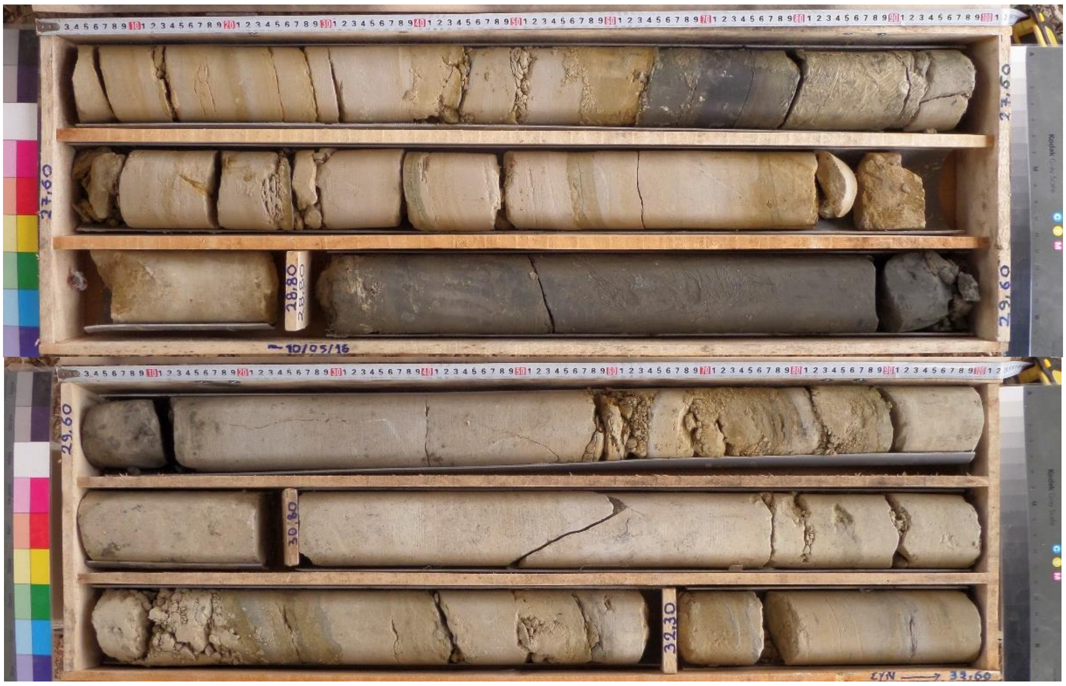
Geological formation: Piraeus Marl

A.7 Calcareous claystone and siltstone alternations.
Triple-track tunnel (~ 16 m dia.), left side excavation face – Line 3, Deligianni shaft to "Dimotiko Theatro" station.

A.8 Left: Roman era aqueduct found at "Dimotiko Theatro" station of line 3.
A.9 Right: Coastal cliff at Kastella hill area in Piraeus.

Geological formation: Lacustrine deposits

A.10 Light yellow marl with grey siltstone intercalations.
Borehole: OP0017 – Depth: 26,60 - 32,60 m – Line 2, future “Anthoupoli” - “Ilion” interstation.



A.11 Light yellow marl with grey siltstone intercalations.
Double-track tunnel (~ 10 m dia.) Open Face Shield (OFS) excavation face – Line 2, “Peristeri” - “Anthoupoli” interstation.

Geological formation: Crest Limestone

A.12 Massive, karstic, locally intraclastic (17,50 - 17,85 m) limestone.
Borehole: GP2565 – Depth: 11,5 - 18,0 m – Line 4, future "Galatsi" - "Elikonos" interstation

Geological formation: Athens Sandstone-Marl Series

A.13 Thin-bedded, folded, marly limestone.
Borehole: GP1515 – Depth: 42,90 - 50,10 m – Line 4, future "Elikonos" - "Kypseli" interstation.

Geological formation: Upper Athens Schist

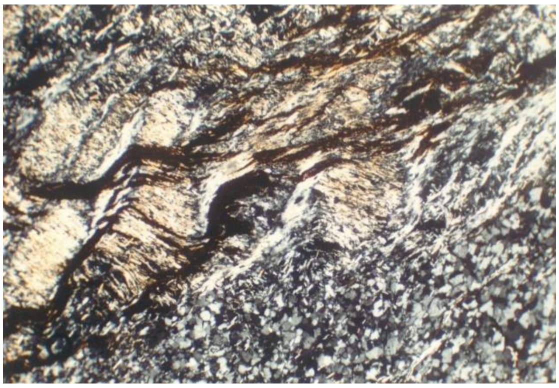
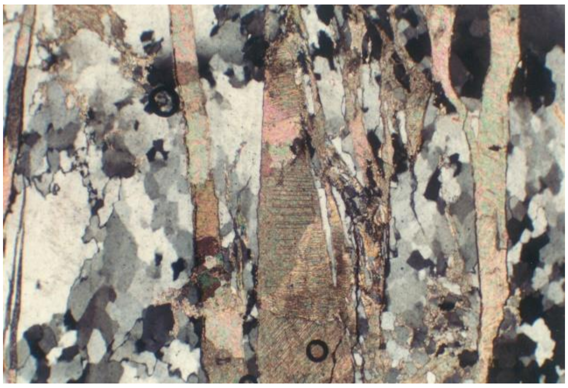
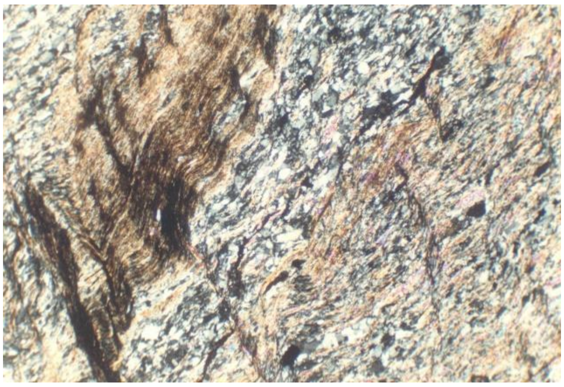
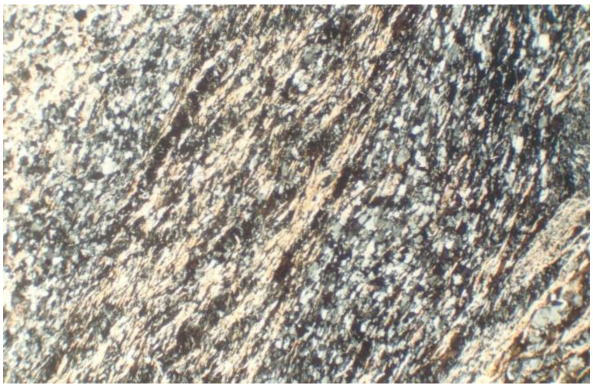
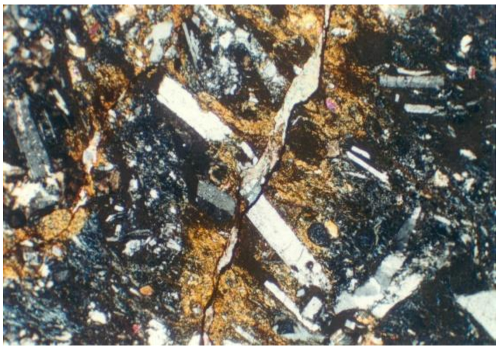
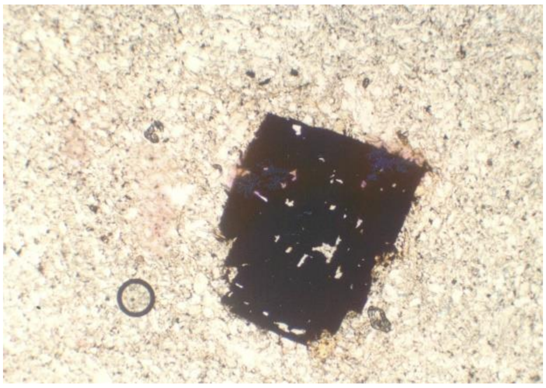
A.14 Metasiltstone with folded quartz lenses.
Double-track tunnel (~ 10 m dia.) excavation face – Line 2, "Aghios Antonios" - "Peristeri" interstation.

A.15 Slightly weathered metasandstone.
Station tunnel (~ 18 m dia.) excavation face, side drift – Line 2, "Peristeri" station.

A.16 Olive green epidote-chlorite schist.
Access tunnel (~ 6 m dia.) excavation face – Line 3, Thivon shaft, “Egaleo” - “Aghia Marina” interstation.

Geological formation: Upper Athens Schist

Microscope images (preparation of thin slices and microscopic analyses by HSGME, 1994)

A.17 Folded muscovite band on top of a quartz rich band in metasandstone. Note impregnations of oxides / hydroxides sub-parallel to foliation. “Syntagma” station. X Nicols, x 25.	A.18 Thin calcite veins crosscutting quartz lens in metasandstone. “Syntagma” station. X Nicols, x 25.
	
A.19 Quartz rich and muscovite rich alternating bands in folded metasandstone. “Syntagma” station. X Nicols, x 25.	A.20 Quartz rich and muscovite rich alternating bands in metasandstone. “Syntagma” station. X Nicols, x 25.
	
A.21 Andesitic tuff with glassy-microlithic texture. A calcite filled fracture cuts and displaces a euhedral plagioclase crystal at the centre of the photo. Note oxide / hydroxide impregnations at the sides of the fracture. “Larissis Station”. X Nicols, x 25.	A.22 Euhedral opaque crystal (pyrite?) in metasiltstone. Unknown location. // Nicols, x 25.
	

Geological formations: Upper Athens Schist / Lower Athens Schist

A.23 Contact of metasiltstone with quartz lenses of Upper Athens Schist with dark bluish grey siltstone of Lower Athens Schist.
Borehole: GP2546 – Depth: 15,00 - 24,60 m – Line 4, future “Dikastiria” - “Alexandras” interstation.

A.24 Contact of greyish green metasandstone of Upper Athens Schist (upper part of tunnel face) with black grey clayey shale of Lower Athens Schist. Note the abundant, white, folded, quartz lenses of the lower part of shale.

Single-track tunnel (~ 6 m dia.) excavation face – Line 3, “Monastiraki” - “Keramikos” interstation.

Geological formations: Ultra-basic Rocks / Upper Cretaceous limestone

A.25 Tectonic contact of serpentinite with Upper Cretaceous limestone.
Borehole: BH2451 – Depth: 23,50 - 31,00 m – Line 3, “Korydallos” - “Nikaia” interstation.

A.26 Tectonic contact of weathered and brecciated serpentinite (top-right) with brecciated Upper Cretaceous limestone (bottom-left).
Open excavation face at building pit – Line 3, “Maniatika” station.

Geological formation: Upper Cretaceous Limestone

A.27 Massive, locally karstic limestone.
Borehole: BP2428 – Depth: 2,80 - 11,30m – Line 3, “Nikaia” - “Maniatika” interstation.

A.28 Massive, grey limestone.
Open excavation face at building pit – Line 3, “Maniatika” station.

Geological formations: Alepovouni Unit (alep) / Ultrabasic Rocks (ub) / Kessariani Dolomite (kd)

A.29 Light pink marble (alep, 11,0 - 14,4 m), rusty orange listwanite (?) (ub, 14,4 - 22,8 m) and weathered serpentinite (ub, 22,8 - 24,9 m).
Borehole: YP0138 – Depth: 11,00 - 24,90 m – Future extension of Line 4 to Vyronas and Ilioupoli.

A.30 Greyish green, weathered serpentinite (ub, 34,1 - 37,30), white, karstic, coarse crystalline, dolomitic (?) marble (kd). Karstic voids were filled with dark brown ferrous, calcareous breccia. Borehole: YP0138 – Depth: 34,10 - 42,70 m – Future extension of Line 4 to Vyronas and Ilioupoli.