DETAILED STUDY OF LITHOLOGY CHANGES, SEDIMENTARY STRUCTURES AND ICHNOFABRICS ALONG THE MARATHOUPOLI COAST IN NEogene DEPOSITS

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Prologue

The present thesis, with title: “Detailed study of lithology changes, sedimentary structures and ichnofabrics along the Marathopolis coast in Neogene deposits” was conducted during the postgraduate program entitled "Geosciences and the Environment" in the Geology Department of the Faculty of Sciences of the University of Patras.

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Abstract
The purpose of this work is to shed light on the tectonic-sedimentary evolution of the Marathopolis coast in NW Messenia, South Peloponnese, a for-arc area in the western part of the Hellenic arc, between the Ionian subduction zone to the west and the Aegean back-arc to the east.
On the Marathopolis coast, a marine terrace, formed by Neogene deposits, was identified. Its formation was influenced by eustatic changes and regional uplift. The Neogene deposits consist of a shallow-marine unit that is interpreted as grainstone and was deposited in a high-energy shoreface-foreshore environment, exhibiting a progradational geometry. Caliche horizons intercalated in the shallow-marine deposits indicate emersion episodes, repeated sea-level changes, and arid to semi-arid climate conditions during the time of deposition. Red soils cover the shallow-marine unit and indicate that during their formation, the sequence was exposed, probably due to a sea level fall. The top unit of the coast is interpreted as aeolianite which was formed after the rework of uncemented sands, while the unit was exposed again during a sea level fall.
A large portion of the bed sets exhibited the trace fossils *Scolicia* isp., *Bichordites* isp., *Ophiomorpha* isp., and *Macaronichnus* isp.
Throughout the Marathopolis coast, 31 samples were collected, and a laboratory and microfacies analysis was conducted on them. The laboratory analysis included the quantitative determination of calcium carbonate of the samples. The microfacies analysis indicated that the main lithofacies are as follows: 1) lithic grainstone, and 2) coated grainstone. They are detrital carbonates.
1. INTRODUCTION

Marathopolis is a coastal region located 5.5 km west of Gargaliani and 11 km south of Filiatra on the SW Peloponnese (Fig. 1). Marathopolis is located on Messenia, one of the most tectonically and seismically active areas of the Hellenic arc, because of its proximity to the Hellenic trench where the African plate subducts beneath the Aegean microplate (Eurasia; Caputo et al., 1970; Papazachos and Comninakis, 1971; Hatzfeld et al., 1989, 1990; Papanikolaou et al., 2007). The convergent plate motion results in intense deformation of the crust and the release of stored elastic energy by seismic slip along large faults (e.g., Papazachos et al., 1991; Papoulia and Makris, 2004).

![Modified satellite image of the studied area. The location of Marathopolis is highlighted with a red box, near Gargaliani and Filiatra, SW Peloponnese.](image)

The subject of this thesis is the study of the Neogene deposits across the almost 1 km rocky coastline of Marathopolis, with an emphasis on the sedimentary structures, the lithological changes, and the ichnofabrics.

The coastline is covered in reddish sandstones covered by red palaeosol and capped with lighter-coloured aeolianites.
2. GEOLOGICAL SETTING

2.1. South Peloponnese

Located next to the convex side of the Hellenic Arc, the South Peloponnese was affected by compression, associated with a NE-dipping Benioff Zone (Hatzfeld et al., 1989), a tensile stress regime, and consequently, widespread rifting (Doutsos & Piper, 1990). In the Aegean back-arc basin, Pliocene tensional fracturing resulted in the formation of new smaller basins. During Upper Pliocene – Quaternary, the Central Cretan Sea had an estimated sedimentation rate of 0.9 cm.Kyr-1 in Zanclean to 9.6 cm.Kyr-1 in Piacenzian and even higher values in Quaternary, indicating continuous basin subsidence (Horvarth & Berckhelmer, 1982).

In the South Peloponnese, a shallow dipping slab was noted with an intense dipping of the subduction beneath Argolida (Hatzfeld et al., 1989). The E-W extensional regime during the Pliocene attributed to the creation of N to NNW-trending basins. Those basins were inundated due to a transgression event that took place during the Zanclean built up in Piacenzian, and affected the marginal areas of the Greek mainland.

Throughout Plio-Quaternary, South Peloponnese was affected by two orthogonal fault systems. The first one was activated during the Pliocene and consisted of NNW-trending faults that produced three adjacent basins and ENE-trending transfer faults. The second faulting system created rotating blocks within the basin and altered the thickness of the deposits (Zelilidis & Doutsos, 1992).

The three main basins—Eleofyto, Messenia, and Laconia —although adjacent to each other and created by the same extensional regime, show different sedimentary evolution from the Zanclean to the Early Pleistocene due to different tectonic activity (Fig. 2). Major bounding faults at each basin's eastern margin resulted in different rates of subsidence, and therefore an increase in the thickness of the sedimentary sequence and depth southwards. This alteration in subsidence is probably related to the distance from the Hellenic Trench, with the basins of Eleofyto (a), Messenia (b), and Laconia (c) being 50 km, 80 km, and 150 km, respectively.
a. **Eleofyto Basin**: According to Zelilidis & Kontopoulos (2001), the Eleofyto Basin is 30 km long and 12 km wide, bounded to the east by a major normal NNW-trending fault. From the Piacenzian to the Early Pleistocene, two transgression events took place in the basin. During the Piacenzian, the Eleofyto Basin was inundated, with the northern part being covered by water, which resulted in the formation of a shallow marine environment.

The 50 m-thick shallow marine deposits consist of grey massive silty sand, sandy silt, and horizontal laminated mudstone deposits at the lower part, and yellow to grey silty sand and sand at the upper part. During the Early Pleistocene, the northern part of the basin was uplifted, and sedimentation stopped, while the southern part was inundated, with a lagoonal environment being formed. Those deposits include massive grey mudstone with root concretions at the lower part and
interbedded yellow to grey laminated sandy silt and massive silty sand beds with coal lenses at the upper part, with an overall thickness of 150 m. In the Early Pleistocene, the Eleofyto Basin was connected with the Messenia Basin through a narrow zone, due to a WNW-trending transfer fault.

b. **Laconia Basin:** In the Laconia Basin, the northern part of the major fault shows little throw during the Piacenzian, reflected in the deposition of a floodplain and shallow marine deposits. During the Early Pleistocene, this northern part of the fault showed less throw and influence on the deposition of the thin lacustrine deposits.

The southern part of the Laconia Basin lies below sea level, up to 1200 m, and its filling is up to 400 m, showing that the southern part of the major fault from the Piacenzian to the Early Pleistocene shows larger throws, as in the Messenia Basin, than the northern part. On the footwall of this master fault, due to synthetic and transfer fault activity, small sub-basins were developed, where thick lagoonal/lacustrine deposits were accumulated.

c. **Messenia Basin:** This basin, which is 80 km eastwards of the Hellenic Trench, is characterized by three transgression events, from the Zanclean to the Early Pleistocene. During the Zanclean, the basin was inundated (the first transgression event) only in its southern parts. In the Koroni area, from drilled cores data, the Lower Pliocene deposits, up to 80 m thick, were recognized. These deposits consist at the base of shallow marine deposits (indicating the first transgression event), which pass upwards to lagoonal deposits with coal beds, forming the first regression sequence during the early Pliocene.

Coal beds consist of very thinly to mediumly interbedded coals and mudstones, with an overall thickness up to 60 m. The above-described sediments in the Koroni area, represent deposition in a back-barrier environment that formed along the western margins of the basin. During the Piacenzian, the whole Messenia Basin was inundated (second transgression). The basin is characterized by the evolution of a fluvial/wave dominated deltaic environment. In the western margins, lagoons were formed behind barrier islands in the eastern margins, and on the foot-wall of the bounding fault, seven small sub-basins were formed.

In the three northern sub-basins, fan deltas were accumulated (Zelilidis & Kontopoulos, 1994). In the four southern sub-basins, mostly braid-deltas were developed, and in one case, alluvial fans accumulated (Zelilidis & Kontopoulos, 1999). Lagoonal deposits (Zelilidis & Kontopoulos, 1994) up to 50 m thick at the western margins (Velika area) are characterized by the accumulation of a
coarsening upward sequence with massive mudstones at the base and silty sand and sand upwards. Between fine and coarse-grained lithologies, and in some places, coal beds, up to 2 m thick, were formed.

The textures and structures of the silty sand and sandy beds depend on the site of accumulation within the lagoonal environment. Lamination, tabular and trough cross-stratification, fossils, and conglomeratic lenses are common in these lithologies. These lagoonal deposits can be compared with the second coal appearance in the Koroni area (Zelilidis & Kontopoulos, 1994). Fluvial/wave dominated deltaic deposits (Zelilidis & Kontopoulos, 1994), more than 300 m thick, consist of massive mudstones with burrows and marine fauna. They were deposited from suspension on the prodelta. Over them, delta-front mudstones/siltstones were developed, which appear, at the base, massive with diffuse banding defined by slight variations in grain size that reflect fluctuations in the supply of suspended sediments. Upwards delta-front is characterized by interbedded sand and silty sand beds and laminated mudstones. Gravely distributary channel deposits and broad sandstone channels with reactivation surfaces may also occur in his facies association. Delta plain consists of interbedded massive sand with cross-stratification and marine fauna, horizontally laminated non-fossiliferous silty sand, and in places of sandy gravel, gravelly sand and sand beds with cross-lamination, trough cross-stratification, ripples, convolute bedding developed laterally, and over peat lenses (Zelilidis & Kontopoulos, 1994).

Fan-delta deposits formed in narrow sub-basins (Zelilidis & Kontopoulos, 1992), consist of fining upward matrix-supported, unstratified, and ungraded greyish conglomerates with sandstone lenses. Sandstone presence increases with the distance from the basement. Fan-deltas prograded eastward and accumulated on the hanging wall of the bounding fault, with an overall thickness of about 100 m. Alluvial fans accumulated in a restricted basin and consist of thick interbedded, poorly sorted reddish-brown conglomerates and yellowish sandstones or conglomerates with sandstone intercalation, up to 200 m thick. These sediments lack fossils.

Braid-deltas, up to 100 m thick, in the four southern sub-basins have different evolutions due to different basin configurations. In wide sub-basins, stacked or isolated intermediate and small conglomeratic/sandstone channel deposits were developed within and lateral to overbank deposits. In narrow basins, over bank deposits were not preserved, and the channelized deposits from stacked or isolated intermediate and small sandstone/mudstone mosaics (Zelilidis & Kontopoulos, 1999).
During the Early Pleistocene, the basin was inundated for the third time, but this third transgression did not cover the whole basin. The main basin was still characterized by the evolution of the fluvial/wave-dominated deltaic environment (sedimentation of an up to 100 m-thick sequence). The three sub-basins, with the fan-deltas, were uplifted and sedimentation was stopped, whereas in the other four basins, sedimentation was restricted basin-wards with the continuous sedimentation of more than 150 m thick braid delta deposits.

The second and third transgressions were recorded in the deltaic deposits, with two coarsening upward sequences (mudstone to sandstone or delta-front to delta plain) (Zelilidis & Kontopoulos, 1994). Sedimentation rate in the Messenia Basin was estimated between 0.4-0.5 mm. yr¹, either for the Piacenzian or for the Early Pleistocene.

2.2. Messenia Peninsula

The Messenia Peninsula borders on Elis to the north, Arcadia to the northeast, and Laconia to the southeast. The Ionian Sea lies to the west and the Gulf of Messenia to the south. The most important mountain ranges are the Taygetus in the east, the Kyparissia mountains in the northwest, and the Lykodimo in the southwest. The main rivers are the Neda in the north and the Pamisos in central Messenia.

Off the south coast of the south-westernmost point of Messenia lies the Messenian Oinousses islands. The largest of these are Sapientza, Schiza, and Venetiko. The small island of Sphacteria closes off the bay of Pylos, while the island of Proti is located opposite Marathopolis, at a distance of 1 km. All these islands are virtually uninhabited.

Messenia is cut by NNW-SSE to N-S and ENE-WSW normal faults (I.G.M.E., 1980a, b; Mariolakos et al., 1985). Southwest of the Messenia Peninsula, these faults regulate the deposition inside the troughs that make up the Hellenic Trench (Vittori et al., 1981). According to Lyon-Caen et al. (1988), Taymaz et al. (1991), Armijo et al. (1992), and others, the N-S faults are thought to be the result of E-W-oriented Quaternary extension over the Aegean fore-arc. This is the result of the Aegean crust's southwestward expansion over the more easily subductable Ionian crust following the continental collision of the African margin with it. However, given that recent microtectonic research in Kyparissia indicated a maximum extension direction that runs N-S, local variations must have been significant (Meijier, 1995). The Messenia Peninsula appears to be composed of alternating areas of
uplift and subsidence, as indicated by the spatial distribution of Plio-Quaternary pediments and marine terraces. These areas include the uplifting sector of western Messenia, the subsiding sector of the Pamissos fluvial plain, and the subdued southwest sector of Proti Island-Pylos-Sphacteria Island (Kelletat et al., 1978) (Fig. 3).

**Figure 3.** Geological map of Greece, scale 1/50.000, Filiatra sheet, the red box highlights the studied area (modified by IGME, Athens. Philippson, A., 1892)

SW Peloponnnesus's neotectonic macrostructure is defined by the presence of sizable grabens and horsts that are surrounded by broad fault zones that strike both north and west. Specifically, the Taygetos horst, the Kalamata-Kyparissia mega graben, the Vlahopoulo graben, the Kyparrisia Mts. morphotectonic unit, and the Pylia Mts. horst. Since block rotation distinguishes the rates of uplift and subsidence along the boundaries of the neotectonic blocks, the kinematic evolution of these neotectonic units is complex (Mariolakos et al., 1994b). There are numerous minor structures located at the edges or inside the first-order neotectonic macrostructures of the Southwest Peloponnnesus. The minor order neotectonic structures are oriented either perpendicularly or subparallel to the trends of the first order ones. They have distinct kinematic evolutions, yet they are dynamically connected because they sprang from the same stress field. This difference has existed from the beginning of their creation or more recently as they have evolved (Mariolakos et al., 1995).
Data derived from the area of Filiatra was used to infer Late Pliocene subsidence at an estimated rate of 0.19 mm/yr., followed by uplift since the middle Pleistocene at an estimated rate of 0.62 mm/yr. (Marcopoulou-Diacantoni et al., 1991). Late Pliocene-early Pleistocene subsidence was also inferred from the Kalamata-Pamisos graben, a structure controlled by N-S to NNE-SSW trending faults (Zelilidis and Kontopoulos, 1994), which propagated during the early Pleistocene and modified "the configuration of pre-existing graben margins". This resulted in the formation of asymmetrical basins with an eastward increase in depth that accommodated prograding deltaic systems. Fan deltas were deposited near the fault-controlled eastern margin of the basin (Zelilidis and Kontopoulos, 1994).

Pliocene and early Pleistocene sediments of the Messenia Peninsula were dated biostratigraphically, using planktic and benthic foraminifera and nannoplankton (Frydas, 1990; Frydas and Bellas, 1994). In areas emergent during the Pliocene-Quaternary boundary, a characteristic pediment surface was formed, followed by Pleistocene terraces at lower altitudes (Keraudren, 1970; Dufaure, 1977). Kelletat et al. (1976) distinguished more than 10 distinct terraces locally (NW Messenia). Faulting and tilting of pediment and terraces took place, with throws decreasing with decreasing altitude/age of the surfaces (Kelletat et al., 1976). Possible inversions in the direction of movement were inferred from the area NE of Kalamata, bounded by the active (Lyon-Caen, 1988) Kalamata Fault. Fault throws in the young (ca. 120 Ka), Tyrrhenian terraces are generally < 1 m (Kelletat et al., 1976). A decreasing altitude of Tyrrhenian terraces towards the south was interpreted as indicating southward tilting of the entire western coast of the Messenia Peninsula (Kelletat et al., 1978).

A southward tilting of the Messenia Peninsula during the late Holocene was inferred from the distribution of submerged archaeological sites (Flemming, 1972, 1978). Statistical analysis of the latter suggested that the late Holocene subsidence of the Messenia Peninsula followed a NW-SE trending pattern. These results contradict the pattern of vertical movement inferred for the whole Quaternary, which comprises alternating areas of uplift and subsidence and persistent directions of movement for each block (Kelletat et al., 1972). Kraft et al. (1977), based on sedimentological data from the Pamisos Plain, inferred an abrupt relative sea level rise of about 5.5 m. This distinguishes the Pamisos Plain from other coastal plains in the Peloponnese, characterized by smoothly rising Holocene sea level curves. This abrupt relative sea level rise could, thus, be attributed to local tectonics (Kraft, 1975, 1977).

Tide gauge data, during a period of 15 years before the 1986 Kalamata earthquake, also suggest subsidence of the head of the Messenian Gulf ('Kalamata Station'), at a very high rate of 9.2 mm/yr.
(Flemming and Woodworm, 1988). A more recent model, however, that also considers isostatic readjustment of the crust since the last deglaciation (Lambeck, 1995), inferred that Holocene subsidence of the Pamisos Plain resulted from isostatic rather than tectonic effects.

2.2.1. Alpine formations

The Messenia peninsula mostly comprises sedimentary rocks of the Alpine orogenesis (Fytrolakis, 1971). The nappe sequence consists of a relatively autochthonous unit, the Tripolis Unit, and an allochthonous one, the Pindos Unit. The Tripolis Unit consists of neritic carbonates and flysch, outcropping mostly at the western part of Messenia. The Pindos Unit occupies mainly the eastern part of Messenia forming a classic nappe, that has overthrusted the Tripolis Unit from east to west. The Pindos Unit is represented with the Triassic clastic formation at the bottom of its stratigraphic column up to the Eocene flysch at the top. The whole unit is intensively folded and faulted, forming successive thrusts of Oligocene motion (Pavlopoulos et al., 2010), cut by neotectonic faults (post-Miocene) of normal kinematics.

2.2.2. Post-Alpine formations

The post Alpine deposits, that are the focus of this thesis, can be distinguished into (i) marine, (ii) terrestrial, and (iii) lacustrine formations. The marine deposits consist of marls, sandstones, and conglomerates. Their total thickness differs from place to place. The marine deposits consist of marls, sandstones, and conglomerates. They occur in all basins except in the land-locked basin of Upper-Messenia. Their total thickness differs from place to place, reaching 200 m at a location near the city of Koroni, where the upper sequences of the marine deposits are of Early Pleistocene age or younger (Mariolakos et al., 2001). Early Pleistocene marine sedimentation is also reported in the adjacent areas of Filiatra and Lower Messenia Basin by Marcopoulou-Diacantoni et al. (1989, 1991). The neotectonic (post-Miocene) structure of Messenia is characterized by the presence of large grabens and horsts bounded by wide fault zones, striking both N-S and E-W. The main structures are (a) the Taygetos Mt Horst, (b) the Kalamata (Lower Messenia) Graben, (c) the Kyparissia graben, (d) the Kyparrisia Mts. Horst, (d) the Vlahopoulo Graben and (e) the Pylia Mts Horst. The pattern and growth of these neotectonic units is complicated because of regional uplift (Ganas and Parsons, 2009), tilting, and normal fault development throughout the Quaternary. 
In the Falanthi Basin, the thickness of these sediments has been estimated, based on drilling data, to be 200 m at a location near the city of Koroni. At this basin, the upper sequences of the marine deposits are of Early Pleistocene age or younger (Mariolakos et al. 2001). In the other basins of the Pylia Peninsula (Pylos, Pygassos and Achladochori basins), according to previous studies, marine sedimentation took place during the Late Pliocene (Koutsouveli 1987; Kontopoulos 1984). The overlying continental deposits consist mainly of red-coloured siliceous sands and sandstones and of polymictic conglomerates, which should be of the Middle and Late Pleistocene age. It is important to mention that these conglomerates consist of pebbles that originated not only from the alpine formations outcropping at the Pylia Peninsula but also from the metamorphic rocks of Taygetos Mt. (that is, from schists, quartzites, and marbles). The Holocene is represented by alluvial deposits and talus scree. Lacustrine deposits outcrop only at the western margin of the Falanthi Basin, consisting of marls with xylite bed intercalations.
3. FIELDWORK

3.1. Methodology
The sedimentological and stratigraphic analysis of the current thesis was based on in-situ descriptions and measurements taken during field work. The faults, joints, and bedding plane orientations were measured with a “Freiberger”-type geological compass, while the bed thickness was measured with a measuring tape. Along with the in-situ descriptions and measurements mentioned above, much of the geological data interpretation was based on photo analysis. The field work also included sampling, during which 31 samples were collected along the rocky coastline of Marathopolis.

3.2. Description of the studied area
The rocky coastline of Marathopolis (Fig. 4) is covered in cemented fine-grained shallow-marine deposits with a red paleosol interval and calcareous aeolianites overlying them, resulting in a complex architecture (Fig. 5). The deposits are cut by numerous closely-spaced normal faults and extensional joints (Fig. 10). The spaces created from those faults are 3 cm wide and locally reach up to 60 cm. Some of these faults extend to the sea area between Marathopolis and Proti. The orientation of the faults measured is as follows: 160/65, 150/55, 160/72, 157/65, 175/75, 190/75, 185/45, 200/80, 340/70, and 275/40.

Figure 4. The rocky coastline of Marathopolis
Figure 5. *The three units of the deposits in Marathopolis. Unit 1 represents the shallow-marine deposits, unit 2 represents the red palaeosol and unit 3 the aeolianites that cap the former two units.*

The first unit is dominated by well-cemented, shallow-marine carbonates with a distinctive intercalation of red palaeosol. The lower part of the unit consists of 100 cm of steep planar-tabular bedsets of grainstone dipping to the WSW. Prograding clinoforms are internally cross-laminated with normally graded cross-laminae. Measured palaeocurrents are mainly WNW, but NNE trends were also noted. The uppermost beds consist of calcirudite with large (up to 7 cm) bioclasts, lithoclasts of white limestone, and calcareous intraclasts.

The fossils that were noted include bivalves, gastropods, large irregular echinoids, and rhodoliths (Fig. 6). Foraminifera are mainly benthic forms of shoreline habitat. The sediment is intensively bioturbated, mostly with *Scolicia*. Also, bivalve escape traces are present. The relative abundance of fossils and trace fossils decreases towards the top.
The red palaeosol layer consists of sandy-pebbly caliche that overlies the grainstones with a marked erosional relief. Locally, it is directly overlain by small in situ colonies of the coral _Cladocora caespitosa_ (Linnaeus). Numerous angular to sub-angular calcarenite intraclasts present in the layer were derived from the subjacent bedsets of the calcarenite and were probably reworked by storms from the foreshore, leading us to interpret it as a transgression event. Elsewhere, this red interval consists of multiple caliche crusts, alternating with layers of normal- or reverse-graded, calcified grainstone, up to 5 cm thick. These caliche formations may be evidence of a storm-induced backshore deposition.

Above the caliche comes trough cross-laminated grainstone (30 cm thick) with shells of bivalves and gastropods, and a few rhodoliths. Almost horizontal trough cross-bedded bedsets (up to 50 cm thick) exhibit an internal cross lamination separated by erosional surfaces (**Fig. 7**). Individual laminae are normal and reverse-graded.
The next unit represents lag deposits and consists of terra rossa, which covers shallow marine sediments. This red interval indicates subaerial exposure and soil formation during a sea-level fall and an arid to semi-arid climate. The thickness is up to 60 cm. Various root clasts and calcified roots are present here. Locally, tectonic breccia mixed with red soil were observed on normal fault planes (Fig. 8).
Figure 8. A) Terra rossa deposit overlied by 1 m thick aeolianites, the black dashed line represents the contact of the aeolianites and the terra rossa, B) Tectonic breccia and red soil on a normal fault plane. The white dashed line showcases the mirror of the fault.

The aforementioned units are capped by well-sorted, fine- to medium-grained, trough cross-laminated grainstone, with sub-rounded to rounded grains. The grainstone locally exhibits various cross-laminations and is extensively calcified. Caliche is a layer-like accumulation of calcium carbonate that is deposited as part of the formation of soil. It represents material that was dissolved by water from the surface and the upper parts of the soil and then precipitated, as a result of continuous weathering. This material has covered much of the normal fault’s scarps and the spaces between the extensional joints. Distinctive organosedimentary root structures preserving the roots of higher plants or root remains in mineral matter, called rhizocretions, are also abundant here (Fig. 9). Throughout the coastline, straight, curved, and winding echinoid burrows were noted, in mostly horizontal and oblique positions, mainly Scolicia and Bichordites.
This unit is interpreted as aeolianite, probably derived by the reworking of sand during a sea level low. Deep solution wells penetrate this sediment, indicating karstification of the sediments, suggesting that the water table fell beneath present-day levels, as expected during sea-level low stands.

The dune morphology is well preserved locally, mostly on the southern part of the coastline (Fig. 11). Due to the observed rhizocretions, in the aeolian deposits, it’s safe to assume that the dunes were, at the time, stabilized and covered by vegetation. The sand is more or less reddish in color due to oxidation, meaning that the dunes remained inactive for a considerable time.

Figure 9. Rhizocretions, in grainstone
Figure 10. *High angle (30°) calichified foresets with dip to N*

On the northern part of the studied coastline, white, rounded pebbles (up to 5 cm) in the sand bed were observed. They show no orientation, lying unconformably on the subjacent beds (Fig. 12).

Figure 11. *Normal fault creating a 50 cm throw. The blue and white lines highlight the angular unconformity on the top of the photograph. The red lines show the faults cutting through the grainstones.*

On the southern part of the coast, an admixture of poorly sorted matrix-supported pebbles and cobbles was noted. They are probably deposits from a river (Fig. 13). The pebbles show no orientation. The existence of a river there is further supported by a change in the trace fossil assemblage, with the echinoid burrows (*Scolicia* and *Bichordites*) being locally replaced by *Macaronichnus* and *Ophiomorpha*, due to a change in salinity.
Figure 12. Fluvial deposits lying unconformably on the sand beds, within the red dashed line. Notice the angular unconformity on the lower part of the photograph highlighted with the black dashed line.

Figure 13. Fluvial deposits between grainstone on the Southern part of the Marathopolis coastline.
3.3. Stratigraphic column

The stratigraphic position of the described units and all the descriptions of the sedimentary structures, the lithological changes, and the trace fossils are depicted in Figures 14 and 15. The correlation of the stratigraphic columns A–D resulted in the creation of the synthetic column in Figure 14.

Figure 14. The stratigraphic columns 1 and 2 of the Marathopolis coast
Figure 15. The stratigraphic columns 1 and 2 of the Marathopolis coastline, whereas the column 1 shows the sequence of the northern part of the coast and the column 2 shows the sequence of the southern part, and the legend of the lithologies and symbols.
4. PALAEOICHNOLOGICAL ANALYSIS

4.1. Introduction

Trace fossils and bioturbation structures are a very useful tool not only for palaeoichnology but also for sedimentology and stratigraphy. Bioturbation can alter porosity and permeability, which has implications for the characterization of hydrocarbon reservoirs (Pemberton and Gingras, 2005; Knaust, 2009b; Cunningham, 2009; Cunningham et al., 2012; Gingras et al., 2012).

Trace fossils are the fossilized burrows, tracks, trails, nests, borings, or any other record of the interactions between an organism and a substrate (Frey, 1975; Bromley, 1996). Trace fossils provide a unique view of paleoecosystems. Studies in recent years revealed a diverse and complex trace-fossil record in not only marine but also continental deposits (e.g., Buatois and Mángano, 2004; Genise et al., 2004; Hasiotis, 2002, 2007). Ichnologic tools have been utilized in palaeoecological, palaeoenvironmental, and palaeoclimatic interpretations of a broad range of terrestrial deposits (e.g., Hembree, 2018; Shanley and McCabe, 1998).

Ichnology is the study of traces made by organisms, including their description, classification, and interpretation (Pemberton et al., 2001). Such traces may be fossil (‘trace fossils’, or ‘ichnofossils’—the object of study of paleoichnology) or modern (recent traces—the object of study of neoichnology), and generally reflect basic behaviour patterns (e.g., resting, locomotion, dwelling, deposit feeding, or grazing—all of which can be combined with escape or equilibrium-adjustment structures; Ekdale et al., 1984; Frey et al., 1987; Pemberton et al., 2001). These behavioral patterns can be directly linked to several palaeoecological controls (e.g., substrate consistency, physical energy, sedimentation rates, nutrient availability, salinity, oxygenation, water turbidity, or temperature), and implicitly to particular depositional environments (Seilacher, 1964, 1978; MacEachern et al., 2010; Buatois and Mángano, 2011; Knaust and Bromley, 2012). Ichnofossils have been documented in all depositional settings, from aeolian (e.g., Bordy et al., 2004) through to deep sea (e.g., Uchman and Wetzel, 2012), as well as from greenhouse carbonates (e.g., Knaust et al., 2012) to glacial environments (Netto et al., 2012).

Trace fossils include a wide range of biogenic structures wherein the results of organism activities are preserved in sediments or sedimentary rocks, but not the organisms themselves nor any body parts thereof. Ichnofossils also exclude molds of body fossils that may form after burial but include imprints made by body parts of active organisms (Pemberton et al., 2001).
Ichnofabric characterizes the texture and internal structure of deposits formed by burrowing. It records the details of animal-sediment responses at the bed (Bromley and Ekdale, 1984). Lateral and vertical shifts in ichnofacies can be used to interpret changes across a sedimentary basin as well as through time in paleodepositional environments, based on the inferred shifts in paleoecological conditions (Knaust and Bromley, 2012).

Ichnofacies recur throughout the Phanerozoic, regardless of the specific ichnotaxa content of trace fossils. For example, even though the ichnogenus Cruziana is restricted to the Paleozoic, the Cruziana ichnofacies may be present in younger sediments. That is because the combination of animal-sediment responses that defines the ichnofacies continues to occur, even while the trace makers and the particular ichnogenera may change with time. This is also the reason why ichnofacies can be employed for interpreting depositional environments, regardless of the age of the rock or the basin in which it forms.

The Zoophycos ichnofacies typically forms under deeper marine conditions, lying below the storm wave base, but may also be found in other low energy settings, such as fully marine lagoons in coastal environments (Pemberton and MacEachern, 1995). Similarly, trace fossils like Ophiomorpha, traditionally regarded as diagnostic of shallow water, may also occur in sandy submarine fans because bathymetry is not the primary control, but rather the combination of physico-chemical conditions that only tend to change with water depth (Frey et al., 1990). This calls for caution when interpreting the paleobathymetry, or the syndepositional transgressions or regressions of a shoreline, based solely on ichnofacies data.

4.2. Trace fossil assemblages and distribution

The trace fossil assemblages on the Marathopolis coast include Scolicia isp., Bichordites isp., Ophiomorpha isp., and Macaronichnus isp.

Bichordites (Fig. 20) is known to be produced by spatangoids that belong to the Echinocardium genus (Plaziat and Mahmoudi 1988). This has also been proved by Broomley and Asgaard (1975) who reported Echinocardium cordatum in life position at the end of Bichordites. These echinoids typically present one tuft of subanal spines that produce a single drain channel. Conversely, the producers of Scolicia are echinoids belonging to the Spatangus genus that, bearing two tufts of spines, produce two drain channels (Uchman 1995).
According to the widely accepted proposal by Uchman (1995, 1998), large meniscate burrows with evidence of the presence of a single drain should be assigned to *Bichordites*, while those with evidence of two sanitary tubes should be assigned to *Scolicia* independently of their preservation features. Spatangoid echinoids (heart urchins) are known from the early Jurassic (Buatois & Mángano, 2018). They are the producers of *Bichordites* and *Scolicia*. Both are noted on the shallow-marine deposits of the studied deposits, with *Scolicia* dominating the majority of the bioturbated portions of the sequence (Figs. 16, 17).

*Figure 16.* The trace fossil *Scolicia* in shallow marine deposits on the Marathopolis coast

The trace fossil *Macaronichnus segregatis* (Fig. 17) is interpreted to be produced by opheliid polychaetes that feed on epigranular microbes and organic matter commonly abundant in shallow-
marine foreshore sands. The resulting traces are horizontal and typically random in orientation, but in places perpendicular to the shoreline. *Macaronichnus* (**Fig. 18**) appears on the southern part of the Marathopolis coast next to the conglomerates of the river source, indicating the influence of the freshwater input on the bioturbation and sedimentation. Next to the *Macaronichnus*, an assemblage of crustacean trace fossils, including *Ophiomorpha*, appears. These are also connected with the incursion of a river source in this part of the coast (**Fig. 20**). The freshwater input changed the salinity of the environment there, leading to the killing of the “echinoids, which are stenohaline. Once the fluvial deposit outcrops stop, the echinoids appear again.

![Image of Macaronichnus trace fossil](image)

**Figure 17.** The trace fossil *Macaronichnus*
Echinoids are known to be extremely sensitive to salinity fluctuations (stenohaline condition). Even considering that salinity variations are attenuated in interstitial waters (Johnson 1967), a rapid
variation of the surrounding waters from normal marine to brackish can be considered a possible killing mechanism of the echinoids in the southern part of the studied area.

Figure 20. Satellite image showing the bioturbated beds and their distribution (blue arrows) on the Marathopolis coastline. The orange arrow indicates a place of the freshwater input from a river and the three smaller arrows point to conglomerate incisions in the shallow-marine deposits.
5. LABORATORY ANALYSIS

5.1 Quantitative determination of CaCO₃

5.1.1 Methodology

To determine the percentage content of calcium carbonate (CaCO₃) in the 31 samples, the Barnavas method was used (1979). This method is based on the complete decomposition of calcium carbonate (CaCO₃) with acetic acid (CH₃COOH), to form soluble calcium acetate ((CH₃COO)₂Ca) and escape of the produced carbon dioxide (CO₂), according to the equation:

\[
\text{CaCO}_3 + 2\text{CH}_3\text{COOH} \rightarrow (\text{CH}_3\text{COO})_2\text{Ca} + \text{CO}_2 + \text{H}_2\text{O}
\]

According to this method, 1g of dry and powdered sample is weighed for each case sample and transferred to a 200-ml beaker. Inside the beaker are added 10ml (excess) 25% w/w acetic acid, and the sample is placed under agitation for four (4) hours in an electric vibrator or remains for reaction for 24 h at ambient temperature since tests performed have shown that the result is the same. After the end of this process, filtration of the remaining sample and reaction products is carried out through a pre-weighed, very fine filter paper filter (Din en iso 9001).

The soluble salt of acetate of calcium passes through the filtering map; for this purpose, 2 or 3 washouts with deionized water are carried out, while the part of the sediment that did not react is restrained. The filter paper with the undissociated precipitate is left to dry in a desiccator and then weighed. The weight difference of the filter map with and without sediment gives the weight of the non-carbonate part of the sample, while the difference of the retained sediment from the original weight of the sample multiplied by one hundred (100) gives the percentage of calcium carbonate contained in the sample. If the original sample weight is not exactly 1g, then the percentage of calcium carbonate is given by the formula:

\[
\% \text{ CaCO}_3 = \left(\frac{W \text{ of sample} - \Delta W \text{ of filter}}{W \text{ of sample}}\right) \times 100\%
\]

where \(W \text{ of sample}\) and \(\Delta W \text{ of filter}\) are the weight of the sample and its weight difference filter with and without sediment.

The method used for the quantitative determination of CaCO₃ in the 31 samples from Marathapolis is based on the decomposition of CaCO₃ by acetic acid CH₃COOH (Barnavas, 1979) and is described below:

1. The 31 rock samples were pulverized to a fraction of 250 μm.
2. Followed by drying at 50°C for 24 h to remove moisture.
3. Then 1g powder from each sample was weighed on a 4-digit analytical balance and transferred to a 200 ml beaker
4. 10 ml of 25 wt.% acetic acid CH₃COOH was added in the beaker, and the solution was placed at room temperature for 24 hours. (Fig. 21).
5. The solution was filtered through a filtration filter (pre-weighed on a precision balance) and allowed to dry out. With the above process, a breakdown of CaCO₃ is achieved, which passes through the filter paper, while the remaining part of the sample that has not reacted is held to it.
6. The filtration filter with the retained sediment is dried and weighed. Its percentage CaCO₃ in each sample was calculated from the difference in the weight of the sediment retained in the filtration filter and the original sample, reduced to %.

**Figure 21. The 200 ml beakers, filled with the 1g powdered samples and the 10 ml of acetic acid during the process of the Quantitative Determination of CaCO₃. Laboratory of Sedimentology, University of Patras**

### 5.1.2 Results and interpretation

The increase or decrease in the percentage of calcium carbonate, in a sedimentological sequence is a useful indicator of the conditions of sedimentation. Moreover, it seems that there is a correlation between its percentage carbonate material and the grain size distribution (e.g., in fluvial - deltaic sediments where conditions of intense sedimentation prevail, an increase in its quantity of calcium carbonate is observed towards the finer fractions, while the opposite occurs as far as the potential of
the river as well as the supplied sediment increase (Manickam et al., 1985). At sea sediments in places of low sedimentation rate, the carbonate material increases towards the coarse fraction (Saadellah A. & Kukal Z et al., 1969).

From the laboratory analysis of calcium carbonate, it was found that the average percentage of calcium carbonate in the samples is 68.92% (Table 1 & Fig. 22). Samples M4 and M7 show the highest percentages in calcium carbonate, with values of 86.41% and 84.28% respectively. On the contrary, samples M26 and M24 show the lowest percentages in calcium carbonate with percentages of 36.04% and 39.05% respectively.

As shown in the Table below, the percentage of calcium carbonate in the 31 samples from Marathopolis is generally quite high, with a slight observed variation. More specifically, it is observed that samples M1 to M22 and M27 to M31 are very rich in calcium carbonate, while on the contrary, samples M23 to M18 are significantly poorer in calcium carbonate, almost 50% less in comparison to the other 26 samples.
Figure 22. Diagram of the CaCO₃ percentage of the 31 samples of the Marathopolis coastline
Table 1. The percentage of CaCO₃ of the 31 samples from Marathopolis

<table>
<thead>
<tr>
<th>SAMPLE CODE</th>
<th>WEIGHT OF SAMPLE CODE (g)</th>
<th>WEIGHT OF SAMPLE (g)</th>
<th>WEIGHT OF FILTER PAPER WITHOUT SEDIMENT (g)</th>
<th>WEIGHT OF SEDIMENT (g)</th>
<th>WEIGHT OF CaCO₃ (g)</th>
<th>PERCENTAGE OF CaCO₃ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>1</td>
<td>1.1951</td>
<td>1.5055</td>
<td>0.3104</td>
<td>0.6896</td>
<td>68.96</td>
</tr>
<tr>
<td>M2</td>
<td>1</td>
<td>1.2352</td>
<td>1.4092</td>
<td>0.174</td>
<td>0.826</td>
<td>82.6</td>
</tr>
<tr>
<td>M3</td>
<td>1</td>
<td>1.2258</td>
<td>1.3909</td>
<td>0.1651</td>
<td>0.8349</td>
<td>83.49</td>
</tr>
<tr>
<td>M4</td>
<td>1</td>
<td>1.2101</td>
<td>1.346</td>
<td>0.1359</td>
<td>0.8641</td>
<td>86.41</td>
</tr>
<tr>
<td>M5</td>
<td>1</td>
<td>1.2054</td>
<td>1.3769</td>
<td>0.1715</td>
<td>0.8285</td>
<td>82.85</td>
</tr>
<tr>
<td>M6</td>
<td>1</td>
<td>1.2235</td>
<td>1.4352</td>
<td>0.2117</td>
<td>0.7883</td>
<td>78.83</td>
</tr>
<tr>
<td>M7</td>
<td>1</td>
<td>1.2032</td>
<td>1.3604</td>
<td>0.1572</td>
<td>0.8428</td>
<td>84.28</td>
</tr>
<tr>
<td>M8</td>
<td>1</td>
<td>1.2298</td>
<td>1.4242</td>
<td>0.1944</td>
<td>0.8056</td>
<td>80.56</td>
</tr>
<tr>
<td>M9</td>
<td>1</td>
<td>1.2131</td>
<td>1.4756</td>
<td>0.2625</td>
<td>0.7375</td>
<td>73.75</td>
</tr>
<tr>
<td>M10</td>
<td>1</td>
<td>1.1891</td>
<td>1.4134</td>
<td>0.2243</td>
<td>0.7757</td>
<td>77.57</td>
</tr>
<tr>
<td>M11</td>
<td>1</td>
<td>1.2035</td>
<td>1.5359</td>
<td>0.3324</td>
<td>0.6676</td>
<td>66.76</td>
</tr>
<tr>
<td>M12</td>
<td>1</td>
<td>1.2016</td>
<td>1.4684</td>
<td>0.2668</td>
<td>0.7332</td>
<td>73.32</td>
</tr>
<tr>
<td>M13</td>
<td>1</td>
<td>1.2049</td>
<td>1.5211</td>
<td>0.3162</td>
<td>0.6838</td>
<td>68.38</td>
</tr>
<tr>
<td>M14</td>
<td>1</td>
<td>1.2265</td>
<td>1.4277</td>
<td>0.2012</td>
<td>0.7988</td>
<td>79.88</td>
</tr>
<tr>
<td>M15</td>
<td>1</td>
<td>1.2381</td>
<td>1.4856</td>
<td>0.2475</td>
<td>0.7525</td>
<td>75.25</td>
</tr>
<tr>
<td>M16</td>
<td>1</td>
<td>1.1967</td>
<td>1.5259</td>
<td>0.3292</td>
<td>0.6708</td>
<td>67.08</td>
</tr>
<tr>
<td>M17</td>
<td>1</td>
<td>1.2128</td>
<td>1.7657</td>
<td>0.5529</td>
<td>0.4471</td>
<td>44.71</td>
</tr>
<tr>
<td>M18</td>
<td>1</td>
<td>1.2238</td>
<td>1.4823</td>
<td>0.2585</td>
<td>0.7415</td>
<td>74.15</td>
</tr>
<tr>
<td>M19</td>
<td>1</td>
<td>1.2005</td>
<td>1.5559</td>
<td>0.3554</td>
<td>0.6446</td>
<td>64.46</td>
</tr>
<tr>
<td>M20</td>
<td>1</td>
<td>1.2242</td>
<td>1.551</td>
<td>0.3268</td>
<td>0.6732</td>
<td>67.32</td>
</tr>
<tr>
<td>M21</td>
<td>1</td>
<td>1.2529</td>
<td>1.7063</td>
<td>0.4534</td>
<td>0.5466</td>
<td>54.66</td>
</tr>
<tr>
<td>M22</td>
<td>1</td>
<td>1.2186</td>
<td>1.4577</td>
<td>0.2391</td>
<td>0.7609</td>
<td>76.09</td>
</tr>
<tr>
<td>M23</td>
<td>1</td>
<td>1.2405</td>
<td>1.6785</td>
<td>0.438</td>
<td>0.562</td>
<td>56.2</td>
</tr>
<tr>
<td>M24</td>
<td>1</td>
<td>1.2455</td>
<td>1.855</td>
<td>0.6095</td>
<td>0.3905</td>
<td>39.05</td>
</tr>
<tr>
<td>M25</td>
<td>1</td>
<td>1.2211</td>
<td>1.8273</td>
<td>0.6062</td>
<td>0.3938</td>
<td>39.38</td>
</tr>
<tr>
<td>M26</td>
<td>1</td>
<td>1.2316</td>
<td>1.8712</td>
<td>0.6396</td>
<td>0.3604</td>
<td>36.04</td>
</tr>
<tr>
<td>M27</td>
<td>1</td>
<td>1.2088</td>
<td>1.5195</td>
<td>0.3107</td>
<td>0.6893</td>
<td>68.93</td>
</tr>
<tr>
<td>M28</td>
<td>1</td>
<td>1.2215</td>
<td>1.4521</td>
<td>0.2306</td>
<td>0.7694</td>
<td>76.94</td>
</tr>
<tr>
<td>M29</td>
<td>1</td>
<td>1.2664</td>
<td>1.5108</td>
<td>0.2444</td>
<td>0.7556</td>
<td>75.56</td>
</tr>
<tr>
<td>M30</td>
<td>1</td>
<td>1.1975</td>
<td>1.5142</td>
<td>0.3167</td>
<td>0.6833</td>
<td>68.33</td>
</tr>
<tr>
<td>M31</td>
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<td>1.247</td>
<td>1.6012</td>
<td>0.3542</td>
<td>0.6458</td>
<td>64.58</td>
</tr>
</tbody>
</table>

5.2 Decalcification of samples

5.2.1 Methodology

For the rocky samples to be dissolved and the sediment to be released from the calcite cement, about 50 g of the 10 selected samples were put into a HCl solution. The samples that were selected were where the ones that were cut into thin sections (see Chapter 6) (M4, M7, M12, M17, M24, and M26) and their stratigraphically adjacent (M3, M8, M18, M25) ones. At first, the 10 samples were placed inside 500-ml beakers and inundated with a HCl 15% solution for 2 weeks until the cement was destroyed.
However, it was decided that a stronger solution was needed for the process to be faster, so a denser HCl solution was added on the beakers. Every day for 10 days, a small amount of HCl 37% was carefully added to the samples until the CaCO₃ was burned and the sediment was released.

Once the cement was finally dissolved, the sediment was carefully washed with ionized water for at least 10 times, in order for the products of the reaction to be removed. Then the 10 samples were put at 90°C for 24 h and until the sediment was completely dry. The sediment was weighted in a precise scale, and the difference between the initial weight and the final weight was noted.

### 5.2.2 Results and data interpretation

After weighting the dry sediment at the end of the process, it was noted that a huge part of the original sample was lost, with the average value of loss being 95.78% (Table 2). Considering the high amount of bioclasts that were identified during the microfacies analysis (see Chapter 6) and the calcareous cement that the samples consisted, the results are rather expected. Most of the remaining sediment was pale and reddish clay and silt, and a small part was siliceous sand. The exceedingly small amount of the remaining sediment leaves no room for further laboratory analysis.

**Table 2.** The percentage of the final weight after the chemical processing

<table>
<thead>
<tr>
<th>SAMPLE CODE</th>
<th>INITIAL SEDIMENT WEIGHT (gr)</th>
<th>FINAL SEDIMENT WEIGHT (gr)</th>
<th>FINAL WEIGHT PERCENTAGE (%)</th>
<th>PERCENTAGE OF BURNT MATERIAL (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M3</td>
<td>55.56</td>
<td>1.71</td>
<td>3.08</td>
<td>96.92</td>
</tr>
<tr>
<td>M4</td>
<td>51.3</td>
<td>2.22</td>
<td>4.33</td>
<td>95.67</td>
</tr>
<tr>
<td>M7</td>
<td>51.12</td>
<td>1.67</td>
<td>3.27</td>
<td>96.73</td>
</tr>
<tr>
<td>M8</td>
<td>55.97</td>
<td>3.97</td>
<td>7.09</td>
<td>92.91</td>
</tr>
<tr>
<td>M12</td>
<td>51.35</td>
<td>1.79</td>
<td>3.49</td>
<td>96.51</td>
</tr>
<tr>
<td>M17</td>
<td>51.38</td>
<td>1.1</td>
<td>2.14</td>
<td>97.86</td>
</tr>
<tr>
<td>M18</td>
<td>55.62</td>
<td>1.07</td>
<td>1.92</td>
<td>98.08</td>
</tr>
<tr>
<td>M24</td>
<td>55.04</td>
<td>2.03</td>
<td>3.69</td>
<td>96.31</td>
</tr>
<tr>
<td>M25</td>
<td>62.18</td>
<td>3.94</td>
<td>6.34</td>
<td>93.66</td>
</tr>
<tr>
<td>M26</td>
<td>52.95</td>
<td>3.61</td>
<td>6.82</td>
<td>93.18</td>
</tr>
</tbody>
</table>
5.3. Interpretation
The quantitative determination of CaCO$_3$ in the samples showed a very high percentage of calcium carbonate, with the average value being 68.92%. At the same time, after the process of decalcification of the samples, through the addition of a HCl solution, only 4.27% of the initial sediment remained, indicating that on average 95.78% of the sediment was calcareous. The carbonate content here is considerably higher regarding the results of the quantitative determination of CaCO$_3$. The reason for this is that the acetic acid did not dissolve all the bioclasts and the calcareous cement in the samples. On the contrary, when the samples were placed in a strong HCl solution for almost 3 weeks, all the calcareous content was burned, and only the argillaceous and siliceous part -clays and sands- remained (on average, almost 2.20 g of the initial 50 g).
6. MICROFACIES ANALYSIS

6.1. Descriptions

Six samples were selected to be cut into thin sections based on their calcium carbonate content (%). More specifically, M4, M7, and M12 were the three samples with the highest percentage of CaCO₃, with values 86.41%, 84.28%, and 73.32% respectively, and M17, M24, and M26 were the samples with the lowest percentage of CaCO₃, with values of 44.71%, 39.05%, and 39.04% respectively. Although microfacies analysis requires the study of multiple samples, the six selected thin sections resulted in valuable feedback for the sedimentological, paleontological, and palaeogeographical conditions of the deposits on the Marathopolis coastline. The two lithofacies that were identified are: 1) lithic grainstone and 2) coated grainstone, and the microfacies type is detrital carbonate.

**Lithic grainstone (Figs. 23,24,27; M4, M7, M26):** The sediment comprises articulating algae and well-rounded quartz and chert grains, surrounded by micritic envelopes. Micritic envelopes around chert grains are probably constructive, deposited from biofilms on the sea floor. Isopachous fringes of acicular calcite cement, which followed, were deposited in the active marine phreatic zone. The transition of the sediment to the freshwater vadose zone was marked by the deposition of ferric oxides in intergranular pores. Primary intergranular porosity is high. The grains are rounded and rather well-sorted so the grainstone is interpreted as aeolianite. The sediment comprises calcite grains of detrital origin, chert, polycrystalline quartz, algae, various echinoids, benthic foraminifera and other bioclasts. Cements include finely crystalline calcite of pendant and meniscus fabric and bladed spar, also of pendant fabric. Moldic dissolution of micritized bioclasts resulted in the formation of secondary pores; a very small amount of silt was deposited in primary interparticle pores. The diagenesis of the sediment took place within the freshwater vadose zone.

**Coated grainstone (Fig. 25,26; M12, M17, M24):** The sediment comprises well sorted, at times well-rounded grains of medium sand size, in a mosaic of spar to microspar cement. Terrigenous grains of quartz, feldspar, chert, and bedrock limestone (of the Tripolis Zone) were noted. The majority of the grains are coated with thick, almost isopachous crusts of inferred blue-green algal-microbial origin. The sediment contains the following bioclasts: benthic foraminifera, mollusk shell fragments, Bryozoa, serpulids, and peloids, that probably derived from the extensive micritization of bioclasts. Almost all carbonate grains are coated with blue-green algal-microbial crusts, thus the sample is interpreted as coated grainstone. Ferric oxide penetration is also exhibited.

Brown, finely crystalline micrite is identified as the intergranular matrix and is extremely rare here.
microfacies. The sediment is well cemented, with a mosaic of microsparite, precipitated in intergranular spaces. The cement locally exhibits a pendant character. Locally, skeletal grains were recrystallized to microsparite, with preservation of the original skeletal fabric.

The primary porosity is high and is observed to be in the form of remnant intergranular pores, reduced by spar cement. Secondary porosity comprises some moldic dissolution of coated grains with a noted local dissolution of cement. However, the distinction between secondary and residual primary porosity is not very clear in these microfacies. Moldic dissolution and cementation of the sediment took place in the freshwater vadose zone, as indicated by a micro-stalactitic cement fabric (Longman, 1978; Tucker and Wright, 1999).

Figure 23. M4: Lithic grainstone with red algae, echinoid fragments, Bryozoa and gastropods. Scale: 1 mm
Figure 24. **M7**: Lithic grainstone with characteristic red algae, bivalves, Bryozoa, echinoid fragments and various bioclasts in a calcite cement. Scale: 1 mm
Figure 25. **M17**: Coated grainstone grains of medium size sand coated with thick, almost isopachous, cryptocrystalline crusts, in a mosaic of spar to microspar cement. Scale: 1 mm
Figure 26. M24: Coated grainstone, well cemented, with a mosaic of clear, equant-drusy microspar, precipitated in intergranular spaces. The cement locally exhibits a pendant character. Scale: 1 mm
Figure 27. *M*26: Lithic grainstone with various bioclasts, interpreted as aeolianite due to its very good sorting of the sediment, the characteristic presence of pendant microspar cement (in addition to outcrop interpretations as described in Chapter 3). Scale: 1 mm

6.2. Interpretation

The study of the six samples showed that the two main lithofacies are determined as 1) lithic grainstone and 2) coated grainstone. The lithic grainstone is characterized by the appearance of algae and well-rounded quartz and chert grains, surrounded by micritic envelopes. Isopachous fringes of acicular calcite cement indicate that the corresponding deposits were deposited in the active marine phreatic zone. The transition of the sediment to the freshwater vadose zone was marked by the deposition of ferric oxides in intergranular pores. The grains are rounded and rather well sorted, so the grainstone is interpreted as aeolianite. The sediment comprises calcite grains of detrital origin, chert, polycrystalline quartz, algae, various echinoids, and other bioclasts.
The coated grainstone comprises well sorted, grains of medium sand size, in a mosaic of spar to microspar cement. Terrigenous grains of quartz, feldspar, chert, and bedrock limestone were noted. The grains are coated with thick, almost isopachous, crusts, of inferred blue-green algal-microbial origin. The sediments contain: benthic foraminifera, mollusk shell-fragments, Bryozoa, serpulids and peloids, probably deriving from the extensive micritization of bioclasts. The sediment is well cemented, with a mosaic of microsparite, precipitated in intergranular spaces. The cement locally exhibits a pendant character. Locally, skeletal grains were recrystallized to microsparite, preserving of the original skeletal fabric. Mouldic dissolution and cementation of the sediment took place in the freshwater vadose zone, as indicated by a micro-stalactitic cement fabric. The microfacies is characterized as detrital carbonate with a noticeable terrigenous content. The diagenetic evolution of the deposits started in the active marine phreatic zone and continued in the freshwater vadose zone.
7. DISCUSSION – CONCLUSIONS

- On the Marathopolis coast, one marine terrace, formed by Neogene deposits, was identified, and its formation was influenced by eustatic changes and regional uplift.

- The Neogene deposits consist of a shallow-marine unit that is built by grainstone and was deposited in a high-energy shoreface-foreshore environment, exhibiting a progradational geometry. Caliche horizons (2–7 cm thick) intercalated in the shallow-marine deposits indicate a sea-level cyclicity and arid to semi-arid climate conditions. The precipitation of isopachous rims of intragranular cement shows that the diagenesis of the unit started in the active marine phreatic zone.

- Red palaeosols (terra rossa) that are mainly sandy cover the shallow-marine unit and show that during their formation the sequence was exposed, probably due to a sea level fall.

- The top unit of the coast is interpreted as aeolianite, which was formed after the rework of uncremented sands, while the unit was exposed during a sea level fall. The cementation took place in the freshwater vadose zone. This unit shows a distinctive dune morphology, with various cross-stratifications. Rhizocreations are abundant here, indicating that the top unit was exposed and stable for a long time, so vegetation developed.

- The laboratory analysis of the 31 samples from the Marathopolis coast showed a very high percentage of calcium carbonate, with the average value being 68.92%, with the highest value being 86.41% and the lowest being 36.04%. During the decalcification process, about 95.78% of the initial sediment weight was lost. Taking into consideration also the microfacies analysis (Chapter 6), the largest portion of the samples consists of bioclasts bounded by calcareous cement and a small part consists of siliceous sands and clays.

- The microfacies analysis indicated that out of 6 samples, M4, M7, M26 were interpreted as lithic grainstone, and M12, M17, M24 as coated grainstone. The microfacies type is characterized as **detrital carbonate**.

- The direction of progradation of the bed sets and the palaeocurrent indicators (fossils and cross-stratifications) indicate an apparent trend to the NW.

- Many closely spaced synthetic normal faults were noted, cutting through the sequence throughout the coast, in a direction mainly parallel to the shore.
• Four horizons exhibit fossils that include bivalves, gastropods, echinoids and rhodoliths. Foraminifera of benthic habitat were also noted.

• A significant portion of the bed sets exhibited bioturbation structures. Trace fossils mainly include *Scolicia* isp. and *Bichordites* isp. On the southern part of the coast, the echinoids disappear, and the trace fossil assemblage consists of *Ophiomorpha* isp. and *Macaronichnus segregatis*. Considering the sensitivity of the echinoids to salinity changes, this probably means that a freshwater input took place nearby.

• In two different locations, fluvial deposits appear in between shallow-marine deposits. On the northern part of the coast, white to grey sub-rounded limestone pebbles (up to 7 cm in diameter) were noted, while on the southern part, a fluvial deposit outcrop of white and dark grey sub-angular pebbles (up to 15 cm in diameter) appear. This leads to the conclusion that at least two river sources emitted on the Marathopolis coastline. The direction of the streams seemed to be controlled by the normal faults of the area, starting from the Gargaliani area (circa 300 m altitude) and following a WSW direction. Due to the fault influence and coastal current trends, the direction of the streams turned slightly to the north; thus, the initial WSW directions of the streams, once approaching Marathopolis seemed to acquire an NNW direction.

• The figures of the cross section of the area ([Figs. 28, 29](#)) show the fault activity and basin configuration, whereas the satellite image of [Figure 30](#) depicts the geological model of the studied area with sediment transportation.
Figure 28. Satellite image of the studied area. The red line shows the cross-section AA’ in Figure 29 below.

Figure 29. Schematic depiction of the cross-section AA’ of Proti Island, Marathopolis, and Gargaliani. The black lines show the faults of Proti, Marathopolis and Gargaliani. The fault on Marathopolis, along with the fault of Proti Island formed the Marathopolis half-graben. The fault of Gargaliani creates an uplifting of about 300 m. There is an estimated source of the river sediments that emit on the coast of Marathopolis. The channels starting from the higher altitudes of Gargaliani follow a WSW route (blue arrow), and once approaching the coast, are affected by the normal faults and coastal currents of Marathopolis that lead them to the NNW (blue arrow).
**Figure 30.** Satellite image of the studied area showcasing the source of the streams in Gargaliani. The red dashed lines represent the faults of Marathopolis and Gargaliani. The blue arrows represent the route that the streams of the area follow from Gargaliani to the Marathopolis coast. Notice the slight turning of the streams to the NW due to fault action.
8. REFERENCES


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