School of Mineral Resources Engineering

MASTER THESIS

OIL AND GAS POTENTIAL OF THE NEOGENE CARBONATE FORMATIONS IN THE SEDIMENTARY BASINS OF NW CRETE

MSC Petroleum Engineering

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Abstract

A reservoir is a rock having the ability of containing fluids such as gas, oil or water. In order to be productive it should be large enough in dimensions and having enough pore space; the connection between the pores and the permeability of the reservoir controls its capacity of fluids to flow. Sandstones and carbonates are the most common reservoir rocks. High values of porosity commonly characterize coralline algae limestones introducing them as potentially good reservoirs and thus globally many carbonate formations which characterized by abundant coralline algae host prominent hydrocarbon fields. Though, carbonate reefs have been proved significant as hydrocarbon exploration targets, the study of the divergent environment of facies can be extremely helpful in identifying patterns for source, reservoir or (rarely) seal settings. This Thesis is relevant to hydrocarbons exploration potential, through the study of the evolution of carbonate facies and their ability to act as reservoir.

Neogene carbonate strata of West Crete comprise several bio- and lithofacies that represent various depositional environments. The present work is based on the study of an outcrop exposed along the eastern coast of Chania city. It describes a significant in size (both in length and thickness) Upper Miocene mostly carbonate succession of coralline algae and Rhodolith-beds from the island of Crete. Moreover, it highlights the presence of coralline algae as a major reef-like contributor while it introduces this new occurrence in the coralline algae/Rhodoliths palaeo-distribution global and Mediterranean map.

Analytically, the studied 'Koumpeli' outcrop with a length of 1900 meters and a thickness of 45 meters, can be subdivided into four distinct lithofacies (A to D). From the base to the top, the succession is composed by two sets of sandstones (a yellowish and a reddish one, parts A and B respectively), passing upwards into rhythmical marine, coralline-red-algal carbonate facies (C) that underlie neritic bioclastic limestones (D). It is the first time that such an extensive occurrence of coralline algae is described from western Crete, therefore the present work is mainly concentrated in this facies (C) in particular. The prevailing biological feature of coralline algae of the outcrop corresponds to an array of palaeo-environmental conditions; the structure and appearance of their development are sequence stratigraphically interpreted to be related as to a Transgressive–Highstand System Track of relative sea-level change (TST-HST). These well-built structures are representative for the Mediterranean region, as a result of events that date back just before the dawn of the Messinian Salinity Crisis (MSC), when the Mediterranean became dry;(Mascle et al., 2000) rhodolith beds were extensive in Miocene platform carbonate and siliciclastic sediments in the Mediterranean and Paratethys (Halfar, 2005; Braga, 2017). Investigations based on paleoreconstructions and actualistic comparisons with the depth distribution of living rhodoliths comprising similar coralline algal assemblages, imply a wide range of palaeodepths of development ranging from 10 to 100 m (Brandano, 2005; Puga-Bernabéu, 2007a).

Nine sedimentological sections were logged in high resolution along the studied outcrop, five of them directly related to the red-algal facies (part C). Recorded data included the thickness of each bed and the depositional environments that deduced by combining lithologies, sedimentary structures and the (macro-) palaeontological content of the deposits, as well as the nature of interbedding surfaces (erosional, subaerial exposure, angular etc). Vertical facies successions and geometries at the outcrop scale were interpreted in terms of progradation, aggradation or backstepping of depositional environments reflecting the interplay between accommodation and sedimentary flux in time.

In an approach of estimating possible reserves of the hydrocarbon content in this individual occurrence, the true volume of the reservoir was evaluated using three different scenarios (different reservoir dimensions and porosity values) that were assessed accordingly. The results offer a good insight into the nature of Late Miocene deposits of Chania region and their ability to act as reservoir rocks. In this context, this research also provides a basis for further evaluation of the hydrocarbon potential of Neogene rocks in Crete Island.

Also, in order to test another scenario, that of the potentiality to act as a Source Rock, laboratory geochemical (ROCK-EVAL) analysis of the organic matter was performed in the matrix of the rhodoliths. The samples are characterized by poor content in organic matter; subsequently they show a rather poor for oil or gas generating potential. Although carbonates have abundant algal organic matter mixed into them there were probably other factors that acted, for example the high energy of hydrodynamic regime and led to the oxidization of the organic content.

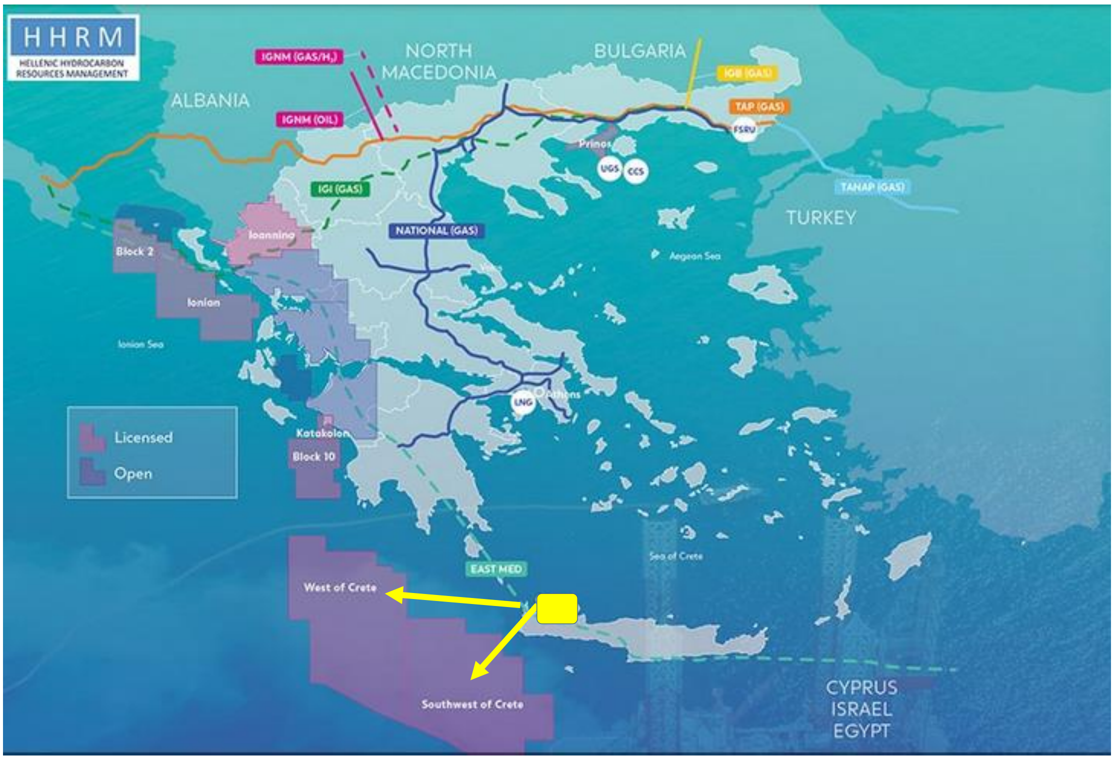
Keywords: Carbonate Facies, Reservoir Rocks, Source Rocks, Chania Region, Neogene strata, Hydrocarbon, Transgressive System Track

Introduction

The Eastern Mediterranean was well-known for its oil reserves (mainly clastics in Egypt-Nile Delta) but is slowly becoming an important gas province as well. Eastern Mediterranean's resources may significantly change the energy game in the wider region, directly affecting many neighboring countries (Egypt, Lebanon, Israel, Cyprus, Syria, Turkey, Greece) and indirectly the whole European Union energy sector, particularly under the current (2022) circumstances. But developing these resources will have major geopolitical implications for the prementioned countries (Karbuz, 2012; modified). An assessment released by the United States Geological Survey (USGS, 2010) estimated the volume of undiscovered natural gas resources, in the Levantine basin alone, to be around 3,450 bcm and the recoverable oil and natural gas liquids (NGLs) as to 5.3 billion barrels (Gb).

Therefore, the Eastern Mediterranean is really the home to large hydrocarbon resources, even though countries of the region, excluding Egypt, have been quite slow to explore for them. It is to mention that Egypt pioneered the discovery of offshore gas (i.e. Abu Qir field) already in 1969, but it was the start of deep waters drilling in 2000 (when technology made that possible) that opened a new Era in the source of energy in the Eastern Mediterranean. To date, more than 2,000 billion cubic meters (bcm) of natural gas have been discovered in the Egyptian offshore sector, not included the recently discovered Zohr field by ENI (2015), which already is in production. And we have to say, that the Eastern Mediterranean remains mostly under- or in some areas completely unexplored and presents rather with good prospectivity for additional reserves identification and development (Karbuz, 2012; modified).

The research for the discovery of hydrocarbons in Greece dates back to the beginning of the 20th century (1903), with the first drilling operations to be carried out by companies such as HELLIS, London Oil Development, PAN-ISRAEL, DEILMAN-ILIO, which mostly concentrated in the Elos-Keri areas of southern Zakynthos (where there is a natural fountain with leakages of asphalt also known as the "*Fountain or Spring of Herodotus*"), in the NW Peloponnese and in the Evros. It is worth mentioning that a book published in 2012 by the Greek Academy of Sciences, entitled "Greek Hydrocarbons: From Research to Development", provides all the necessary basic information and relevant bibliographic references in very detail for the first steps of this important energy sector (Bellas, 2019).



Map.1 Hydrocarbon Blocks and pipeline network for gas in Greece and the related area of this Thesis research in yellow (Modified Map; https://www.greeceinvestorguide.com/companies/energy/hellenic-hydrocarbon-resources-management-hhrm/)

Greece started its new efforts for E&P in 2011, following a number of licensing rounds, and other pathways that the new hydrocarbons law (4001/2011) officially provided. By 2018, there were already four (4) onshore, and eight (8) offshore blocks awarded for Oil & Gas Exploration in western Greece, Ionian Sea and south of Crete, while in the northern Aegean Sea there was an additional productive field (Prinos, including Epsilon) and another offshore block for E&P (Thracian Sea). Presently (October 2022), three of the onshore and one of the offshore blocks awarded in the past decade have been returned by the Operators and JVs back to the State, so they remain "open" to any expression of interest or to the Open Door procedure. But the interest is still very high and recently has been reestablished by the Operator of the two blocks offshore west and southwest of Crete, making the energy production "game" again important.

This is also the significance that this MSc study is based on, i.e. to explore for new opportunities (geological analogues), particularly in western Crete, that may help in the identification of new prospects in these two blocks to the west of our study area. Subsequently, the scope of this work is to search for new Source Rocks (SRs) and Reservoir Rocks (RRs) in the Neogene deposits of western Crete. To investigate two possible scenarios, one for the SRs, another for the RRs, utilizing literature data, new geological mapping and field work, profile logging and sampling, geochemical laboratory analysis i.e. Rock-Eval pyrolysis and combing these data in order to get new ideas for the hydrocarbon prospectivity of the study area.

Tectonics in southern Aegean

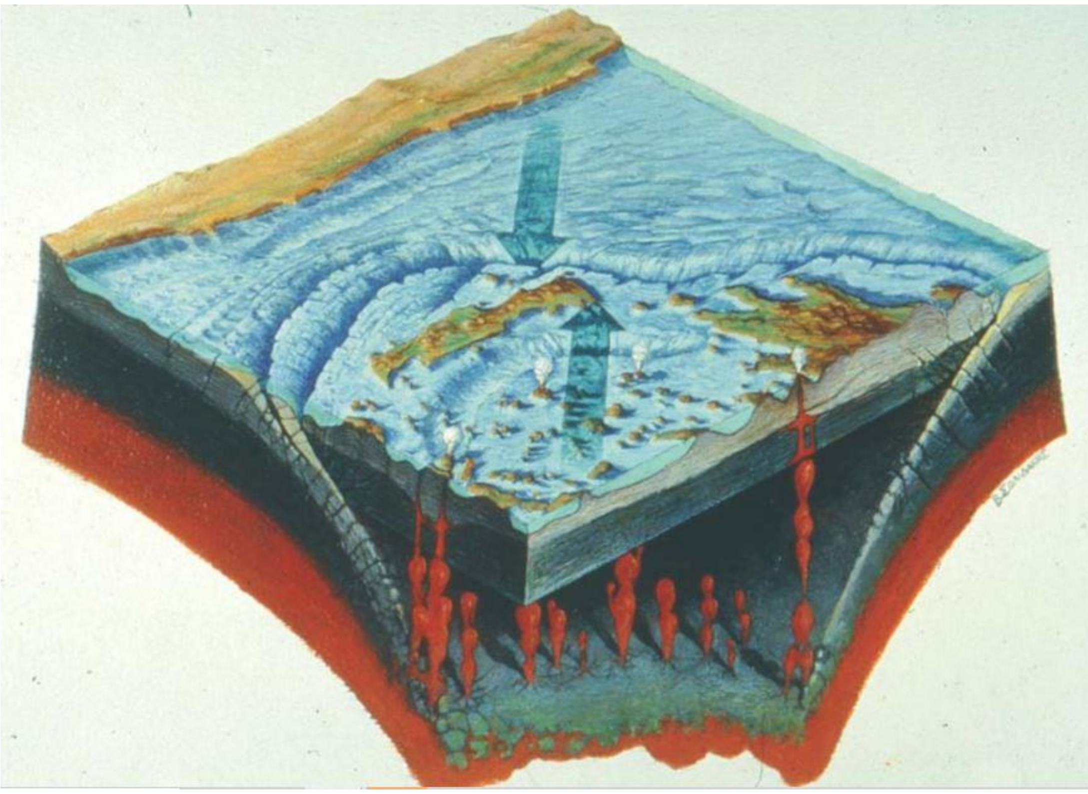
As soon as the processes of alpine orogeny were finished, which was the case for the Hellenic area in the middle Miocene, the new tectonic process began, through which the continental and marine Hellenic area acquired its final shape and form. The island of Crete is the southernmost extension of the Aegean Arc, which formed in the middle Miocene (10 million years) as the convergence of the European and African lithospheric plates; this convergence causes the African plate to sink below the European plate, whose active margin is the Greek area. The subduction is believed to have an amphitheatrical shape that explains the arc shape of the Aegean Arc. Note that the subduction of the African plate under the European plate was determined by the definition of the seismic and the mechanisms of origin of earthquakes attributed to the Benioff zone (Papazachos & Comninakis 1969,1971). The dip of the subductive zone (Benioff) was estimated at 35degrees NNE and the maximum depth of it reaches up to 200km.

The subduction mechanism is not simple to understand; rather, it is complex; as the African plate moves northward, thrust displacements along the Dead Sea fault zone cause compression between the Eurasian and Arabian plates (Molnar and Taponier, 1975) as the Arabian plate moves away from the African plate. This process results in crystal thickening in eastern Turkey and extension of the Aegean region toward the eastern Mediterranean as the Aegean and Anatolian plates are pushed westward (McKenzie, 1972; McKenzie 1978a; LePinchon and Angeller 1979; Angeller et al., 1981). In addition, the movement of Turkey with respect to Europe is a right-lateral displacement along the North Anatolian Fault, a seismically very active right-lateral strike-slip fault (Brune, 1968). A roll-back procedure of the African slab, corroborated to the extension of the Aegean, its crustal thinning and the development of the back-arc extension basins of the northern Cretan basin (Makris, 1978, Angelier et al., 1982, Le Pichon,1982; Meulenkamp et al., 1988,1994).

It is obvious that in the development of the Hellenic arc not only the subduction of the African plate under the Eurasian one played an essential role, but also the development of lateral stress regimes. The related studies have shown that the stresses in the outer region of the Hellenic arc are under compression and lead to deformations of the sediments in the Hellenic rift region, but also affect the outer sedimentary arc. These deformations correspond mainly to inverse fault structures in the new marine deposits south of Crete and the Peloponnese and by field observations in the sediments of the Ionian Islands. In contrast, in the inner region of the Hellenic Arc, from Crete to northern Thrace and across the Aegean and continental areas, an extensional regime of stresses is detected by in situ geophysical measurements. The stresses have a general N-S trend causing normal faults in east-west direction. In addition, older fault groups become active again by the same mechanism, and faults with a trend toward NW-SE were originally formed in older geologic periods. This general trend of normal faulting and extensional regime leads to the formation of tectonic trenches and horsts, mainly in the E-W direction, but also in parallel and ciliary paths to the Hellenic Arc. All recent and historical earthquakes in the inner-Greek area have occurred precisely on these normal faults. It should be mentioned, however, that very close to the convergence boundary of the lithospheric plates, along the inner part of the Hellenic Arc, the extensional stresses run in an east-west direction, perpendicular to the arc, as suggested by seismicity studies (Papazachos et al. 1986). In Crete, where most of the nappe tectonics (compression) probably predate the middle Oligocene (30 million years) according to

Aubouin et al. (1976), widespread normal faulting (extension) began in the Serravallian-Tortonian or even a bit earlier. Progressive reactivation of offshore grabens accompanied the post-Pliocene uplift of Crete (Durmeijer et al. 1998; Fortuin 1978; Leite and Mascle 1982; Le Pichon et al. 2002; ten Veen and Kleinspehn 2003). The Neogene basins in northwestern Crete are generally considered to be the result of the aforementioned subsidence. NNE- and WNW-directed fault systems that developed in the middle Miocene represent the dominant structural feature controlling the configuration of these basins. Clastic sediment deposition began in most, if not all, of these basins in either the late middle or early late Miocene, usually in the Serravallian and/or lower Tortonian, respectively (Freudenthal 1969, Meulenkamp et al. 1979, Keupp and Bellas in collab. with Frydas and Bartholdy 2000).

The upper Late Miocene (Messinian) is characterized by the gradual shallowing of the area, resulting in the "Messinian facies", attributed to the late Miocene Salinity Crisis (MSC) of the Mediterranean (Hsu et al., 1976). The carbonate deposits and particularly the shallow, locally reefal to lagoonal ones became more pronounced throughout the island of Crete. Before the end of the Messinian, marine conditions re-occurred, resulting in submarine slumping and subsidence of the Late Tortonian-Messinian limestone deposits in the southern coastal areas (Fortuin, 1977).



Picture 1. The subduction of African plate beneath the Eurasian margin in the South Aegean territory (by Angelier, 1979).

Methods of study

The thesis is based on data that were collected during field work, which later were elaborated and interpreted so that certain conclusions could be conducted. A detailed multidisciplinary geological research was performed in order to determine the stratigraphical and geometrical relationships between the various sedimentary facies and the formations of the studied area. Nine sedimentological sections were logged in high resolution along the outcrop (named 'Koumpeli'), five of them directly related to the red-algal facies (part C). We used a multi-platform software for creating graphic sediment logs, the SedLog, which is particularly designed for geological descriptions. Recorded data included the thickness of each bed and the depositional environments that deduced by combining lithologies, observed sedimentary structures and the (macro-) palaeontological content of the deposits (with a number of them collected for further research), as well as the nature of interbedding surfaces (erosional, subaerial exposure, angular etc). Vertical facies successions and geometries at the outcrop scale were interpreted in terms of sequence stratigraphic terminology, such as progradation, aggradation or back stepping of depositional environments reflecting the interplay between accommodation and sedimentary flux in time.

Due to major restrictions according to COVID-19 pandemic, the fieldwork was carried out in autumn of 2021. Laboratory analysis of the sediments from selected sections of the sequence from 'Koumpeli' outcrop was performed, qualifying the organic matter preserved in the various depositional settings resulting for testing the scenario of source rocks relevant to their hydrocarbon potentiality.

Sedimentary facies, textures and structures are discussed in detail in order to lead to strong conclusions about the depositional paleaoenvironments that prevailed. In addition, the samples were examined in order to determine their palaeontological content that could support the above-mentioned paleo-reconstructions.

Oil and gas in Eastern Mediterranean

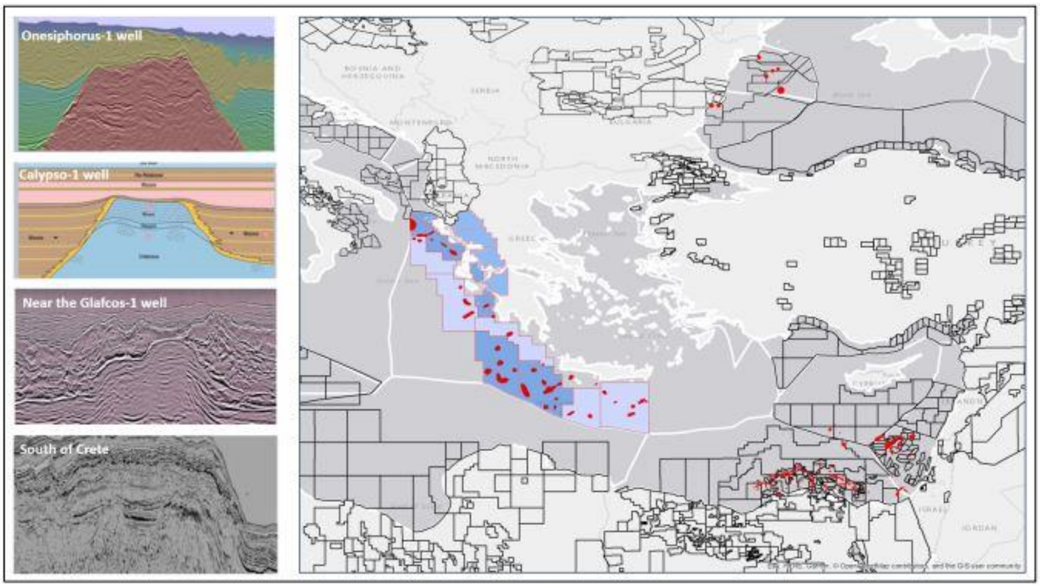
Converging plates host large hydrocarbon fields. In the Eastern Mediterranean, the African plate undergoes the Aegean microplate just underneath the island of Crete. Hence, the possibility of having large hydrocarbon deposits should be further investigated (Bruneton, 2012). Out of Egypt (Nile Delta), the Eastern Mediterranean has become a target area for exploration rather in recent years; however, the total hydrocarbon potential of it is still unknown. Proven hydrocarbon reserves have been identified in the surrounding region (e.g., the Levantine Basin), while regions that merit further exploration (e.g., the Herodotus Basin and offshore Crete) have also been highlighted (Gardosh and Druckman 2006; Roberts and Peace 2007; Semb 2009; Bruneton, 2012, Konophagos, Foscolos, 2011; Elia and Zelilidis 2013; Maravelis et al. 2015).

The high success rates in discovering biogenic gas (95-99% methane) in the sandstones of the upper Levant Basin, reported mainly from the Oligocene, led to an intensive search for gas in the clastic hydrocarbon habitat (Ford, 2017). The introduction of carbonates as a potential reservoir lithology in the eastern Mediterranean and their high success rates added a second petroleum system to the clastic one of the Levant and the Nile Delta (USGS, 2010).

*Originally, the industry was concentrated in the Herodotus Basin with carbonate outcrops around the foothills and the lower slopes of Mount Eratosthenes. Further west, however, powerful Miocene to Cretaceous deposits such as those at Zohr (Egypt; https://www.eni.com/en-IT/operations/egypt-zohr.html), Calypso, and Glafkos (Cyprus) are expected. In this sense, both the reservoir rocks below sea bottom of the Ionian Sea and those west and south of Crete have great geological similarities with the discoveries in Egypt (*Zohr), or Cyprus namely Calypso, Onesiphoros or Glafkos.

There are also other geological structures similar to those of the Aphrodite or Leviathan reservoirs, but with a different geological habitat. This development has enhanced Greece's position on the energy map in the wider Mediterranean region. Most of the gas deposits in the Mediterranean (SE) have been discovered in the last decade through deep drilling in deep to ultra deep waters by international companies with experience in exploration and production. Late Miocene hydrocarbon recovery potential on the coast of Crete and surrounding regions has been documented in the Messara Basin in central Crete (Pasadakis et al. 2012; Maravelis et al. 2013), Gavdos island, south of Crete (Pyliotis et al. 2013), Zakynthos Island in western Greece (Maravelis et al. 2014), Preveza basin in western Greece (Zelilidis et al. 2003; Maravelis et al. 2012), Ionian and Adriatic seas (Zelilidis and Maravelis 2015; Zelilidis et al. 2015) and Levante basin in SE Mediterranean (Gardosh and Druckman 2006; Roberts and Peace 2007; Semb 2009). For a review of the Neogene sequences of Crete potentiality see Maravelis et al. (2022).

The Upper Oligocene-Lower Miocene Asmari Formation of Iran region is the most productive Iranian reservoir (51 oil reservoir which produce near 90 % of the Iran oil; Amirshankarami et al. 2007) and one of the largest worldwide (31 billion of barrel of oil in place; Perry and Choquette 1985). This carbonate setting deposited in a tropical shallow water environment. Skeletal assemblages are abundant, large benthic foraminifers and coralline algae; bryozoans and corals were present in some of the facies of the succession.



Picture 2. Left: Reprocessed seismic sections (published in NVentures, Mediterranean and Europe Exploration/New Ventures Activity Reports, September 2017, January 2018, June 2019). South of Crete analogue geological structure (Source: HHRM Reports, May 2017). Right: Large geological structures south and west of Crete with possible build-ups and reef features similar to those of the fields bearing gas in the Southeast Mediterranean. A number of similar structures were identified in the Central Ionian Sea.

In the deep waters of Greece, some potential targets are buried in rocks below 1,500 to 2,000 metres of water depth. Most targets are located (according to geophysical imaging) in water depths greater than 2,500 metres, while some other targets are located at depths less than 3,500 metres. Ultradeep waters below 3,000 metres are now considered a fringe area of technological innovation, whereas ten years ago it was impossible to plan drilling and installation in water depths greater than 3,000 metres, and fifty years ago it was unthinkable to drill in water depths equal or slightly deeper than 50 metres. Environmental conditions, hydrates, rig size, riser damage, well control, and drilling techniques are the major factors affecting drilling operations, production, day rates, drilling performance, efficiency, and cost of drilling operations. Technical challenges in deepwater drilling include difficulties with the wellhead in silt or mud, wellbore stability issues, high pressure leading to loss of fluid circulation, and variable sticking due to seafloor composition (Cummings et al., 2014).

Recent political decisions in global energy policy are targeting modern, environmentally friendly energy sources and clearly show a transition to clean "fuels." A new map of disciplines and practices to be followed, with the goal of causing less harm to humanity and the planet, and overall protecting these precious non-renewable reserves, has been introduced by the United Nations as the 2030 Agenda. In this spectrum, it is crucial for the O&G sector to adapt or maintain its performance to these new challenging conditions. Therefore, innovative ideas and improved techniques are needed in the O&G industry, since the transition era is going to last at least for the next 30 years.

Geology of Crete

The island of Crete is composed of carbonate units accumulated on a former microcontinent within the Neotethys Ocean known as Apulia (Robertson 1998; Robertson and Kopf 1998). During the Mesozoic and early Tertiary, this microcontinent included two shallow-water carbonate platforms (Gavrovo and Plattenkalk) and a failed rift arm of Permian age (phyllite-quartzite unit). To the north there was a second oceanic basin, the Pindos Ocean, and further north was the Pelagonian microcontinent. The Alpine-induced convergence between Africa and Europe led to the closure of the ancient Pindos Ocean and the southern Neotethys Ocean, which later deformed with Apulia to form the Aegean Arc (Kissel and Laj 1988). The Africa-Europe convergence began near the Pelagonian microcontinent during the Jurassic and led to the complete closure of the Pindos Ocean during the early Tertiary (Robertson and Kopf 1998). From the late Eocene to the early Miocene, the Apulian microcontinent and adjacent oceans were accreted further south in the Neotethys Ocean, creating a series of (Hellenic) lobes that form the alpine basement of Crete (van Hinsbergen et al. 2005)

Structurally, the island of Crete is composed of at least 7 different allochthonous units that were stratified during the Oligocene (Bonneau 1984, Papanikolaou 1988, Fassoulas 1999). In addition, the Cretan geology can be divided into two parts: the "preneogene rocks" or the "alpine basement" (Peters, 1985) and the Neogene and Quaternary deposits separated from the preceding ones by an angular, erosional unconformity (Fortuin, 1977; Fortuin and Peters, 1984; Peters, 1985). Several stratigraphic and tectonic units are involved in the geologic setting of the Chania region, as follows from the lower to the upper one according to their stratigraphical position:

(i) Plattenkalk Group (parautochthonous), (ii) Phyllite Nappe, (iii) Tripolis Nappe, (iv) Pindos Nappe and (v) Uppermost Nappe (in Manoutsoglou et al., 2022 and references therein).

Picture 3. Map of Crete and area of investigation (https://earth.google.com/web)

Uplift and exhumation of the Nappes was accompanied by structural fragmentation of the pre-Miocene basement into several blocks and resulted in the formation of sedimentary basins in the lower to middle Miocene. This exhumation has been attributed to regional extension (Meulenkamp et al. 1988; Fassoulas 2001; Meulenkamp and Sissingh 2003) or to extensional detachment faulting (Papanikolaou & Vasilakis, 2008, 2010). However, recent publications suggest that exhumation processes are primarily controlled by contractional deformation (Chatzaras et al. 2006, 2013; Zulauf et al. 2015). According to Vafidis and Tortorici, the late Miocene to early Pleistocene southwestward migrating overthrust led to the formation of several thrust-related basins (Tortorici et al. 2010; Vafidis et al. 2012).

The Hellenic Nappes have a high-pressure/low-temperature (HP /LT) metamorphosed sequence at the base, the lower sequence (Plattenkalk and phyllite-quartzite units), and an upper sequence (Tripolitza, Pindos, and Uppermost units) without HP /LT metamorphism. In Crete, the lower and upper sequences are separated by a northward extensional detachment (Fassoulas et al. 1994; Rahl et al. 2005; Ring et al. 2001; cf. Stoeckhert et al. 1999; Thomson et al. 1999).

The Plattenkalk comprises Paleozoic clastics (Kastania phyllites), Mesozoic to Eocene carbonates, and Oligocene metaflysch forms a lateral equivalent of the Ionian unit in continental Greece (Kowalczyk and Zuegel 1997). The overlying phyllite-quartzite unit consists of Late Carboniferous to Middle Triassic marine phyllites interbedded with meta-volcanics sediments and meta-debris flows, unconformably overlying the Variscan floor (Finger et al. 2002). The Tripolitza unit contains metamorphosed carbonates and phyllites of Kimmeridgian to Oligocene age. The Pindos unit consists of Upper Triassic to Eocene flysch interbedded with meta-sandstones and carbonates. On the island of Gavdos, basement unit is observed which it is supposed to correspond to the sub-Pelaginian and Pindos units (Anastasakis et al. 1995).

Picture 4.IGME, Geological Map Sheet “Chania”

Neogene Formations in NW Crete (literature)

The Neogene deposits have a large extension in the northern part of the province of Chania. Although the pre-Neogene deposits were strongly influenced by the tectonics during the Triassic and Cretaceous periods, the Neogene deposits seem to be undisturbed and mainly affected by the sea level fluctuations.

According to Christodoulou, the Pliocene following the Neogene corresponds to a transgressive phase in which yellow, sandy marls form, changing upward into marly limestones. Locally, the Pliocene begins with thin conglomerates that grade upward into cemented, sandy limestones with marly intercalations. In general, Miocene depositional sequences consist mostly of transgressive and upstanding system tracts. The boundaries of the regressive system correspond to discontinuity surfaces with numerous features of subaerial exposure, clear evidence of sea-level subsidence.

Fraundenthal was the one who studied the area (1969), and 11 Neogene formations with specific lithostratigraphic correlations were distinguished (see: Picture 5). In detail, Fraundenthal describes eleven formations from west to east, as follows:

Messonisi Formation: the formation consists of red conglomerates composed of preneogene, well-rounded constituents and yellow or grey marls. The conglomerates do not contain macrofossils, while chara sporangia are common in the marls. The Mesonisi Formation unconformably overlies black, recrystallized, preneogene limestone, while it is conformably overlain by the Roka Formation.

Roka Formation: Three different units can be distinguished in this formation. Its basal part consists of kaoric, angular, polymictic, red or reddish-brown conglomerates. The thickness of the conglomerates varies from 1 to 60 m, but generally does not exceed a few metres. The conglomerates reach the greatest thickness between Koukounaras and Kharkhaliana. Upward, they are coarse- or fine-grained, red or reddish-brown sands, locally cemented by a calcareous matrix that forms strongly indurated calcareous sandstones. In many places macro- and microfossils are present in the sands, most commonly Clypeaster, Pecten, Ostrea, and Heterostegina. Outcrops with good macro- and microfauna are found at Nokhia, Afrata, Gourlia, Palaiokastro, Koukounaras, Platanos and Kalathainai. The thickness reaches up to 30 m at Platanos. Cross-bedded sands are found at Gribeliana and at Potamidha. At both sites, the relatively steeply dipping sand layers at Kalathainai are truncated by more horizontal overlying sands. Heterostegina-bearing sands pass laterally into strata that show signs of subsidence. Thick-bedded or unbedded, yellow or orange, bluish-weathering, hard, organic limestones are exposed in the uppermost part of the sequence. Macro- and microfossils are abundant, including mainly Pecten and Clypeaster; Heterostegina is sometimes found. The thickness of the limestone varies from 0.5 to 50 m, but generally does not exceed 10 m. The type section of the Roka Formation consists only of these limestones and is 8 m thick. In almost all places where the Roka Formation is exposed, limestones are present, locally overlying the conglomerates (a) and the sands (b). A nice example of the conglomerate-sand-limestone sequence is found near Nokhia. It clearly shows a decreasing grain size from bottom to top. According to Martini (1956) the Clypeaster limestones belonging to the Roka Formation are assigned to the marine Upper Miocene (Tortonian?), while the conglomerates are described as fluvial Upper Miocene.

<u>Khatzi Formation</u>: In the Khatzi Formation two lithological units are distinguished;

a coarse clastic unit consisting of conglomerates, subordinate marls and clays, and a fine clastic unit consisting of numerous thinly graded layers and layered clays. Gypsum deposits may be present in its upper part. In the southern part of its outcrop area, the Khatzi Formation is overlain by the Khairetiana Formation, and in the northern part by the *Tavronitis* Formation. The Khairetiana and Tavronitis Formations are considered, at least in part, to be lateral equivalents of each other.

Kissamou Formation: The Kissamou Formation consists of blue or purple amorphous clays, but locally stratified. Within these clays, strongly indurated, graded and ungraded sandstones, calcarenites, and organic limestones occur at various stratigraphic levels. In the Kissamou district, the formation conformably overlies the Roka Formation, while in the Kydonias district near Mournies, the Kissamou Formation is underlain by the Ayios-Yeoryios Formation, but is also a lateral equivalent of the top of the latter formation. In addition, it is probably overlain by the Tavronitis Formation between Ayia Marina and Chania, and near Mournies it is overlain by the Akrotiri Formation.

Koukounaras Formation: The formation is composed of indurated, graded layers with a thickness between 0.5 and 2 meters. At their upper end, the graded layers change to laminated and amorphous blue clay, whose thickness varies but rarely exceeds the thickness of the graded layers. From south to north, the thickness of the graded layers decreases, while the thickness of the clays increases in that direction. The basal part consists of coarse limestone, well-rounded algal spherules and clay spherules. The coarse basal parts of the graded layers often erode the underlying amorphous clays, forming irregular undulating contacts. The same author claims that in some places it is difficult to distinguish this formation from the sands of the Roka Formation, because the bearing sands of the Roka Formation pass laterally into layers composed of an irregular mixture of sands, gravels, and clay balls, with undulating lower contacts.

Agios Georgios Formation: the formation consists of conglomerates, sands, clays and orgallic detrital limestone. The formation is named after the village of Ayios Yeoryios

Kydonias in the valley of the Varvara River. The formation is underlain by preneogene shales and black recrystallized limestones, the age of which is unknown. At the type locality, the Ayios Yeoryios Formation is overlain by conglomeratic or sandy sediments of the Akrotiri Formation, while in the northern part of the Varvara Valley it is overlain by the Kissamou Formation.

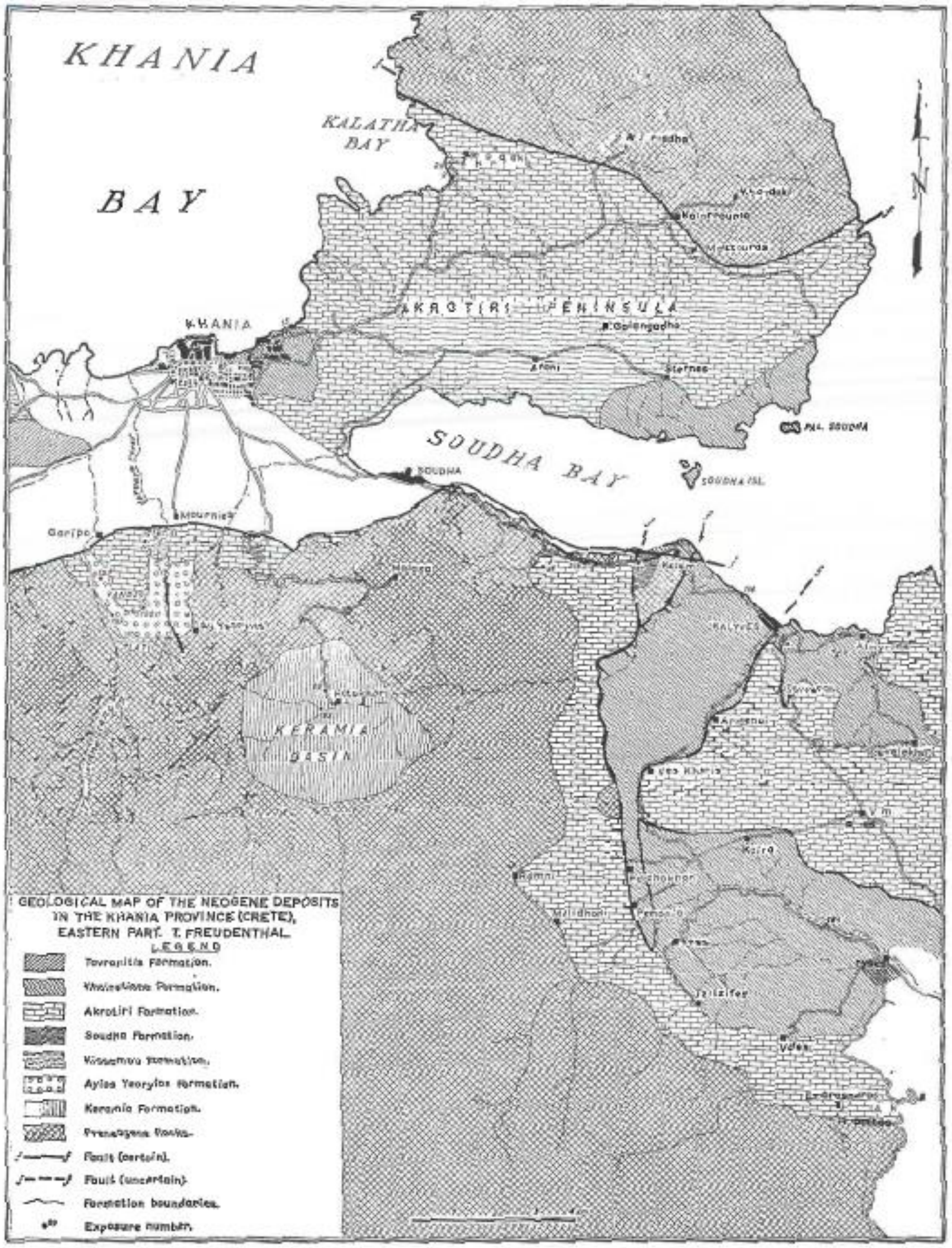
Akrotiri Formation: The Akrotiri Formation consists of either unbedded or of thick, well bedded, white to yellow marly limestones. They are consist of organic detritus, mainly of algae and in minor occurance of shell debris or fragments mollusc shells. Its basal part is generally exist as coarse- to medium-grained, brown, uncemented sands, but frequently with conglomerates. A rich fauna of macro- and microfossils, amongst which Ostrea, Pencten Clypeaster and Heterostegina exist in the beds of sand. This fauna is similar to the one from the Roka Formation and of the limestones in the uppermost part of Khatzi formation as well. At most other locations, in which the base of the Akrotiri Formation is exposed in the surface, it is overlying preneogene shales or black crystallized limestones. In a small exposure along the southern flank of Soudha Bay the latter is underlain by the Soudha Formation. This formation is not overlain by other Neogene strata but in the Apokoronou district laterally passes into or overlain by the Khairethiana Formation. This Formation is referred in literature as "pietra di Malta" by BONARELLI (1901).

Chairethiana Formation: The Khairetiana Formation consists of plenty of alternations of yellow to brown predominantly, laminated marls, clays or sandy clays, and yellow amorphous marls or marly limestones. Coarse, graded intercalations are not often. In general, the thickness of one sequence of laminated and amorphous layers does not exceed 5 m. Graded beds generally are 0.5 m thick or less. The amorphous marls contain scarce molluscs or other macrofossils, but microfossils occur in abundance, especially Discospirina, and other, smaller miliolids. These foraminifera are not reported from the laminated clays and marls, which contain plant debris. Furthermore, sponge needles and diatoms are very common in the laminated beds. In the Apokoronou District the Khairetiana Formation is overlying the Kissamou Formation in the area of Vryses village. Also, it is overlying partially and also lateral equivalent of the Akrotiri Formation. The exact same superposition and lateral transition can be seen on Akrotiri Peninsula. In the Kydonias District the Khairetiana Formation is overlain by the Tavronitis Formation but it is also a lateral equivalent of it (Khairetiana Formation in the south, Tavronitis Formation in the north). In the Apokoronou District the Khairetiana Formation is not overlain by any other strata of Neogene age.

Tauronitis Formation: The Tavronitis Formation consists of amorphous marls, which in the upper part of the formation mainly alternate with graded beds. In the marls many slumps of coarse material can be observed. In its lower part this formation consists mainly of white, amorphous marls. The middle part consists of gravel masses slumped into similar marls and finally, the upper part is composed of grading sand layers alternating with amorphous marls. The Tavronitis Formation is not covered by any other Neogene deposits. The Tavronitis Formation conformably overlies the Khatzi Formation. In the western part of the Kissamou District, near Lardhas this Formation is seen to overlie the Khairetiana Formation, which is its lateral equivalent in the eastern part of the Kissamou District.

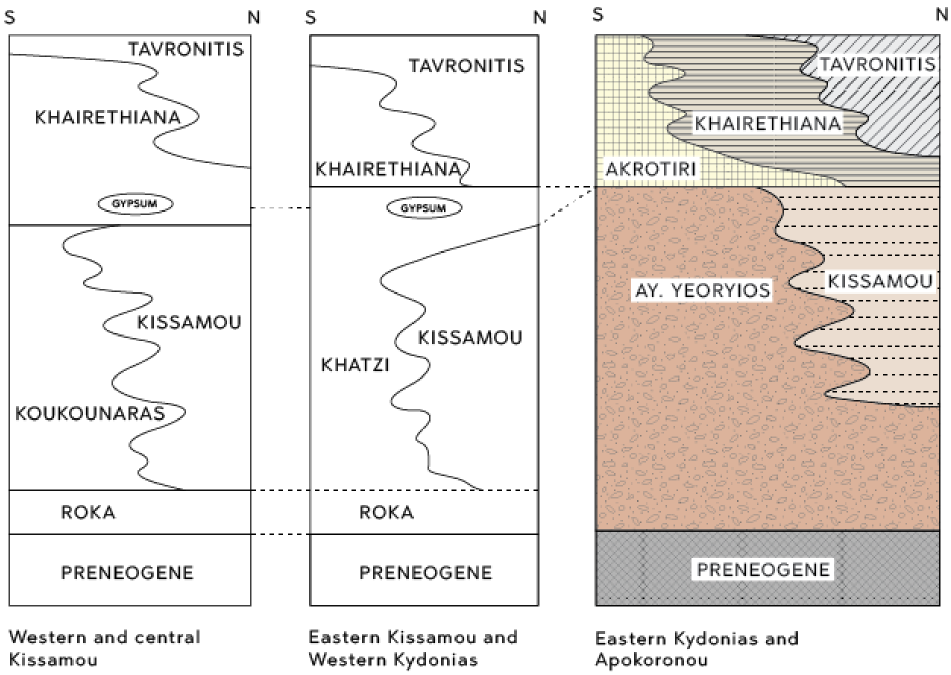
Soudha Formation: The formation consists of very thin-bedded or platy, brown, yellow or white, dense limestones or slightly sandy limestones. Frequently thin, sandy and marly beds were found interbedded. Neither macrofossils nor microfossils are reported. The Soudha Formation is underlain by brecciated, preneogene (maybe Cretaceous) crystallized black limestone whereas is overlain by the Akrotiri Formation.

Keramia Formation: The formation consists of dense, thin- bedded limestones, of thick bedded bioclastic limestones and of brown clays usually with a content of oysters. The base of the Keramia Formation has not being exposed in any location but it is assumed that it uncomfortable overlies shales and limestones and is not overlain by other formation of Neogene age.



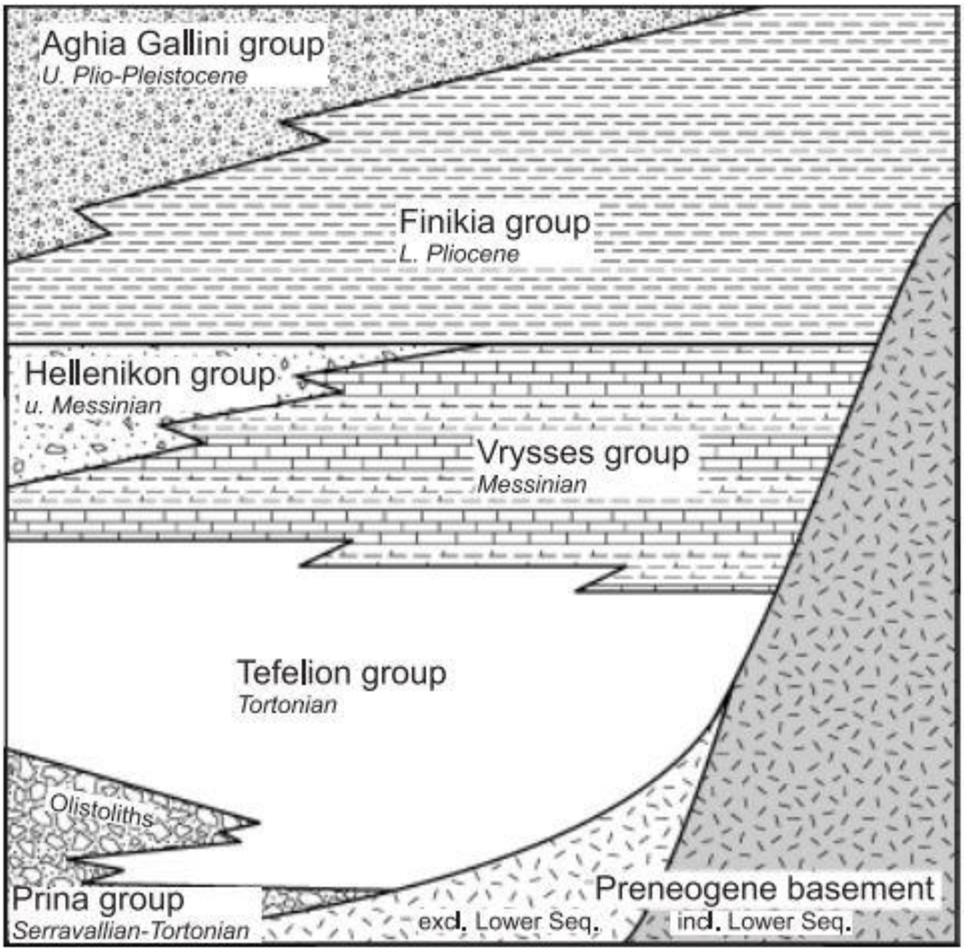
Picture 5.Map of Neogene Formations of Chania region (after Frauntheda1, 1969)

This study would be focus on the Eastern Kydonias and Apokoronou district and the lateral transitions and the correlations between the formations are depicted in Picture 6.



Picture 6.Shcematic lithostromatography of West Crete. Lateral transitions and lithostratigraphic correlations of the formation in several parts of Chania Province, Crete (after Fraunthedal_1969) See text for further explanation.

Meulenkamp (1979) subdivided the Neogene sedimentary sequence of Crete into six lithostratigraphic groups (see Pict.7), mainly based on data published by Freudenthal (1969), Meulenkamp (1969), Gradstein & Van Gelder (1971), Sissingh (1972), Drooger & Meulenkamp (1973), Gradstein (1973, 1974), Zachariasse (1975), Fortuin (1977, 1978) and Meulenkamp et al. (1979). The Akrotiri Fm is categorized and referred as Vrysses Group by this modern classification; it is conformably overlies the Tefelion Group or unconformably overlies the pre-Neogene basement. It consists of marine bioclastic or reefal limestonesor alternating laminated and homogeneous marls, which contain evaporite intercalations in some spots. Its age is determined within late Tortonian to Messinian (Meulenkamp et al., 1979)



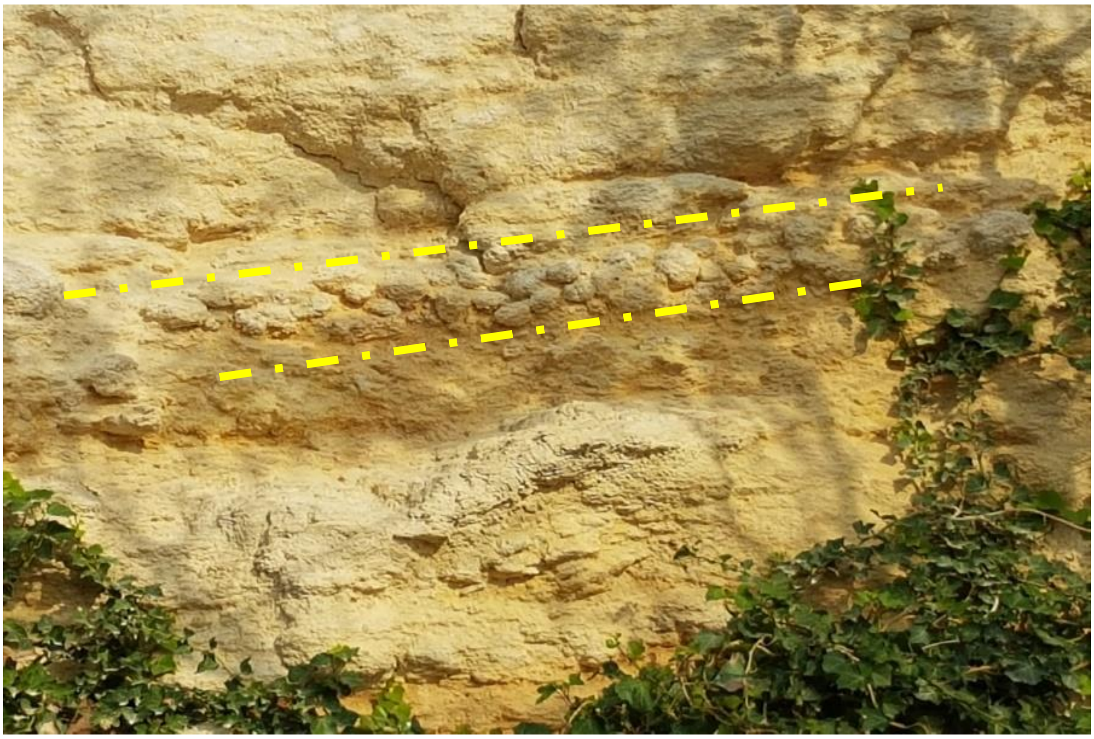
Picture 7. Schematic lithostratigraphy of Crete, with the major facies groups and their relative vertical and lateral superposition and intercalation (Hinsbergen and Meulenkamp, 2006). This study focuses on the Vrysses group.

Coralline algae Formation

Coralline algae are benthic organisms belonging to the family of Corallinaceae. They have a hard outer shell made up of calcite as a component. These organisms form reef-like colonies at the bottom of the sea floor that live and thus reefs and biogenic structures are created by their skeletons when they are dead. The creation process is very slow during the geological time and extensive formations and deposits can be constructed through it; new generation grow overlying the remains of the previous generation of algae. The calcareous red algae are originated through decalcification and form biological societies that are frequently observed in the wider region of the Mediterranean Sea (Bosence et al., 1985), but elsewhere as well. Some Mediterranean corallines algae are thought to be ecosystem engineers that combine several biogenic habitats (e.g.,coralligenous concretions, Lithophyllum byssoides rims, maerl/rhodolith beds).

Red algae grow in sandy or muddy bottoms of the seafloor, usually in 30-90 meters depth (Georgiadis et al., 2009). The fragments of the calcareous red algae have the capacity to unite and transform into rhodoliths in spherical shape with diameter that reaches up to 30 cm (Adey, Macintyre,1973). Coralline (red) algae are commonly found as components in reef frameworks, accompanied with encrusting Porites skeletons together with microbial crusts and foraminifers (Riding et al., 1991; Perrin et al., 1995; Martín et al., 1997; Bosellini et al., 2001, 2002; Bosellini, 2006). Also, red algae occur as loose bioclasts in several reef sub-environments (Perrin et al., 1995; Pomar et al., 1996; Bosellini et al., 2001; Braga and Aguirre, 2001)

The development of rhodoliths requires a slow movement and a repositioning of the fragments of the red algae as the surface that comes in contact with the bottom deposits is restricted to the further development of the outer calcareous shell (Prager, Ginsburg, 1989).



Picture 8.Rhodoliths: nodular structures composed of the superimposed thalli of calcareous coralline algae

Rhodolith beds were extensive in Miocene platform carbonate and siliciclastic sediments in the Mediterranean and Paratethys Sea (Halfar and Mutti, 2005; Braga, 2017). They were commonly found in carbonate ramps associated with small coral buildups, and occasionally occurred in reef-rimmed shelf deposits (Hrabovský et al., 2016; Braga, 2017). Coralline biostromes (coralligène de plateau) were reported in the Maltese Islands (Bosence and Pedley, 1982). Rhodoliths and coralline debris are also reported as deep re-deposited sediments (Bassi et al., 2017).

This work highlights the presence of red algae in the island of Crete, particularly at the western part of the island, and ascertains that the red algae act as a major Miocene reef contributor, a fact that can further led to identification of certain locations bearing reservoir-like geologic structures, which is of major importance for the exploration of hydrocarbons in the wider offshore area that is awarded for E&P within the territorial waters of Greece.

Description of the Facies

This interpretation is based on observations from the Neogene succession that crops out along the eastern coast of Chania city and further unpublished data (pers. communication by Dr. S. Bellas). The Neogene succession of the area studied is composed by rhythmical marine, carbonate formations underlying neritic bioclastic limestones. The settings correspond to divergent environmental conditions. A vertical zonation appears that can be associated with a sequence stratigraphic model, that resembles a lowstand–transgressive–highstand cycle of relative sea-level changes.

A) Sandstone facies (basal part)

This sub- facies is distinguished into two different packages of sands (Part A and Part B).

Part A consist of non-cohesive sands that at its basal part appears light- olive to green- yellow color, of fine to medium sized grains and thin to laminate bedding. These organic rich sands having undergone oxidization since clear horizons of Fe oxides were observed at locations. Going- upward to the succession, the top sandy members turn into cohesive carbonate sandstone. Calcite concretions were observed in these profiles indicating low or moderate sedimentation rates by precipitation of calcite. These sands contain a rich fauna of macro- and microfossils, amongst which Ostrea, Pecten, Clypeaster and Heterostegina are most frequent. Trace fossils were also observed. Benthic foraminifera as Heterostegina are locally abundant inside these sandy depositions. All these facts are clearly indicative of a shallow marine environment such as an inner shelf environment, possibly exposed to air periodically. The sandstones seem very fragile, not very good compacted and cemented, medium to fine grained but without inner gradation in parts, of yellow to beige color. However, the laminated bedding observed in some locations shows a low energy environment. In juxtaposition of it,

Part B includes red to brown sands locally with abundant Ostrea shells, sometimes double-shelled (probably a restricted low energy environment or an inner barrier). These sands also appear as non -cohesive partly and as a sandstone in other parts of the outcrop with rare fossils inside, as we continue eastwards.

B) Carbonate- Rhodolith/Reef-like facies

This succession presents a cyclic variability that is the product of frequent, short-term changes in sea level and can be divided into structural cycles of the types of the deposits shown in the logs. Each cycle ideally consists of two interval strata grading into each other from bottom to top; a) coralline algae crusts and b) rhodolith beds. At the basal part of ***Part C***, reef-bioclastic limestone without inner -bedding or interchanges can be identified, containing aggregations of coralline algae. At the middle and upper parts of the sedimentary succession, the frame becomes either marly or sandy, characterized by in situ growth of calcareous organisms interbedded with sands. The framework of coralline algae gives the image of ‘crusts’ alternating with horizons of variant thickness of beds that contain medium-size nodules of rhodolith. These medium and upper parts of the succession show a thin bedding general appearance.

Analytically, at the east part of the succession rhodoliths appear small, as irregular size pieces that lie inside the debris- reefal carbonate mass but as the outcrop is developing upwards and westwards, their appearance is extensive and form well seen horizons of beds with a thickness ranging from 0.40m to 2m. The total height is 14m.

These strata are characterized of intensive cohesion partly, which mainly originated from the carbonate binder content of them.

This Rhodolith facies is not described by any researcher until now. Its extension both laterally and vertically is considered important and therefore is distinguished and described herein.

C) Carbonate Platform-Neritic Facies

Part D, (Akrotiri formation according to Freudenthal,1969) completely consists of white, sub-white to yellow, highly bioclastic, marly limestones appear massive of a strong cohesiveness but brittle in locations, very divided sometimes, locally abundant in coralline algae fragments and plentiful in fossil fauna of Neogene age (Echinoids, penctinoids, Dentalium, Ostrea, Balanidae). Sorting and grading are absent. It is this specific formation of Akrotiri that indicates a turn in the depositional environment between a deeper and a neritic neashore environment. A function of a transgression system track with NNE-SSW direction was operating during late Neogene era and the basin was uplifted at or near the sea level base. Bioturbation evidences of shallow water depth are observed at the surfaces. Its base can be conglomeratic or sandy. Very similar algal limestones are formed at present in the intertidal zones of some of the beaches of the islands.

D) Deep Marine Facies

Fine grained, white dense marly limestones, very well thin bedded. Also, mudstones with slump phenomena. Occasionally thin, marly layers are found interbedded. Macrofossils were not found. This formation is visible only at the eastwards of the section that is studied and overlies the Akrotiri Formation. No clear contact is observed between the formations.

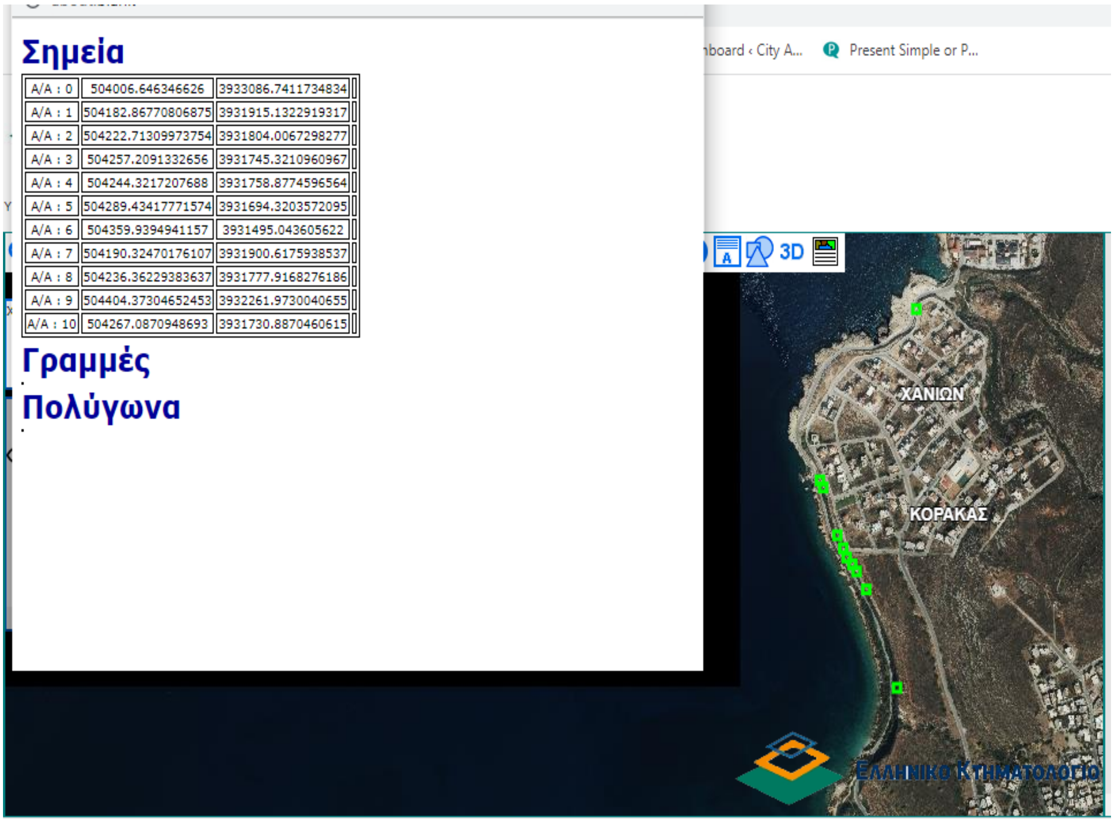
E) Mass Flow Facies

Sediments in the upper parts of the succession show an image that triggered by tectonics or other instabilities and redeposition in deeper water. It seems that steepening of the slope angle during refilling of the area at the beginning of Pliocene may have triggered slope instabilities resulting to flow of the deposits downslope.

Fieldwork

General Profile of 'Koumpeli' outcrop (E-W)

The profile of the sedimentary succession from which the samples for laboratory tests of ROCK EVAL have been selected is developed at the east of the city of Chania, at the location of the road –path that leads to the biological- cleaning industrial fascility of the city. The outcrop is about 1900m in length, considered of late Neogene age with a general array of E-W direction. It is formed mainly of carbonate sediments and silty sandstone deposits. The samples were selected mostly from the carbonate frame that is consisted of numerous coralline algae, interbedded by strata that are characterized by in situ growth of condyles of rhodoliths, multiple in diameter and size that consist of different lithofacies.



Picture 9. Map of Location of samples and their Coordinates

Picture 10. Satellite view of studied outcrop (Koumpeli outcrop, google.earth)

The Neogene succession of the study area, which exhibits cyclic variability attributable to high-frequency changes in the sea level, can be divided into distinct cycles as shown in the detailed logs. Each cycle ideally consists of two interval layers that pass into each other from bottom to top.

In general, rhodoliths occur in the basal part (layer) of the sequence as small, irregularly sized nodules lying within the rubble-reef carbonate mass, but as the outcrop section progresses upward and westward, their occurrence becomes more extensive, forming highly visible horizons of layers between 0.40 m to 2 m thick. The widespread and quantitatively important development of strata appear along the entire length of the slope (studied outcrop), until the western side of the park, which meets and overlies the sandstones of Agia Kiriaki.

Such deposits are very common when successively events in rotation caused by sea level rise, or by the fact that these areas are actually exposed to flooding conditions. These specific vertical movements correspond to changes in sedimentation, accumulation and in the structure and the morphologic type of the depositional settings.

Picture 11.Gentle Dipping platform with development of coralline algae lithofacies cropping out on the Eastern outskirts of Chania Region, West Crete.

Sections and data interpretation

General

A number of sections was logged in detail along the main outcrop of Koumpeli. The idea is the follow the side-to-side development of the Rhodolith bearing stratigraphic unit, in order to identify lateral changes in the sedimentary facies, depositional environments, thickness variation and every other possible observation to be made, for addressing and document the scenario of a potential reservoir of a Late Miocene age in western Crete. Every log-location is given with exact Geographical Coordinates (northern, eastern), along the road-path to Agia Kiriaki as mentioned above. Description of logs begins from the northeastern most location, moving to southwest.

Section 1

In this first location of description (N 35 31 56,3203 /E 24 02 53,7335), two main lithologies are to be clearly distinguished; the carbonates of the Akrotiri formation and those of the Coralline-Algae/Rhodoliths unit.

The former, comprises the upper part of the studied section and consists of white, sub-white to slightly yellow in colour bioclastic limestones, massive of a strong cohesiveness but also brittle in locations affected by faulting, sometimes with abundant in coralline algae fragments and locally plentiful in fossil macrofauna of Neogene age (echinoids, pectinoids, dentalium, Ostrea, Balanidae). Sorting and grading are absent. The Akrotiri formation unconformablyoverlies the coralline algae unit (lower part of the studied section). Thin sandy intercalations are present within the marlstones of the Red-Algae stratigraphic Unit.

The dip of Akrotiri formation beds has been measured at the bottom (lower) surface of it. Shows a NNE 10/27 direction and it is this exact inclination surface that the two different formations can be separated apart.

Picture 12.Sequence Boundary between Akrotiri Formation- Coralline algae Formation

At the basal part of this section the sedimentary succession is composed by a reef-bioclastic carbonate without inner -bedding or interchanges, frequently containing “aggregations” of coralline algae. At the middle and upper parts of the succession, the frame becomes either maerly or sandy, characterized by in situ growth of calcareous organisms (encrusting) interbedded with sands. The framework of coralline algae can be better described as ‘crusts’ horizons, alternating with horizons of rhodolith nodules. The medium and upper parts of the succession show a thin bedding general view while these strata are characterized of intensive cohesion-cementation, which mainly originated from the carbonate binder content of the matrix. The sedimentary profile is depicted below.

It is this specific formation of Akrotiri that indicates a turn in the depositional environment between a deeper and a neritic seashore environment. A function of a transgression system track with NNE-SSW direction was operating during Neogene era and the basin was at the sea level base. Evidence that should be under consideration:

The Akrotiri formation appears highly karstified at its base, a strong indicator of a sub aerial exposure erosional contact. Also, a normal fault system was detected. A small scale fault was measured, of a north inclination, conceivably occurred during sedimentation (synsedimentary faulting).

In this location at the west of the fault, samples of Balanus fossils were collected, large in size and quite plenty in number.

Picture 13. Balanus macro fossils

Section 2

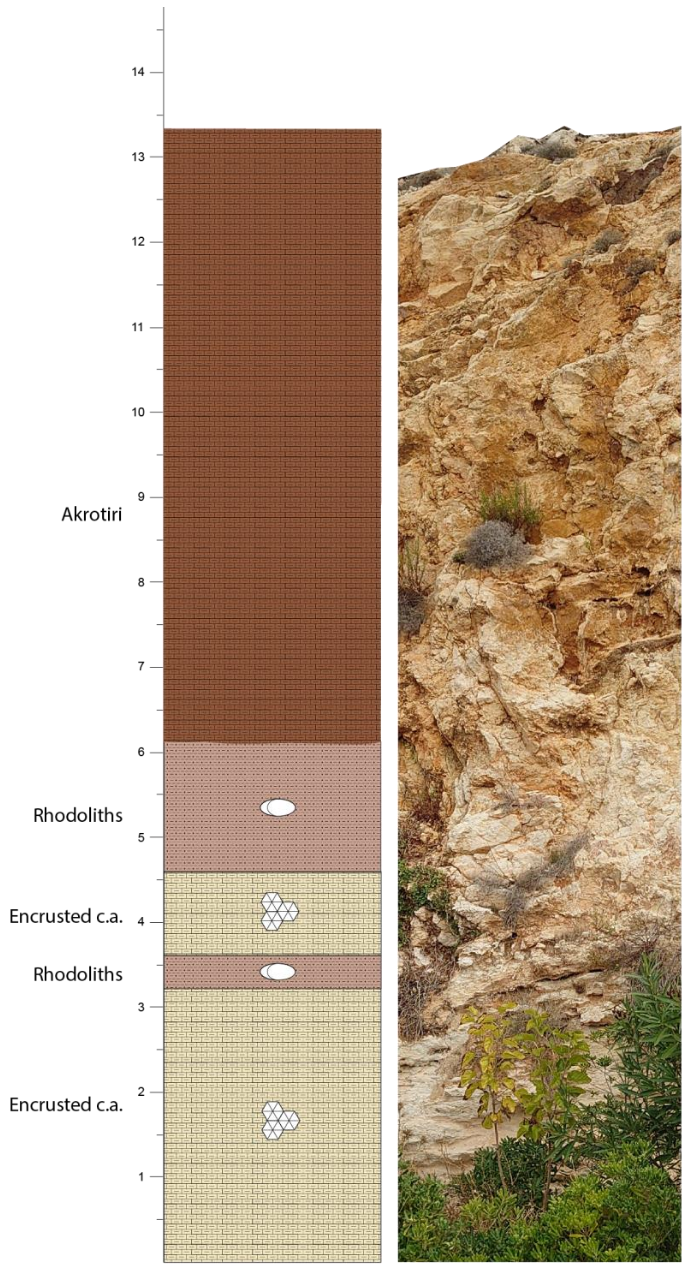
At this location (N 35 31 56, E 24 02 53) developing upward, five (5) Horizons of strata can be distinguished that are the following:

The first A1 Horizon of the reefal –debris carbonate, abundant in coralline algae with a total thickness of 3,20m that is considered as the base of the subsequent succession, appears hard that endures in shear.

Moving upwards, the first rhodolith stratum named as R1 Horizon of 40-45 cm thickness develops and exactly above it, the second A2 Horizon stratum begins. The bottom surface of R1 Horizon that contains the rhodolith nodules seems irregular, with a discontinues contact to the previous underlying A1 Horizon whereas the upper surface of R1 Horizon exhibits a rather linear, i.e. normal contact to the upper one. The A2 Horizon appears white, marly, thin-bedded and has a total thickness of 1m. The coralline algae crusts characterize the whole development of this stratum.

The succession continues with the second stratum (layer) of rhodolith nodules named as R2 Horizon, presenting a thickness of 1,5m above the A2 Horizon.

The sedimentary cycles of Profile 2, close at the top with the Akrotiri formation carbonates that unconformably (erosional contact) cover the R2 Horizon. The minimum thickness of Akrotiri formation is 7m in this location of the profile. A variable thickness red soil (terra rosa like) covers the Akrotiri formation, resulting by the uplift, subsequent karstification and oxidation. This layer is widespread all over the western Crete, where the area was uplifted and no Pliocene and/or Pleistocene sedimentation occurred.

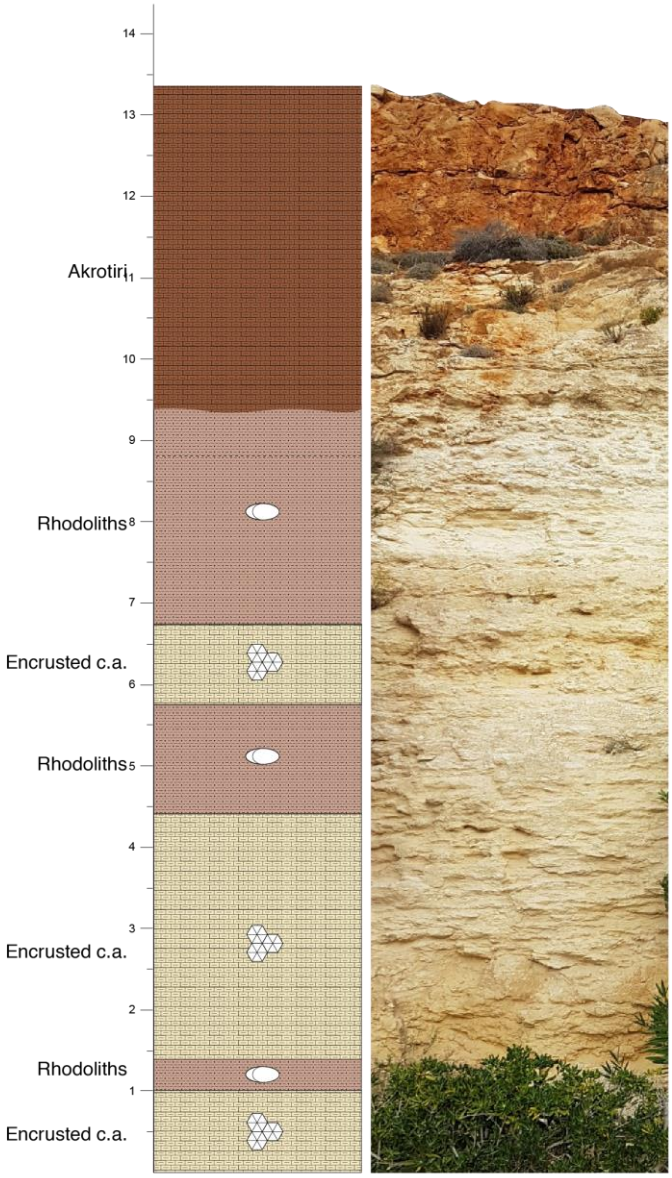


Picture 14. Sedimentary log_ Section_1 (from bottom to top: Encrusted coralline algae, Rhodoliths, Akrotiri Formation)

Section 3

In this location of description (N35 31 56, E 24 02 55) as the section prograding to the west, the strata thickness increases gradually and appear with gentler inclination, appearing at almost horizontal level; the inclination of the strata appears at almost parallel depositional strike, around 10 degrees dipping towards a NNE direction.

The thickness of A1 Horizon increases to 3m. Similarly, R1 Horizon of nodules of rhodolith to 1,30m. Moreover, subjacent of the A1 Horizon, is now revealed the A0 Horizon that at this place constitutes the base of the succession. The new A0 Horizon has a thickness of 1m in this location but also gains thickness while continuing westwards (Towards Agia_ Kiriaki church). The total thickness of the location profile is 14,40m. The Akrotiri formation reaches the height of 4m.



Picture 15. Sedimentary log_ Section_3 (from bottom to top: Encrusted coralline algae, Rhodoliths, Akrotiri Formation)

Section 4

At this location (N35 31 54, E24 02 55) there is a continuity of the sedimentary succession with all the previous strata as described above in full development. Moreover, a new occurrence of another cycle of alteration is observed at the bottom of the succession. The A2 Horizon now has a thickness of 2m and resemblance to a patch framework consisted of coralline algae crusts (encrusted algae) with very sharp edges at the surfaces of the crusts. Beneath the A2 Horizon, the strata of R1 Horizon has a thickness of 40 cm while a hard bench of biogenic carbonate thickness of 85cm can be clearly distinguished, where on its base, a small scale layer of rhodolith can be also recognized. The thickness of this layer is 10cm. The total thickness of the location profile reaches the 14.50m.

Picture 16. View of sedimentary sequence in full length development (E-W)

A characteristic structure of onslope starts to be formed (see Pict. 17), a structure that is clearly observed within the stratum of coralline algae carbonate at the location N35 31 54, E24 02 54 a little further to the west.

Picture 17. Onslope structure inside the coralline algae strata

At N3531053, E24 02 55 a sample was selected between the two layers consisting of coralline algae, which position is remarked due to the appearance of a laminated to thin- bedding layer, grey to green color, its matrix dominated by carbonate material but also containing pieces of coralline algae on the top of it.

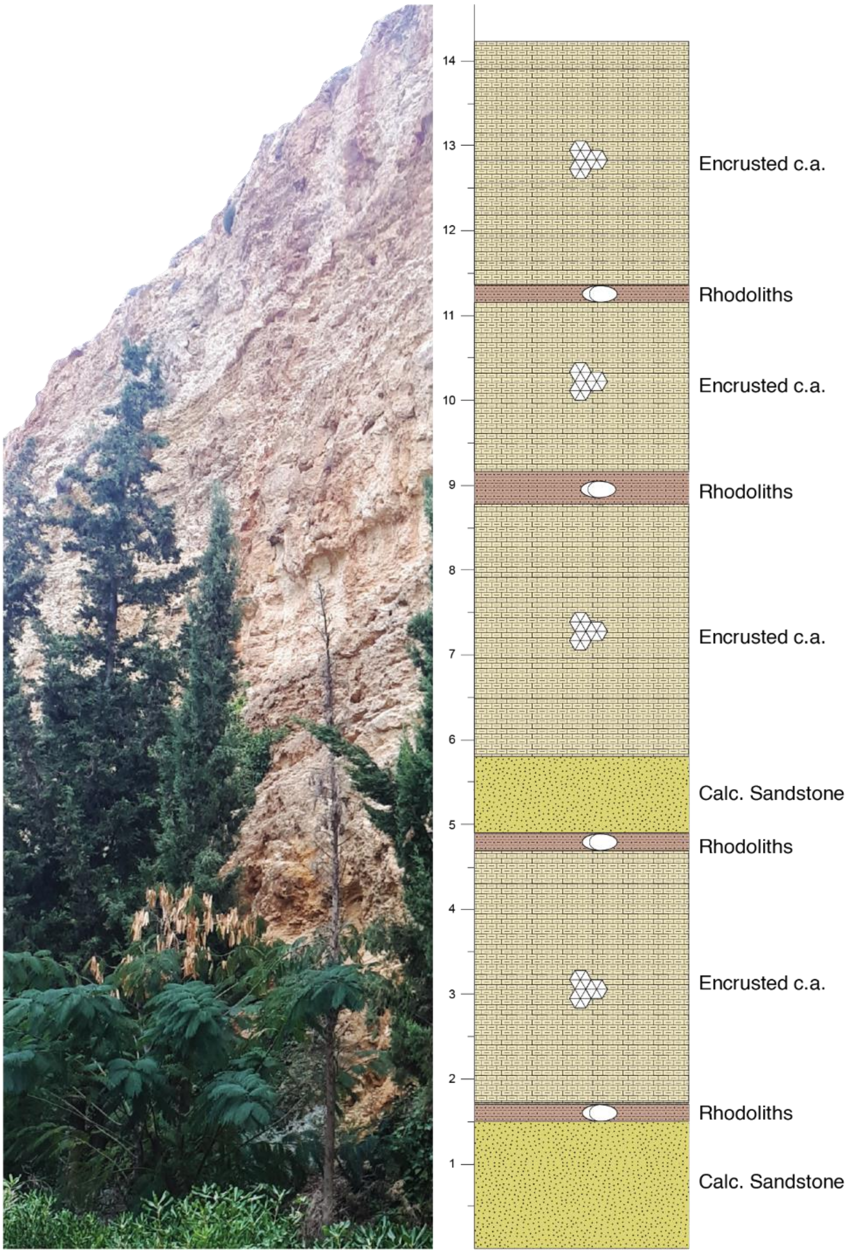
Picture 18. A green zone (layer) within two coralline algae strata, Sampled for Rock-evaluation

Section 5

In this location (N35 31 47, E24 02 58) the appearance of a bioclastic amorphous sandstone, with a thickness of 25-60cm which is also containing coralline algae is observed. These sandy members appear in benches within the strata of rhodoliths.

At its base, this bioclastic sandstone seem eroded, fragile, without any inner-bedding, fine-grained, sub-yellow to beige colored. Likewise, the strata above are continuing to alternate with rhodolith strata that appear with a thickness ranging between 10 to 60 cm. Several rhodolith diameters of their nodules were measured, found to be between seven (7) cm to twenty (20) cm. It should be mentioned that within the bottom horizons of these sandstones there are layers that also consist of coralline algae in their cohesive parts; where these pieces grow large in numbers, the layer becomes amassed and the sediment subsequently becomes harder (seem like encrusted algae). These layers are also rich in fragments of fossil bivalve shells.

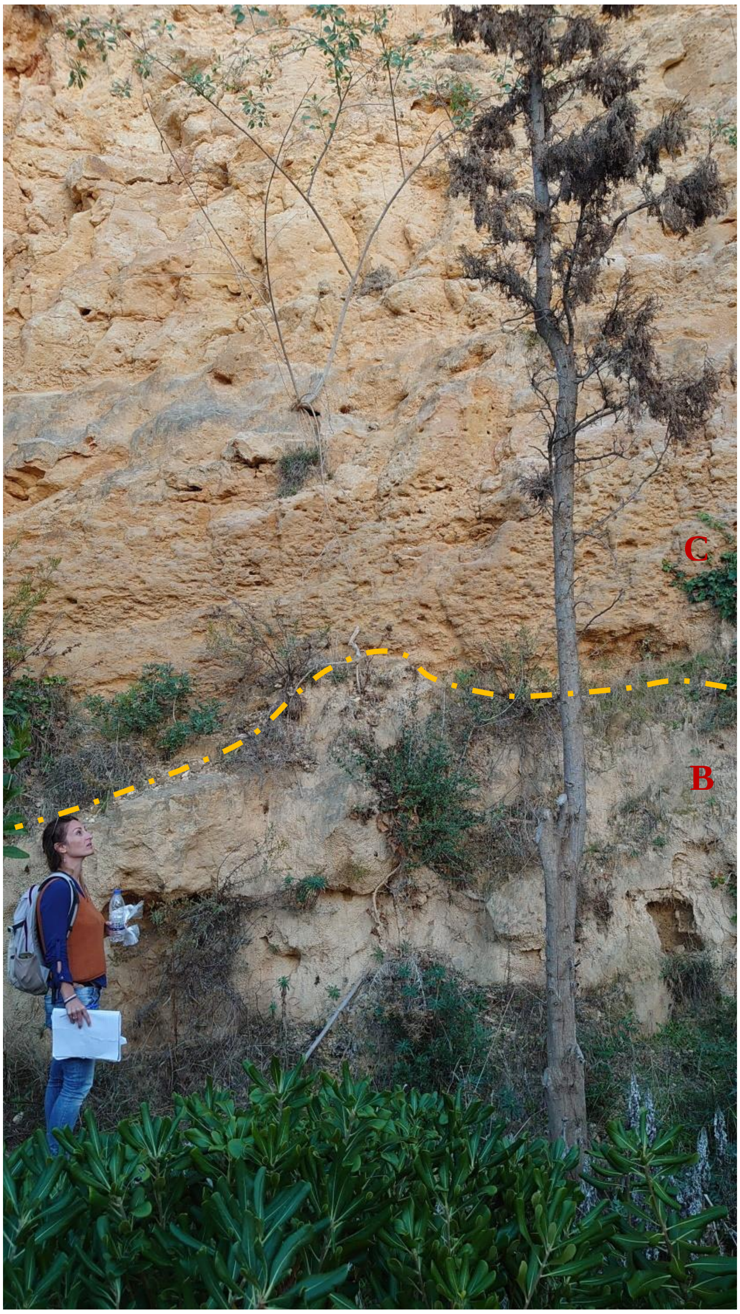
In this location and inside these bioclastic sandstones Echinoids of the genus *Clypeaster* were observed, an indication of Late Miocene age. Moreover, their appearance in living position shows a non-high kinetic energy in these settings during sedimentation, which permits an interpretation aa a low energy paleodepositional environment.



Picture 19. Sedimentary log_ Section_5 (from bottom to top: Calcareous sandstone, Rhodoliths, Encrusted coralline algae)

Moving further westwards, at another location (N 35 31 46, E24 02 58) there is an undulated contact (see: Picture 15) observed between the benches of the sandy members of Part C (calcareous sandstone) and a clastic, soft sandy formation; thickness 1.80m in the specific point (Part B). It may be due to overload of superimposed sediments.

These sands are mainly silty, soft (lack of adhesive carbonate or other material) thin to midium-grained, yellow to beige colored and without inner bedding structure. At the base-contact of these sands with the upper stratum of bioclastic sandstone, the latter appears ideally soft. (Samples 13,14,15).



Picture 20. Undulated contact between the Sandstone (part B) and coralline algae sandy members of Part C

Section 6

At this location (35.528069 24.048874) it is clearly that the well bedded carbonate strata which are composed of rhodoliths nodules overlap an older sandstone formation. This silty sandstone appears yellow to beige - brown colored. The formation is very fragile and can be easily split apart, very eroded at the surface, with cavities and hole- forms. The thickness of it, reaches 6m at this profile. At the base appears as non-cemented sands thickness of 1m. A trough cross sedimentary structure is observed within the benches of the sandstone.

From the top of these benches of sandstone, the succession turns to the carbonate formation with the alterations of beds between marls-sandy marls with condyles of rhodoliths and the appearance of coralline algae, total thickness of the formation is 10m. At this location seven sedimentary cycles can be distinguished. The thickness of each cycle is noted as below:

1st cycle: 1.50m

2nd cycle: 1.50m

3rd cycle: 2.0m

4th cycle: 1.0m

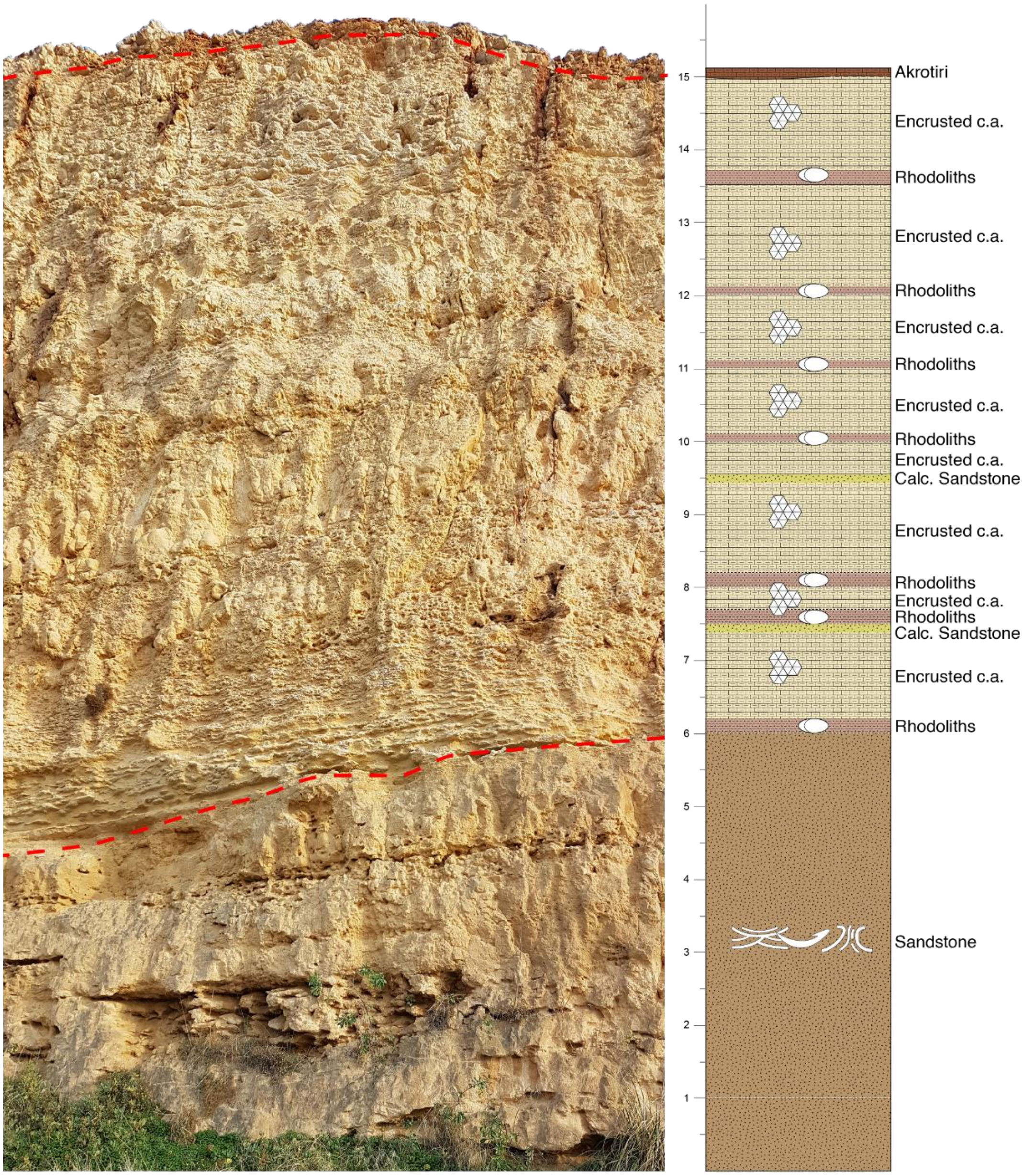
5th cycle: 1.0m

6th cycle: 1.50m

7th cycle: 1.50m.

At the upper parts of the succession (12-14m), slump structures can be identified, proof a general unstable condition in the depositional environment. The Akrotiri formation at this location cannot be seen or forms a thin eroded bed of 1m the most. The total thickness of the section is 16m.

Some depositional structures are even indicative of very specific processes, for example, herringbone cross stratification indicates a tidally-dominated environment. After deposition, various forces acting on the sediments can alter the preserved structures. An understanding of the combination of processes that lead to erosional, depositional, and post-depositional structures in a sediment can lead to sound reconstructions.



Picture 21. Sedimentary log_6. Alternations of 7 "sedimentary cycles" each one mainly composed of two different morphological types of coralline algae grading into each other as developing upwards: a rigid bindstone of patches of coralline algae that resemble a 'crust-like' pattern and a rhodolithic floatstone composed of various diameter of red algae nodules. At the base, the Sandstone B is clearly to be seen (below the red dashed line).

Trough cross-beds have lower surfaces which are curved and truncate the underlying beds. The cross-beds reflect the steep faces of ripples and dunes. These steep faces tilt down-current and thus indicate current flow direction. Cross-beds are commonly curved at the base; this gives a handy way of determining right-side up in complexly deformed rocks. In generally such conditions reflects mild environment of carbonate deposition that can be found in shallow tidal channels. In such environments cross beds primarily depict bidirectional orientation whose strike signifies the direction of paleo-coastline.

Picture 22. Trough Cross bedding inside the part B sandstone in 'Koumpeli' outcrop

In the photograph below you may see float marks which are observed within the sandy members of Part C that show water directional movement at the time of deposition.

Picture 23. Float Marks between the contact of sandstone (Part B) and Part C, Water influx direction

Section 7

At this location as we have reached the margin of the basin the below profile is observed that indicates the closure of the basin at that area.

The Akrotiri formation overlies a grey to yellow -beige colored-marly limestone that consists of a fine- grained, sandy to silt part as well. The part of the sand is around 10 %.

A carstified surface is observed at the contact of the two formations with terra rosa development that indicates eroded conditions within the time that the two deposition settings took place. The discontinuity plane separating both complexes points to a radical change in marine morphology.

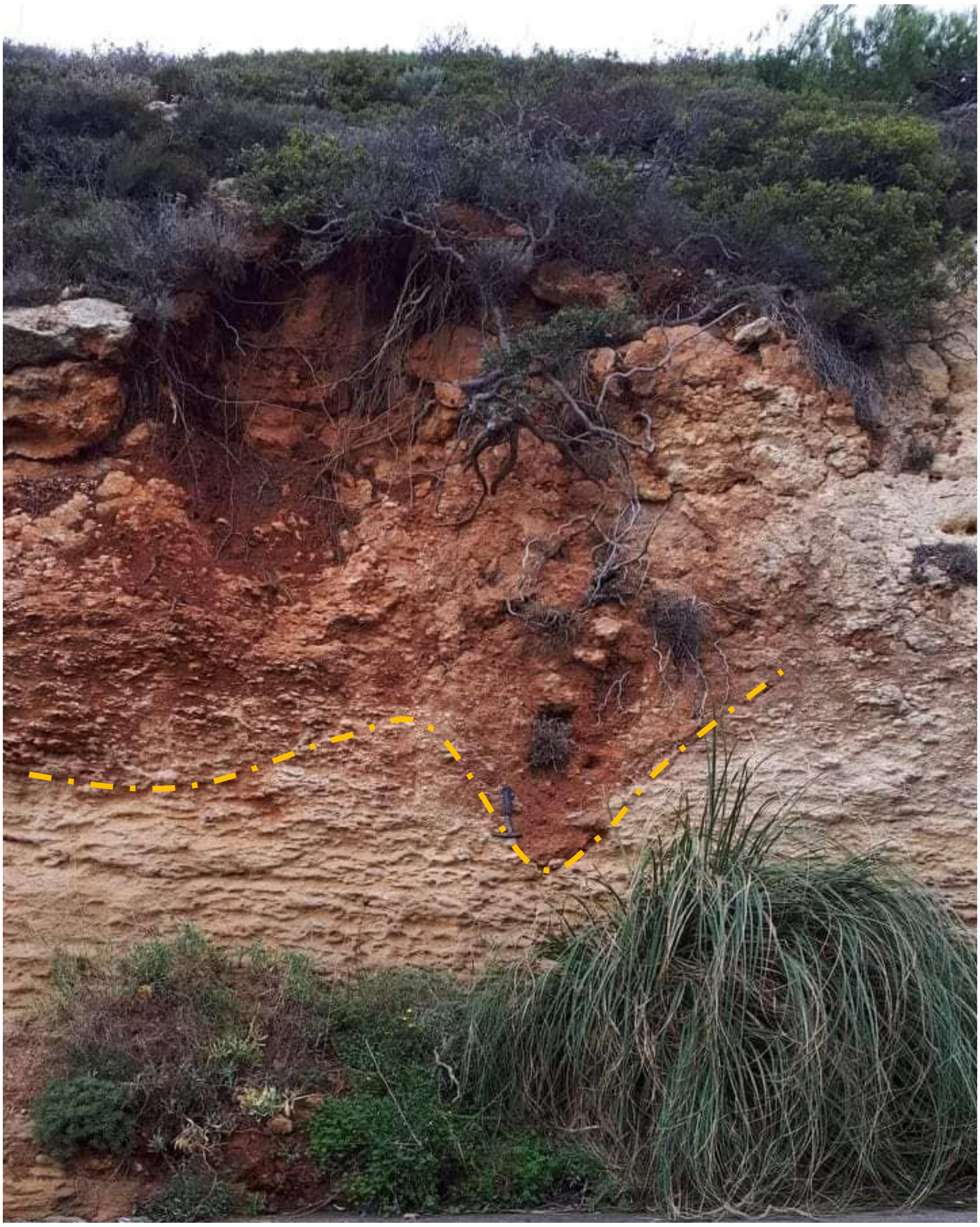
In a near position, underneath the Akrotiri formation and in juxtaposition of the marly limestone two complexes can be distinguished. The first one is a horizon composed of rhodoliths and underneath of it a well bedded marlstone with coralline algae in it.

The karstified surface between the contact of Akrotiri and the horizon of Rhodoliths is less intense than it appears between the Akrotiri and the marly limestone formation as described above. The transition now seems almost gradual from the one to the other. The observation leads to the fact that little time of disruption of sedimentation occurred before sedimentation was reactivated.

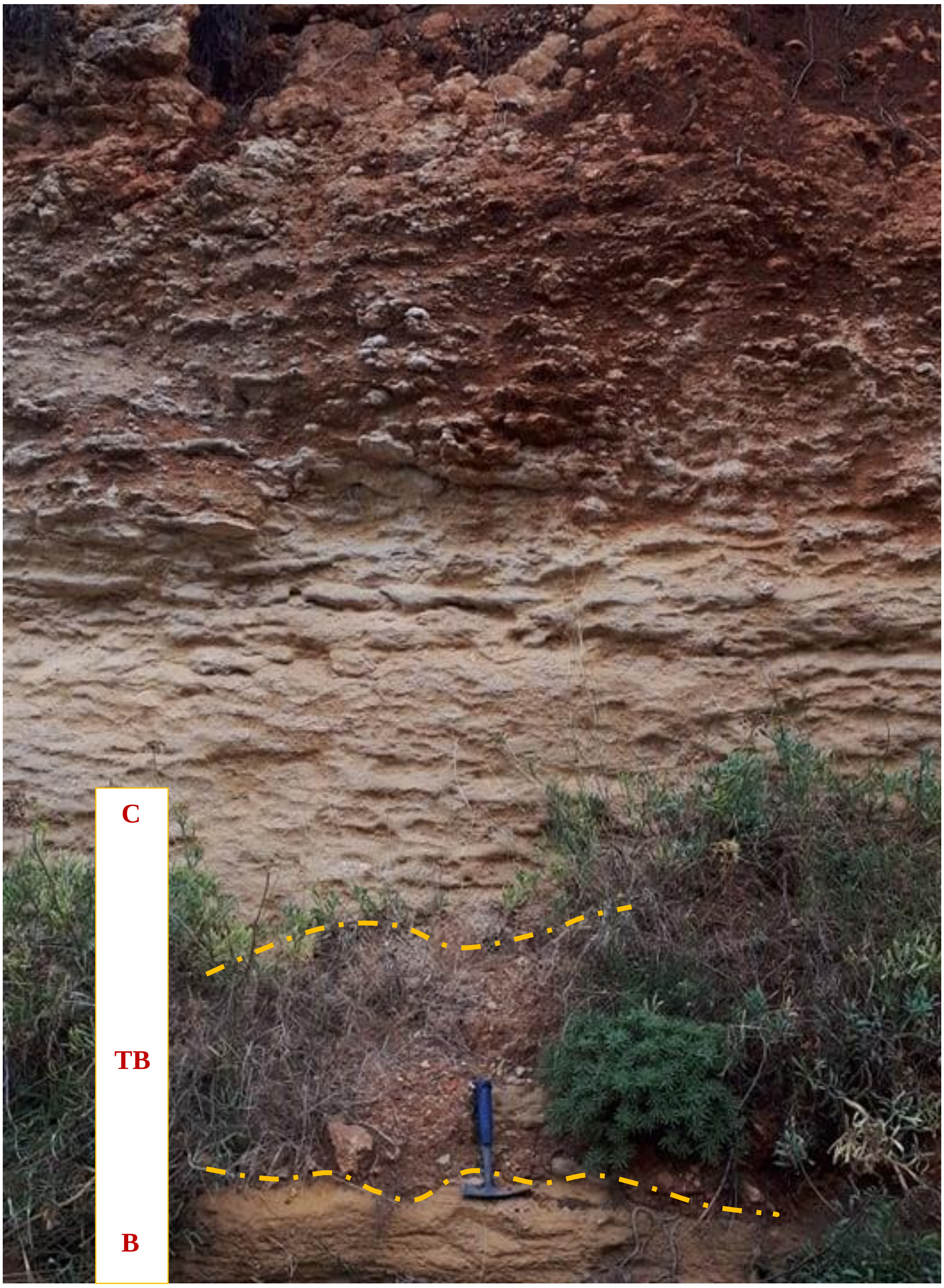
Fossil fauna that are founded inside the marlstone point out to benthic foraminifera and fragments of pencten, pinna, lumanchella. Lumachela originate from bioclastic sedimentation that are formed through the accumulation of organic remains of animals characterized by the presence of a shell or a rigid mineralized skeletal structure of the type: lamellibranches, gastropods, brachiopods, ammonites, echinids and nummulites, but also of corals and plant organisms such as some calcareous algae. Then comes the diagenesis, a transformation process that hardens the original sediments, which often includes, in these lithologies, an abundant deposition of crystalline calcitic cement, called sparite, in the original porosities of the sediment and the internal cavities of the organic remains not filled by the sediments during deposition and burial.

Normally the formation environment is found in sea depths of modest depth, within the photic zone where remarkable colonies of molluscs can be found. The bioturbation marks (barrows) that are observed refer to organisms escaping from burial. On the whole, several kinds of structures produced by organisms are attributed to a rather low-energy tidal or shallow water depth environment.

As the profile continues towards the shore, Akrotiri formation is not present at the top of the succession and the sedimentary succession ends as a hard ground (paleosol), indicator of a sub aerial exposure. Rhotholiths strongly prevail at the whole section. A great amount of sands that obtain declare the closure of a sedimentary cycle and the further swallowing of the water depth. The surface contact between strata of rhotholiths and coralline algae marlstones has an undulating shape. An inner channel that crosses these two formations, probably by Miocene age can be observed at this location (see: picture 24).

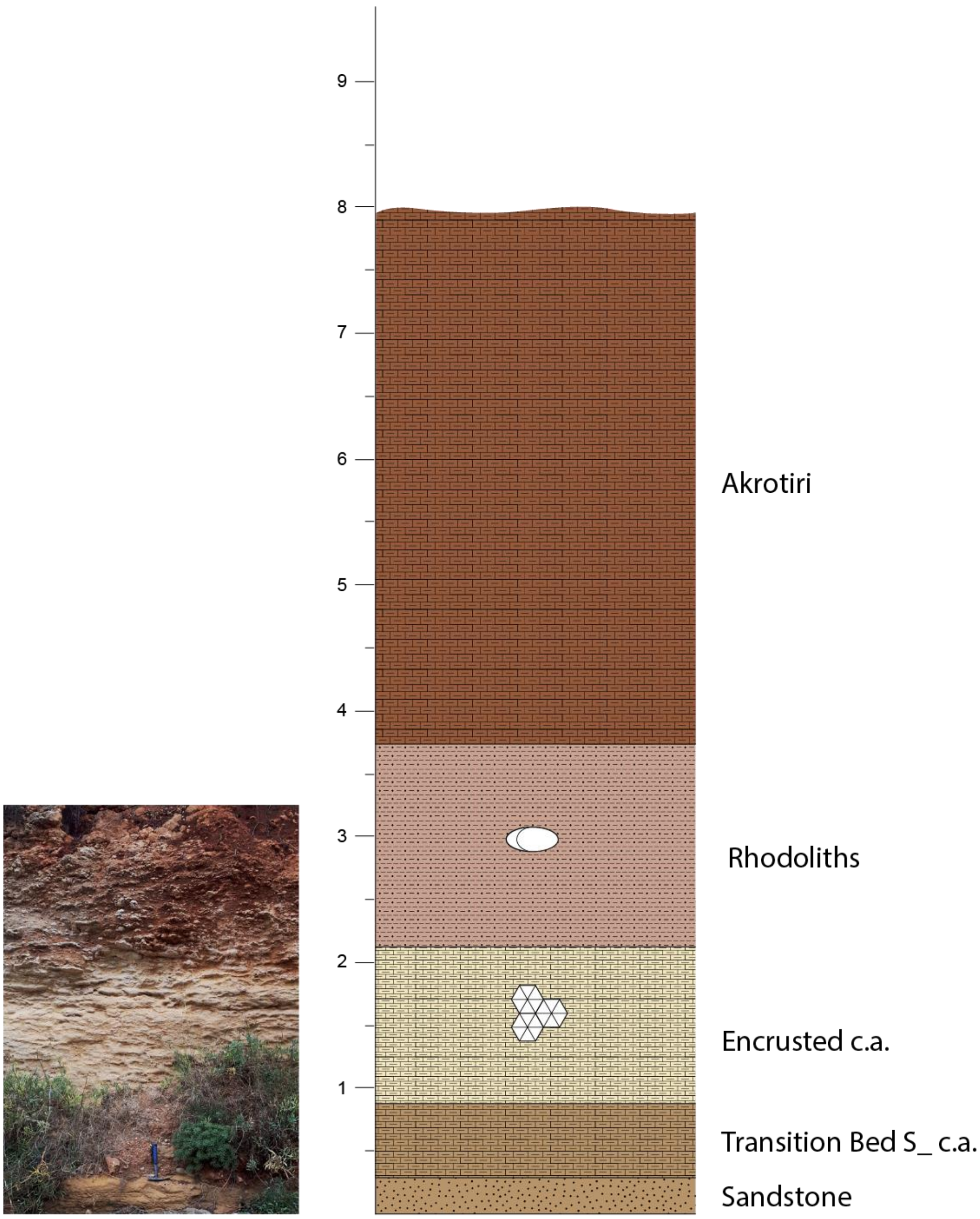


Picture 24. Inner Miocene channel within the Coralline algae formation



Picture 25. Transitional beds. From bottom to the top: B: Sandstone, TB: Transitional bed (sandy –coralline algae), C: Coralline algae formation

The diagnostic features facts that deposition must have taken place at shallow depth, above wave base. Slight bioturbation in several types at sandy units is being related to tidal deposits.



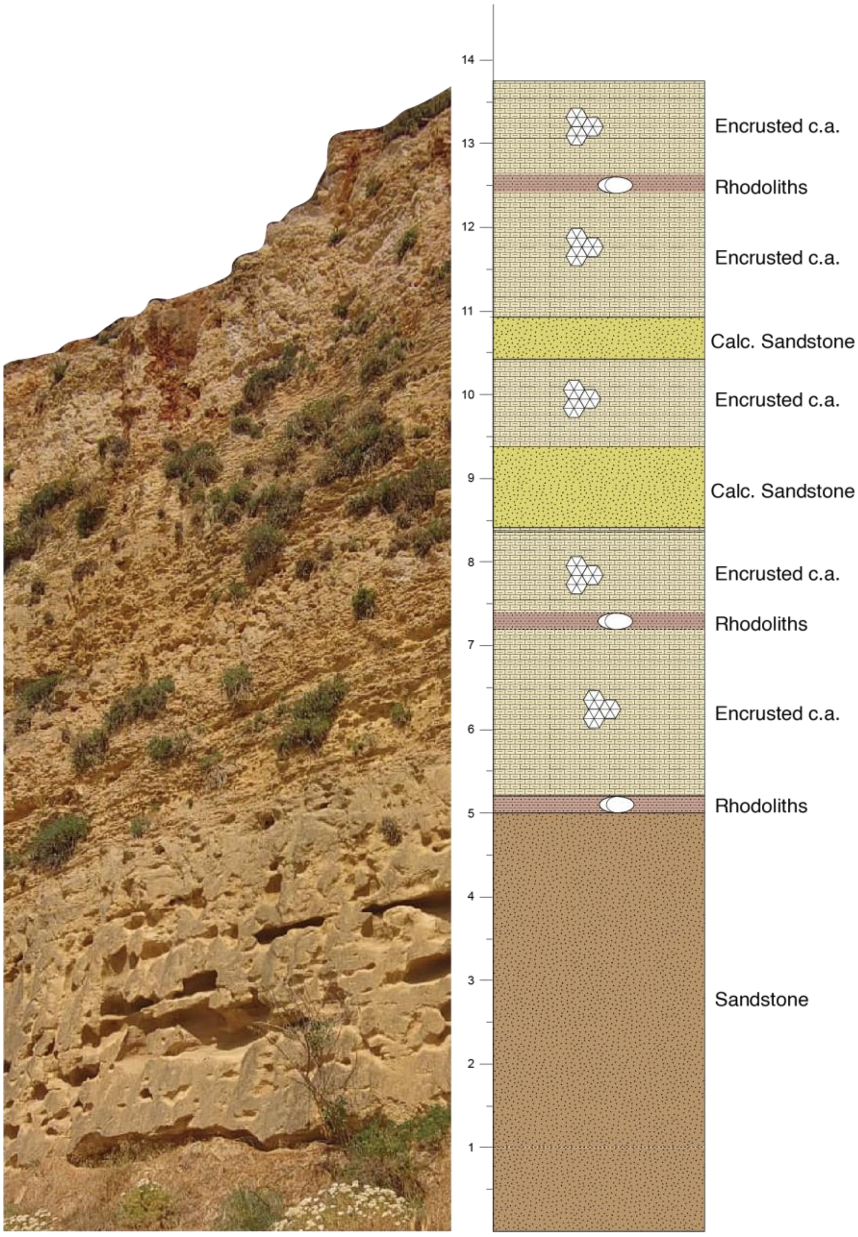
Picture 26.Seddimenary log-Section 7. From bottom to the top: B: Sandstone, TB: Transitional bed (sandy –coralline algae), C: Coralline algae formation

Section 8

The same profile can be seen as the section continues further westwards to Agia Kiriaki port (35,528069 24,0048874). The sandstone is the main formation with a total thickness of 15m from the sea level (5m at the profile). The sandstones seem very fragile, not very good compacted and cemented, medium-grained but without inner gradation, of yellow to beige to brown color. However, laminated bedding is observed in a near location that shows a low energy environment.

The succession continues upwards with the development of the carbonate strata by the in situ growth of nodules of rhodoliths for 1m of thickness and upwards the coralline algae crusts as patches carpet semblance. These alterations within patches and rhodolith beds continue till 15m height (see: Picture 24, 25). Due to erosional conditions there are large- scale broken pieces on the ground by the strong detachment of the upper layers.

Picture 27. Contact between the red to brown sandstone (Part B) and the rhodolith beds (Part C). Sandstone reaches 8m height at the location



Picture 28. Sedimentary log_ Section 8. Alternations of coralline algae beds grading into rhodolith (Part C) overlying the sandy formation (Part B).

The Akrotiri formation lacks of appearing in this profile section but is appearing on the top of this succession further on the hill. These sandstone contain a fauna of macro fossils, amongst which *Ostrea and Pectenids*, are the most abundant that indicates a marine (near shore) environment.

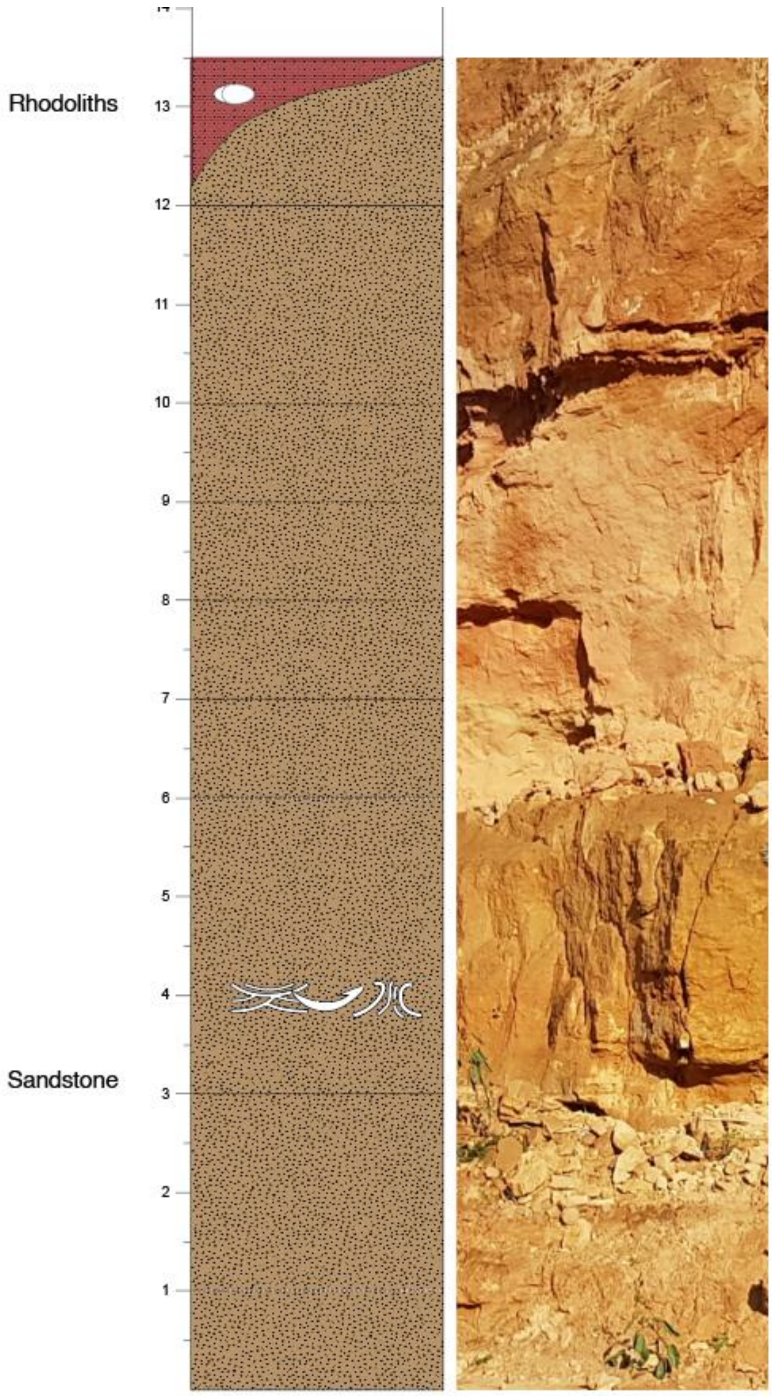
In a near location this normal profile with the basal sandstone and the rhodoliths on the top ends. The sands are covered by an irregular appearance of rhodoliths strata or are not covered by any other Neogene strata. The angular discontinuity between these two strata points out to a fluvial source of the latter stratum. Calcite concressions development for some meters at the top of the sandstone show a source and a contact with fresh water (see: Picture 30).

Picture 29. The contact between the 8 m sandstone (Part B) and the overlying rhodolith beds (Part C) in situ.

Picture 30.Calcite concressions at the top of the sandstone show a near source and contact with fresh water

Picture 31. Lateral evolution of Part B in a probably more lagoonal environment; *Ostrea* biostom on the top is observed.

Picture 32. Sandy formation (Part B) with an *Ostrea* biostom at the top layers. Height =8.20m.



Picture 33. Sandy formation (Part B) with abundance of *Ostrea* bivalve shells. Total Height =13.5m (from the bottom to the top: Sandstone.- reworked Rhodoliths transferred by currents)

Section 9

Agia Kiriaki Port

Alongside of Agia Kiriaki church, the Neogene sedimentary succession includes a non-cohesive sandy formation that at its basal part appears light- olive to green- yellow color, of fine to medium sized grain and thin to laminate bedding (Part A). These organic rich sands having undergone oxidization since clear horizons of Fe were observed at locations.

Going- upward to the succession, these sands turn into the overlying cohesive carbonate sandstone. Calcite concretions were observed in these profiles indicating low or moderate sedimentation rates by precipitation of calcite. Ostrea (in an opposite state position) and Penctinidae fragments were collected from the sandstone formation. Also, trace fossils and Echinoids (*Clypeaster*) were observed. *Heterostegina* is abundant inside these sandy depositions.

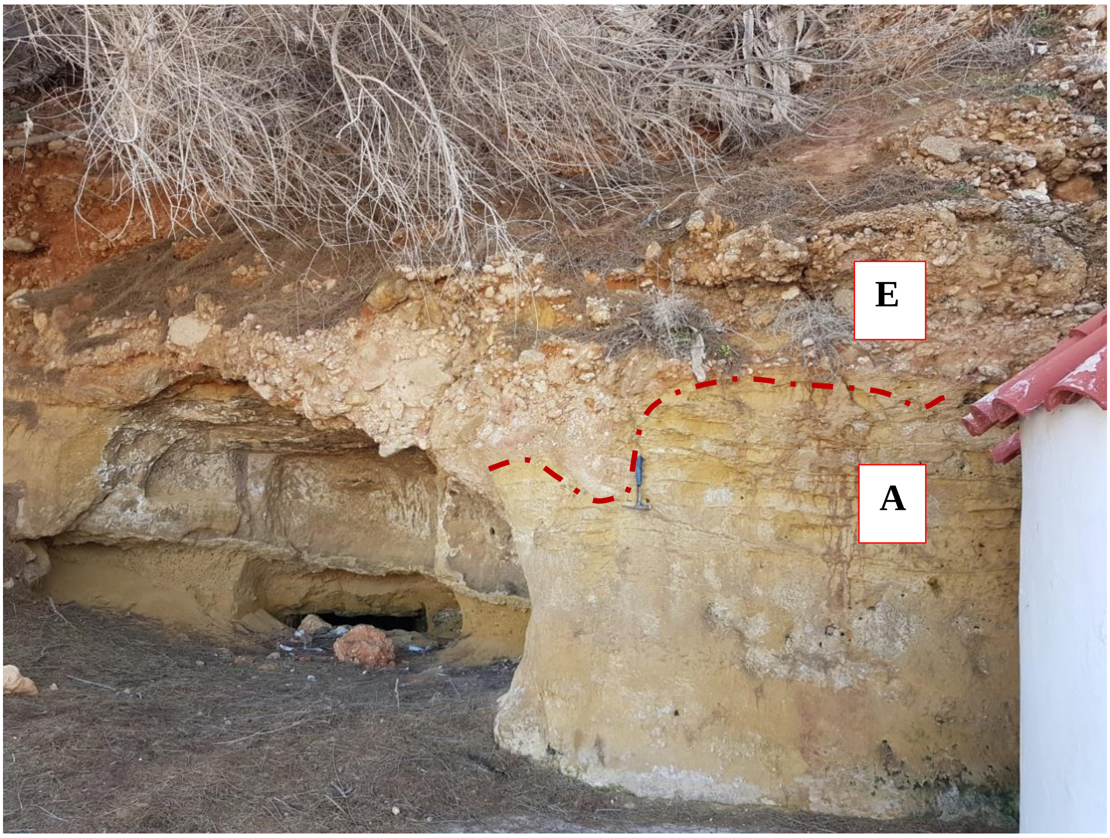
However, *Heterostegina* sands constitute a skeletal consecration that is known to be formed during events of low net sedimentation, during short in time or prolonged intervals of sedimentation starvation, dynamic bypassing, winnowing or erosional reworking (Sensu Kidwell at al., 1986). No direct observations in the field allowed us to observe the lateral transition between the *Heterostegina* sands and the previous red sandstone (Part B).

Picture 34. View of *Heterostegina* Sands (Part A) in Agia_ Kiriaki Port

However, several arguments allow supporting a same age lateral correlation in a near environment.

Picture 35. General View of *Heterostegina* Sands (Part A) in Agia_ Kiriaki Port

In addition, a clast- supported, irregular- coarse grain sized conglomerate have been observed. The contact between the conglomerate and the sands is strongly erosive. The fluvial conglomerate stratum is composed of gravel sized debris of rhodoliths derived from the Neogene carbonate frame that appears at the East side of the section, dispersing into it by flow and mixed up with sand. It characteristically has a chaotic texture, it is probably of Quaternary age or contemporaneous and attributed to channels and paleocurrents that were active at the time. The water washout the older Neogene sediments and redeposit them by the flow. The general frame of size, amount and the roundness (angular) of the fragments prove a near source of rhodoliths and a strong sudden tectonic event.



Picture 36. Paleo–channel, chaotic texture-redeposited rhodoliths, A: Basal Sandstones, E: Channel of Quaternary age

Paleo- current directions were identified where was possible indicating an Eastwestward direction flow. Many structures of flow were observed inside the fluvial system. (see: picture 36,37).

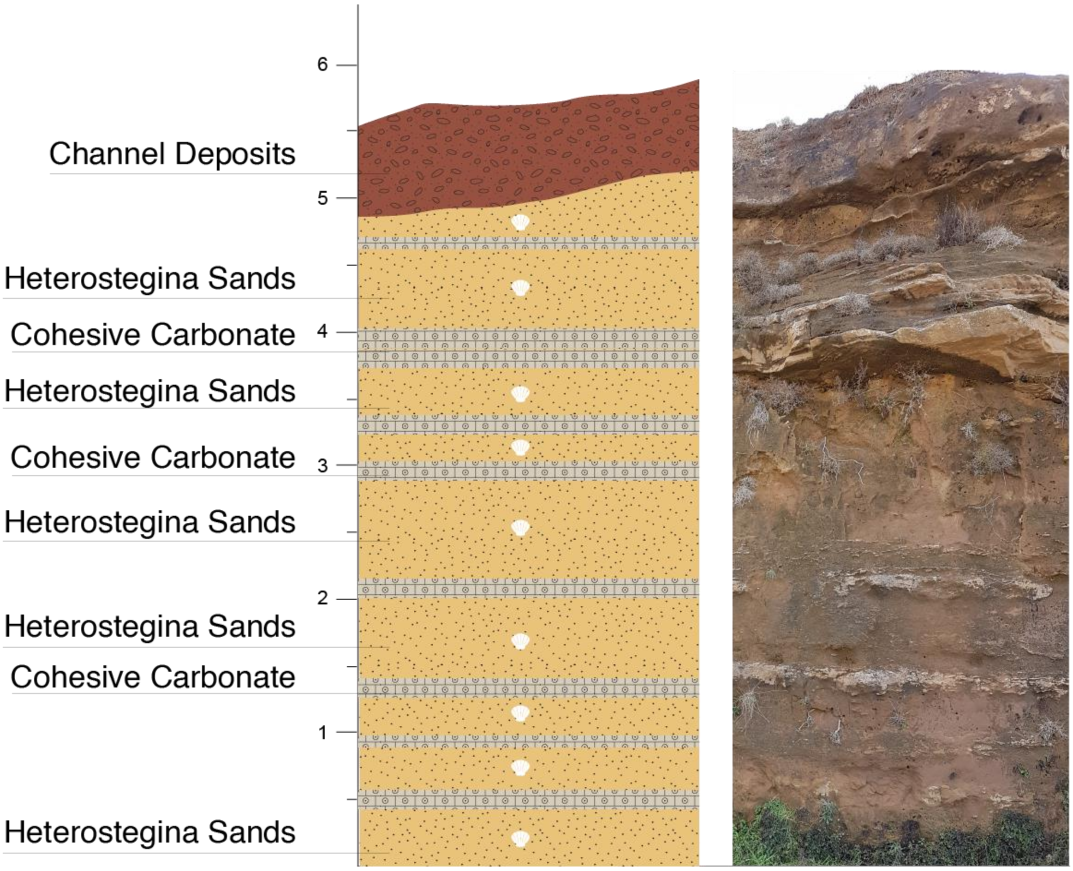
A local fault system was observed that is influencing the sandstone formation, a fault of N-W inclination and of Southwestward direction was measured. The upthrow was 40cm.

Also, another local fault system with upthrow of 30-40cm directly affects the conglomerates above the sandstone formation.

Fragments of fresh sea water shells were observed in these sandstones. The general view of this sandstone (color/ fine- grained/shells/laminated bedding/limited compaction) facts the depositional environment that lacks of high wave energy.

This environment is characterized by two concomitant factors, the steadily water supply and the low energy of wave; in general representing a shallow water environment.

Indicators of marine environment the fossil fauna content such as fragments of echinoids and molluscs that are common and larger benthic foraminifers such as *Heterostegina* are present as well (*Heterostegina*, *Ostrea*, *Clypeaster*).



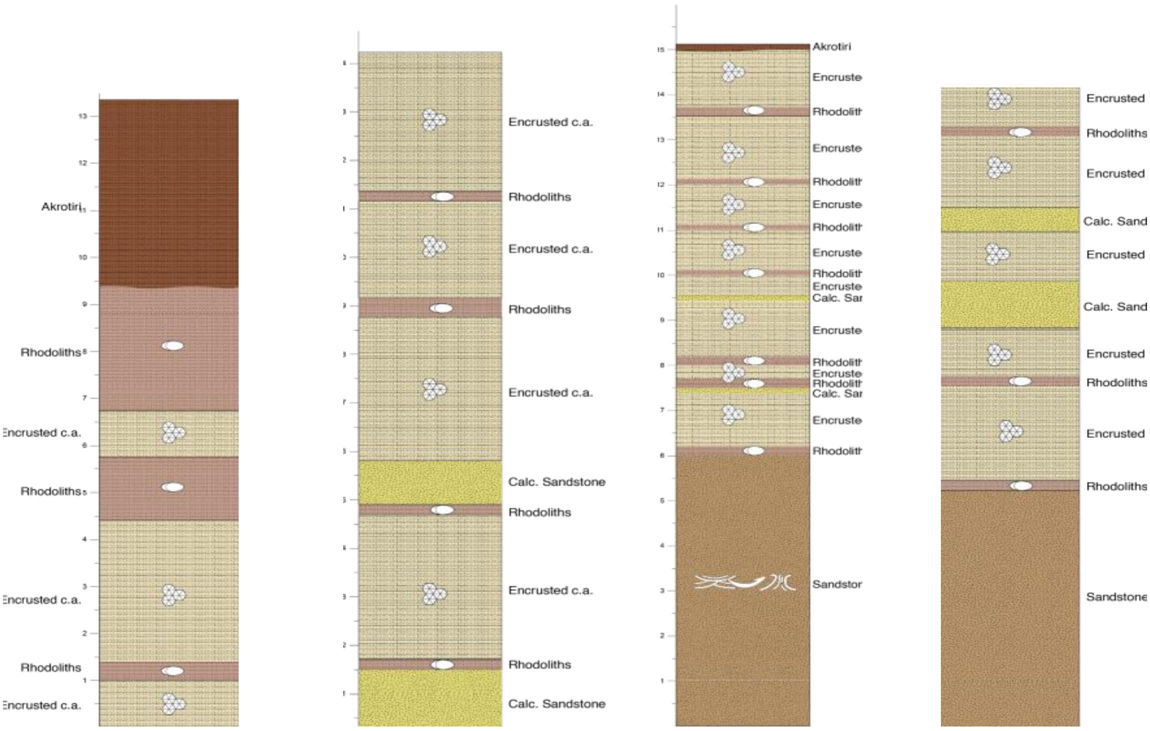
Picture 38.Sedimentary log-Section 9. Heterostegina sands alternated by cohesive carbonates , on the top: Channel of Quaternary age

Depositional Profile

From the general observations on structures, the type of the strata and the position of the fossils that are found correspond to a transition between a shallow marine and a floodplain environment with fluvial channel deposits that were developed at that west side of the ramp and diminish at the eastern side of the ramp. A geological setting is proposed for the area with respect to neighboring Neogene basins and the eastern Mediterranean domain during the Late Miocene. Several events of base-level drops associated with area restriction and re-flooding are correlated with eustatic lowering of base-level and were amplified by regional uplift following the onset of the transgressive movement. Lateral and vertical development and correlation of the strata along the studied sections is depicted below (see: Pict.38).

The effect of frequent, low amplitude sea-level fluctuations is to produce facies heterogeneities in sedimentation. Elevation of base level during water level rises resulted to the inner- and middle ramp lithofacies to develop; whereas lowering of base level during water level falls increased erosion and down-slope sediment transport.

Within the ramp slope, alternations of a rigid bindstone of patches of coralline algae that resemble as ‘crust-like’ pattern with a rhodolithic floatstone composed of various diameter of nodules is the result of high-frequency sea-level cycles.



Picture 39. Vertical and Lateral development of the outcrop. Correlation of sedimentary loggings from East to West

Akrotiri Formation

The section of the sedimentary succession that samples were selected is a profile of NW-SE direction and of NE inclination in the region of Kalathas, at the East of Chania city.

The formation was initially evaluated with regards in its mineralogy components. The formation is reported as a carbonate sedimentary rock consisting by white to yellow bio-clastic maerly limestones inter-bedding with sandy horizons as the succession prograding upwards whereas the total section height was defined at 20-22 m.

The formation is referred at the literature by Bonarelli (1901) as "pietra di Malta" and by Freudenthal (1969) as Akrotiri Formation of Neogene age. Later on it was included in the Vrysses group of van Hinsbergen & Meulenkamp (2006). According to the later author, the Akrotiri Formation consists of unbedded and of thick well bedded, white or yellow limestones or marly limestones. These limestones are composed of organic detritus, mainly of algae and in minor quantity of shell debris or complete mollusc shells. Its basal part is generally developed as coarse- to medium-grained, brown, uncemented sands, but occasionally also with conglomerates. These sands are containing a rich fauna of macro- and microfossils, amongst which *Ostrea*, *Pecten Clypeaster* and *Heterostegina*. At most other localities, where the base of the Akrotiri Formation is exposed, it is overlying preneogene shales or black crystallized limestones (the preneogene basement being usually metamorphic). This formation is not overlain by other Neogene strata but in the Apokoronou district laterally passes into or overlain by the Khairethiana Formation.

At the section studied, at the base of it there are no evidences of preneogene rocks or other formations of Neogene. Permeability, granular size and the porosity should be further laboratory evaluated in a future work.

At the section four different horizons were identified, with discrete changes in the inner core, even though they are referring in the exact same paleo-geographic shore line system. The horizons from bottom to top are as follows:

1. At the basal part the A0 horizon that begins from the road level and continue up to 3-4 m. It is consisted of a white, cohesive strong bench of limestone with hard split. No bedding can be seen inside of it.
2. The A1 horizon, as a white to subwhite massive limestone plentiful in fossils but very brittle in regards with the A0 horizon. The total height of the horizon reaches the 5-6m. In the inner a huge amount of marine fossils can be intensified such as Lamelibranchians, bryozoa and debris of shells of organisms in varied sizes. The ages will be further evaluated in the lab ().In the inner part of this horizon and especially as prograding upwards at the upper beds, distinguished light compact white carbonate horizons of 2 cm thickness can be observed. These horizons point to the conclusion of possible light changes in the deposition conditions such as the change in the depth of the water (shallowness) and reveal a relatively calm and steady deposition environment.
3. The in between A2 horizon that the latter A1 of the white limestone passes into gradually. The upper parts seem fine grained, more soft and clearly more easy to split. The transition between the two is smooth, with the lower parts having a massive appearance whereas the upper parts of the succession look squamous. This horizon is middle bedded with no cross bedding but rather with parallel beds with a little North

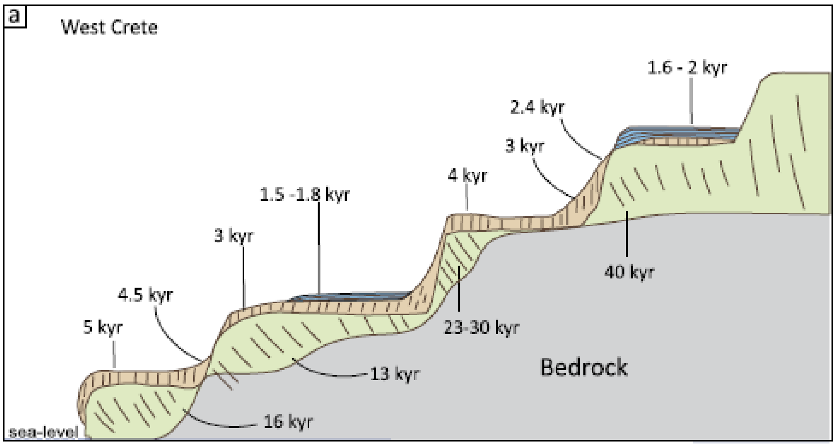
inclination. The beds are of 0.4-0.5m thickness and are more discrete in relative with the A1. The total thickness of the horizon is 7m

4. Lastly, the horizon A3, consists of alterations of almost parallel or with little inclination of middle size limestone slabs and amorphous layers of the same inclination of sandstones- silty-stones of yellow to sub-yellow color. The limestones have a middle well bedded with 0,3-0,4m. It is characteristic feature that the horizon begins with an amorphous layer of sand-silt-stone of subyellow color and of 0.8m thickness containing thickly gravels of 3cm diameter size. Total thickness of the horizon is 4-5m.

In the middle horizon A2 and in the upper A3 two small scale vertical faults were observed with a subsequent small offset-slip between the two parts.

In the opposite profile of the section five (5) horizons of different levels that paleaogeographical declare successive withdrawal of the water in a near shore marine environment – a neritic environment. They considered as paleoshorelines. These cycles represent sea level changes rather of Late Quaternary age, that affected western Crete not only at its northern part but also at its southern part (co. Mouslopoulou et al., 2015). Sea level changes probably coincide with successive climatically driven changes, rather than with tectonic movements, since they seem very consistent and they are organized in well denoted cycles, a fact that is rather impossible to represent tectonic expulsions and uplifts.

Picture 40. Upper part: Akrotiri Formation and at least five (5) observable sedimentary cycles of shallow marine bioclastic carbonate sediments, Kalathas area. Lower part (below): Beachrock stratigraphy for western Crete according to Mouslopoulou et al. (2015). Compare the great similarities in the two figures.



Geochemical Results

As a test of the first scenario, i.e. looking at the Rodolith sedimentary facies as possible Source Rocks (SRs) of Neogene age in Crete, RockEval pyrolysis was performed on 23 samples in total along the "Koumpeli" outcrop. The results of the TOC measurements are presented linked to the depositional paleoenvironment, indicating the paleo-biological interaction within the geological framework and the oceanography of the specific location during Late Miocene.

Sampling applied on three different litho-bio-facies of the outcrop:

a. the Sandstones Member (stratigraphically the lower lithofacies B)

b. the coralline Red Algae/Rhodolith Member (medium lithofacies, C), and

c. the bioclastic limestones (uppermost member, s.s. Akrotiri Formation)

and

d. to transitional facies of the above.

Picture 41. Sampling of carbonate deposits, 'Koumpeli' outcrop

The geochemical analyses of the Rock –Eval pyrolysis are given below in Table 1. The studied samples show generally very low TOC values, ranging from 0.01% to 0.23%. The ratios show a stability and similarity in all samples with small variations, an indication of stable conditions in organic matter input and integration.

Although carbonates have abundant algal organic matter, this organic material has been probably oxidized coming in contact with fresh waters or the succession material remained uncovered for a period of time, thus the high percentage of organic matter couldn't be maintained. However, a sufficiently high organic content to serve as a hydrocarbon source could be a possible scenario in other regions of Crete where the marine sedimentation is still constant and continuous. The difference in the quantity and quality of organic material between the different layers and sections could also be associated with specific depositional environments in the region.

Table 1 : *Results of Sample Analysis*

Analysis	Sample	S1 - (mg/g)	S2 - (mg/g)	Tmax(°C)	S3 - (mg/g)	TOC(%)	HI	OI	MINC(%)
smpl_1.r00	smpl_1	0,00	0,00		0,08	0,04			8,8
smpl_1r.r00	smpl_1r	0,00	0,01		0,10	0,05			10,0
smpl_2.r00	smpl_2	0,01	0,04		0,42	0,09			9,6
smpl_3.r00	smpl_3	0,00	0,01		0,79	0,15			8,6
smpl_4.r00	smpl_4	0,00	0,00		0,46	0,01			10,7
smpl_5.r00	smpl_5	0,00	0,00		1,29	0,18			10,7
smpl_6.r00	smpl_6	0,00	0,00		0,51	0,08			9,5
smpl_7.r00	smpl_7	0,00	0,00		1,15	0,15			10,7
smpl_8.r00	smpl_8	0,00	0,00		1,00	0,16			9,9
smpl_9.r00	smpl_9	0,00	0,01		0,96	0,17			9,8
smpl_10.r00	smpl_10	0,01	0,02		0,80	0,19			9,6
smpl_11.r00	smpl_11	0,00	0,00		0,73	0,15			9,3
smpl_12.r00	smpl_12	0,00	0,01		1,43	0,24			9,1
smpl_13.r00	smpl_13	0,00	0,00		0,63	0,13			10,1
smpl_14.r00	smpl_14	0,00	0,00		0,57	0,11			9,7
smpl_15.r00	smpl_15	0,00	0,10		0,23	0,02			0,0
smpl_16.r00	smpl_16	0,00	0,01		0,68	0,20			5,5
smpl_17.r00	smpl_17	0,00	0,01		0,43	0,01			9,1
smpl_18.r00	smpl_18	0,00	0,01		0,54	0,02			0,3
smpl_18r.r00	smpl_18r	0,00	0,01		0,51	0,02			10,7
smpl_19.r00	smpl_19	0,00	0,01		0,50	0,10			10,0
smpl_20.r00	smpl_20	0,00	0,00		0,85	0,12			10,7
smpl_21.r00	smpl_21	0,00	0,00		0,57	0,11			7,1
smpl_22.r00	smpl_22	0,00	0,00		0,69	0,16			9,7
smpl_23.r00	smpl_23	0,00	0,01		0,89	0,23			8,9

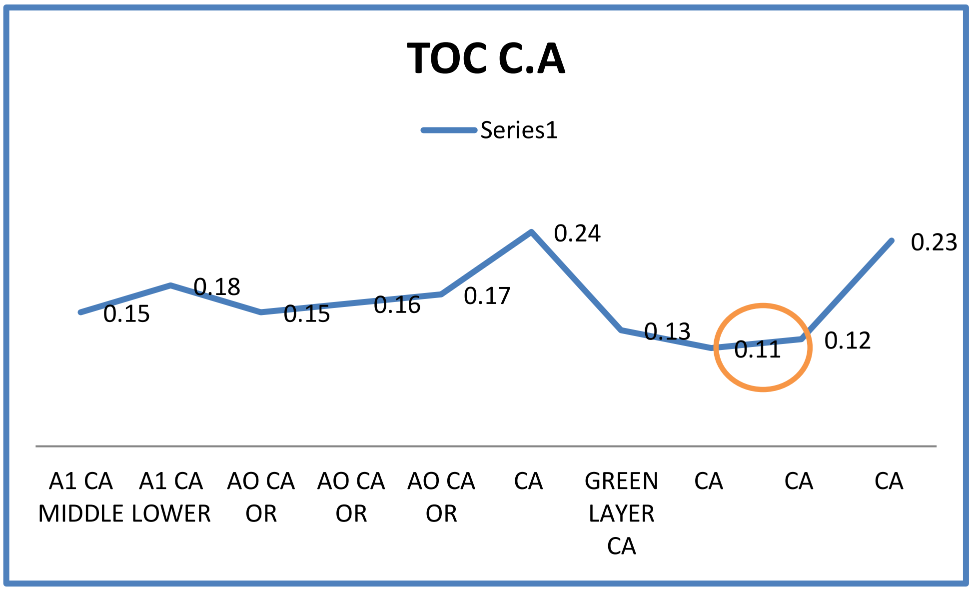


Diagram 1.TOC values of coralline algae Fm.; high wave energy > depletion of TOC)

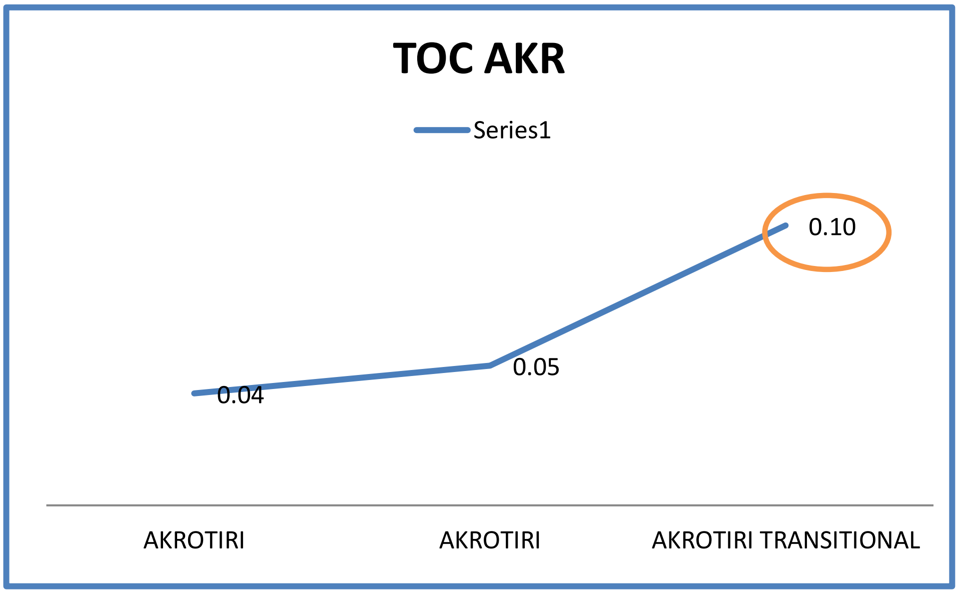


Diagram 2.TOC values of Akrotiri Fm., very shallow marine environment; high wave energy > depletion of TOC)

It is noticeable that the lowermost TOC values of Coralline algae formation, are the highest resulted from the Akrotiri Formation. Also, these low values of TOC pointing to a high energy environment which prevailed during the deposition of the Akrotiri bioclastic limestones.

Analogue Reservoir and source Rock Potential – Examples worldwide

In general, the reservoir is a porous and permeable rock that hosts capable amounts of hydrocarbon reserves. Analysis of reservoir requires an evaluation of their porosity, in order to calculate the volume of hydrocarbons and their permeability in order to validate how the hydrocarbons flow inside the rock; chemical processes result to texture, composition, distribution and consequently have a role over properties such as over porosity and permeability. Porosity and permeability in turn affects mechanical properties and its reservoir potential. Thus, understanding the factors controlling the coralline-algal carbonate formations is crucial for exploitation of reservoirs. On the other hand, the seal rock is a formation of low permeability that prevents the loss of hydrocarbons from the reservoir rock. Frequent seals include evaporates, chalks and shales. Analysis of seals involves assessment of their thickness and extension; additionally, the trap is a stratigraphic or structural feature that ensures the seal of the reservoir such that hydrocarbons remain trapped. In order to prove the mechanism of migration on hydrocarbons movement from the source rock to reservoir many studies required; these studies lead to quantify the source of hydrocarbons in a particular area. (Elia, 2013). According to Elia, potential reservoirs might be turbidite sands and sand formations rich in carbonate material of Pleistocene age, biomicrites, bioarenites, fossiliferous micrites and calcarenites of Miocene age and Jurassic and Cretaceous age porous sediments.

Very essential is the observations that oil and gas are excellent stored within grain-supported, coralline-rich layers, while mud supported, highly fractured beds represent their preferential transport line (Wennberg et al. 2006). Also, Coralline-algal and benthic foraminifer packstones considered as the best reservoir potential since they have high porosity and permeability values (Büyükutku 2009).

For example, one of the best oil reservoirs in coralline limestone is the Lower-Miocene age Zujiang Formation in the South China Sea. These carbonate strata, consisting predominantly of coralline algae and corals, are the reservoir of Liuhua 11-1 huge oil fields that provide 1 billion barrel of oil in place, (Heubeck et al. 2004). The top part of the succession is mainly composed of rhodoliths and is one of the *highest-porosity layers of the reservoir* (Sattleret al. 2004).

Also, the quality of a reservoir can be improved by fresh-water diagenesis; such the example from Karaisalı Limestone Formation of the Adana Basin in Southern Turkey, deposited in a tropical environment in Lower Miocene. The formation is the reservoir of the small Bulgurdağ oil field. The skeletal grain combination is consisted of coralline-algae, corals and benthic foraminifers (Büyükutku 2009).

Another great example of reservoir related to coralline algae is the Malampaya-Camago gas field (Nido Formation) (Fournier and Borgomano 2007). The Nido Formation is a reef-bounded isolated platform; the reservoir is a reef-related carbonate formation, including red-algal floatstone (Moore 2001). Reservoir quality was affected by the original position of the carbonate deposits relative to the open ocean. On the ocean-ward margin, porosity-destructive marine cementation was dominant. Reservoir characteristics at Malampaya-Camago field are then controlled by the platform early diagenetic factors, driven by sea level and climate, and are not influenced by lithofacies (Moore 2001).

Physically, porosity is the volume percentage of “void” space in a rock, whereas permeability is defined as the rate of flow of water at a given pressure gradient through a unit volume. As mentioned above good reservoir rocks must possess high porosity and permeability values and a high proportion of open pore spaces enhance the capacity of a reservoir to store fluids.

Porosity (φ) based a reservoir can be categorized as below:

- Low: $\varphi < 5$ %
- Medium: $5\% < \varphi < 10\%$
- Medium-good: $10\% < \varphi < 20\%$
- Good: $20\% < \varphi < 30\%$
- Very good: $\varphi > 30\%$

In order to estimate the reserves in a possible reservoir, the volume V that refers to the true value of the space of a reservoir that is dominated by the oil fluids should be calculated.

Analytically and taking into consideration the Vt term that refers to the (total) volume of the tank, the true volume(1) that remains to the fluids can be directly estimated as below:

$$V=\varphi*Vt \quad \textbf{(1)}$$

where, φ is known as the porosity.

In a first approach to estimate possible volumes and subsequently reserves in this individual occurrence, we had two stable (known) parameters and an unknown one. Based on the latter, differentiation, three scenarios were evaluated. The dimensions of the reservoir have been measured in the field in both directions (x-length and y-thickness) in several locations and an average height (thickness) value was attributed to the reservoir rock while it was not possible to measure the z dimension (extension in width) due to the physical geometry of the section. Therefore, the three scenarios based on hypothetically different values of width (z) and were evaluated accordingly. We have to say that this is a rough hypothesis, based on the widespread rhodolith beds observed in the surrounding area of the studied outcrop.

In the first scenario a width value of a) W_1=1km was attributed in the section, in the second b) W_2=1,5km while at the third c) W_3=3km.

Firstly, using the term (2) the total volume of the orthogonal shape reservoir of specific dimensions of an average height H= 14m, and length L=900m was easily calculated and consequently using (1) the true volume of it is given. The results can be seen in the *Tables 3,4 and 5* assuming the three different values of width (i.e. lateral extension of the Red algal unit, below the Akrotiri formation which dominates the whole peninsula), respectively and taking into account the porosity values of coralline algal limestones and rhodoliths from published data in the literature. According to Florian Nitsch (2015) the porosity within rhodoliths can develop through two mechanisms:

a) constructional voids are present as primary voids within single cells and conceptacles and as voids produced by conjoined protuberances of coralline algal thalli and

b) de-structional voids are caused by dissolution and decay of nuclei as well as soft-body organisms and bioerosion.

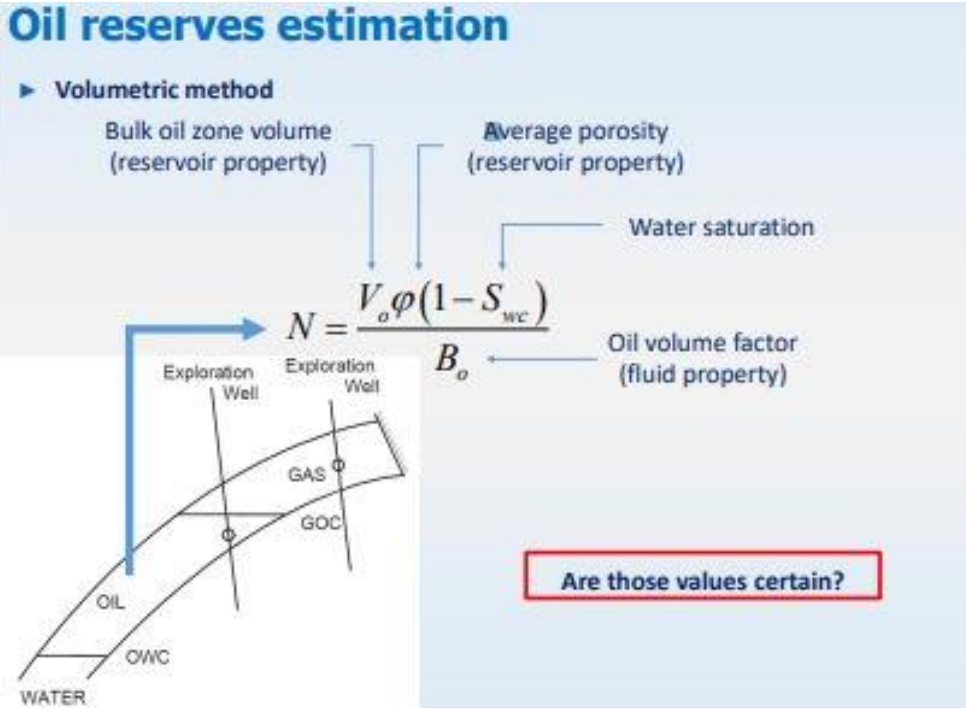
The range of values that was measured presents a great variation, ranging between 3% and 45% in volume (Nitsch, 2015).

$$Vt=L*W*H \quad \textbf{(2)}$$

where L, W and H : the main dimensions of the reservoir, if we try to simulate it as a simple parallelogram,

and Vt: the total volume of the potential (simulated) reservoir.

Due to the fact that the reservoir assumed as a tank, the total volume of oil reserves is known that is given by the below term:



Picture 42. Oil Reserves Estimation (Petroleum Engineering Master Course, Web_ Notes, 2021)

__Table 2__: Dimensions of the Reservoir (where L=length=Width, H=Height)

Dimensions	m	m	m
H	14	14	14
L	900	900	900
W1,W2,W3	1000	1500	3000

__Table3:__ Scenario1, Actual Volume of Reservoir

V(m^3)	ϕ	Vtotal
378000	0,03	12600000
567000	0,03	18900000
1134000	0,03	37800000

__Table 4__: Scenario 2, Actual Volume of Reservoir

V(m^3)	ϕ	Vtotal
2520000	0,2	12600000
3780000	0,2	18900000
7560000	0,2	37800000

__Table 5:__ Scenario 3, Actual Volume of Reservoir

V(m^3)	ϕ	Vtotal
5670000	0,45	12600000
8505000	0,45	18900000
17010000	0,45	37800000

Based on the geological setting we could conclude that the rhythmical carbonate deposits of the shallow waters (Corallinacea unit) could potentially serve as a reservoir rock or even a source rock.

In order to act as a **source rock**, it would be crucial to have been sealed immediately after their deposition in order for the organic matter not to be oxidized. Maybe in a deeper part of the basin, where sedimentation is still continuing till present this could be a possible scenario.

In contrast, the most realistic scenario of this case study is that the coralline algae carbonate member of the sedimentary succession could act as a potential ***__Reservoir rock__***. Once again this scenario requires the hypothesis, that the reservoir is also to be found in the deeper offshore area, therefore an adequate seal would have been developed and existed before the migration, in order to "keep" the potential hydrocarbons trapped (talking for a stratigraphical trap).

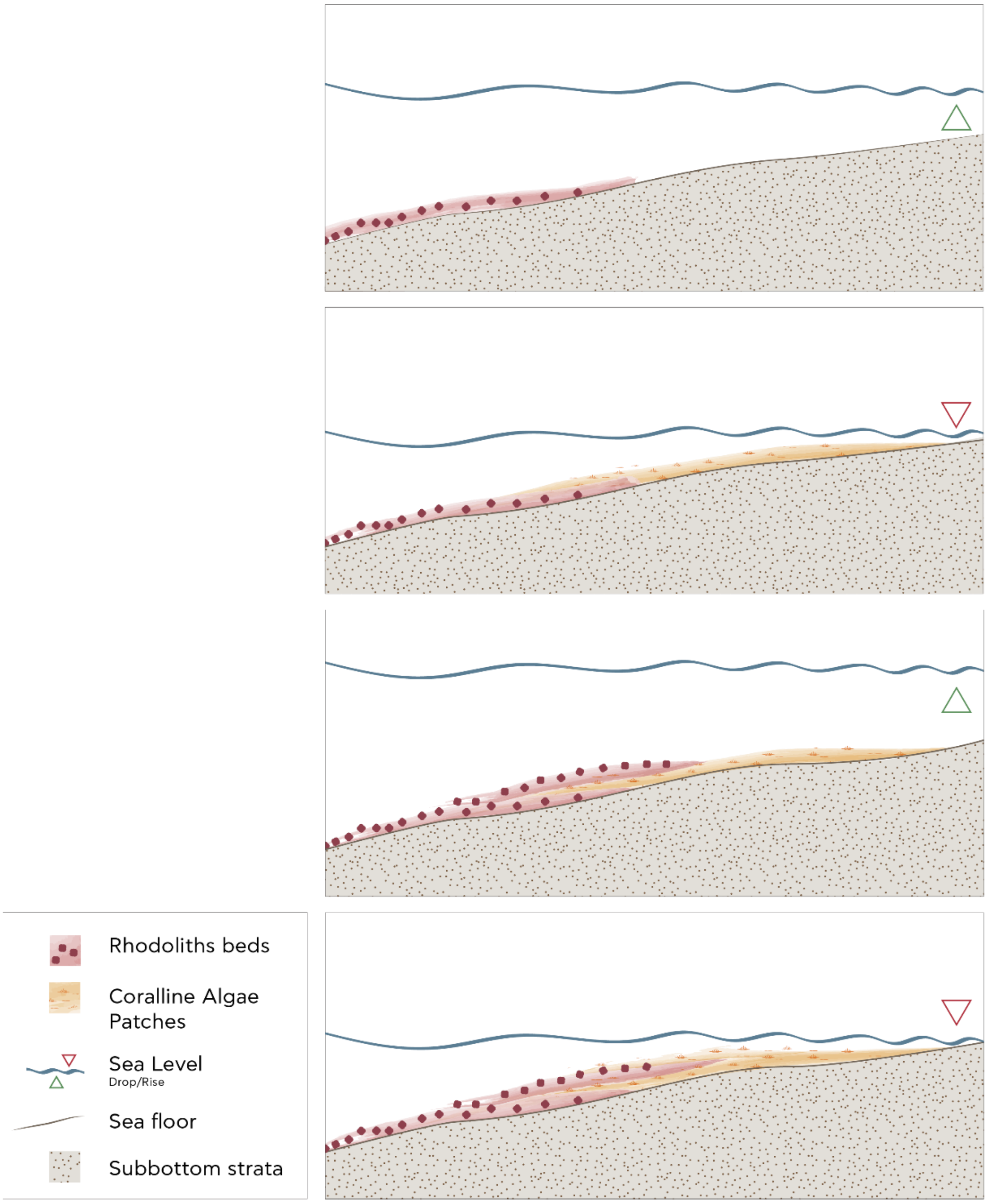
The results of the study further combined with the data from the region could provide a good insight of the paleo- environmental conditions related to the hydrocarbon generation potential during Neogene. The regional geology and geometry of the reservoir rock can be understandable by further investigations through seismic data along with drilling exploration wells, to understand the geometry and the architecture in the "missing" dimension (i.e. width).

Palaeo-depositional Environment

Coralline algae which are the dominant biological feature in the studied outcrop correspond to an array of palaeo-environmental conditions; their structure and appearance are related to a transgressive–highstand cycle of relative sea-level changes. The palaeodepths of growth range between 10 to 100 m. Due to their global distribution, it is a useful tool for environmental reconstruction.

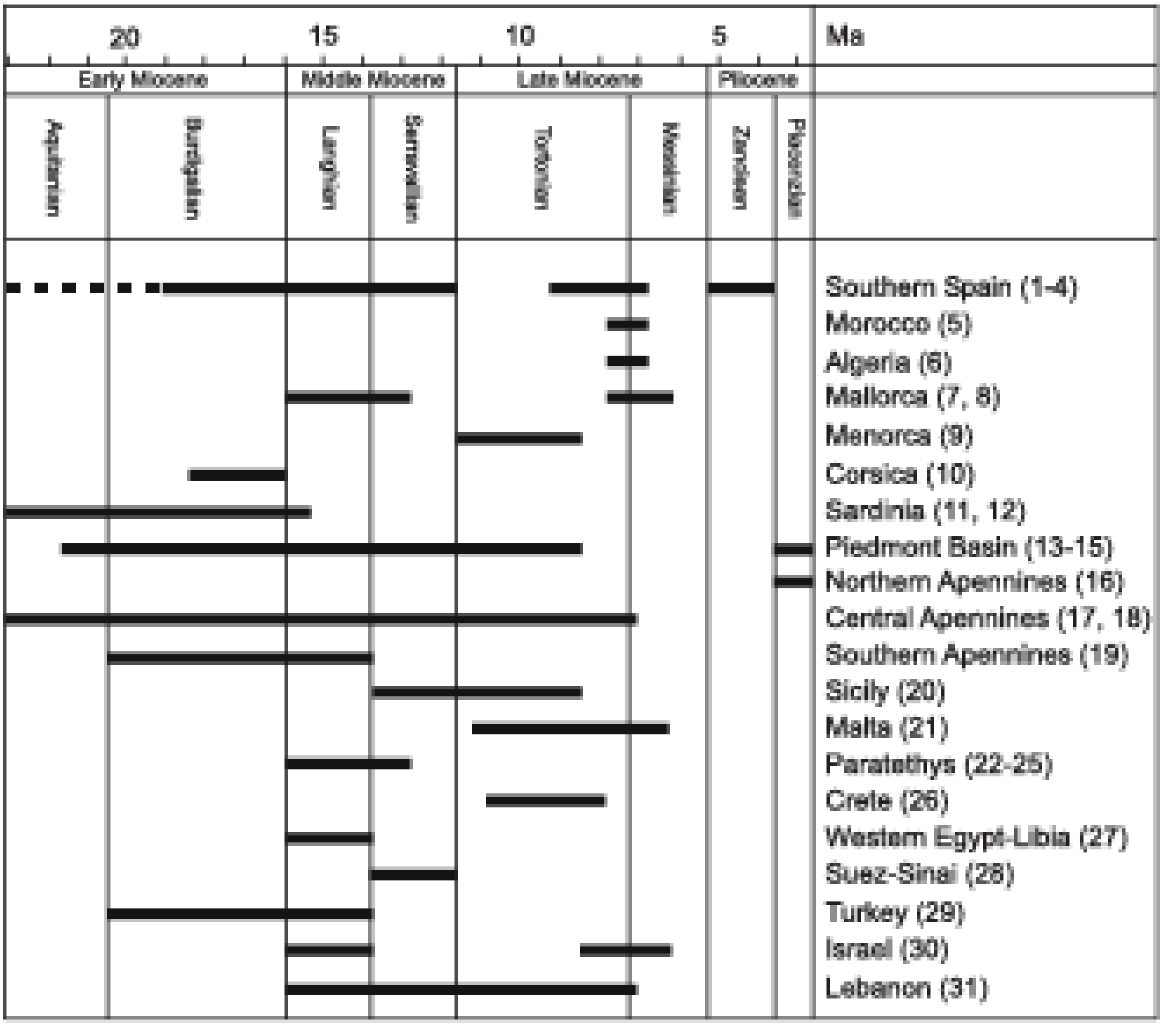
Rhodolith layers considered to be deposited in the middle ramp, while Coralline algae crusts indicate a shallower depositional environment of the upper ramp to almost sea-shore correlated with present day data from Crete.

The basal part of the outcrop (part A) consists of non-cohesive red to brown sandstones, organized in thick beds, with frequent *Ostrea* shells, including an *Ostrea* biostrom at its upper part. It points to a restricted possibly of lagoonal character depositional environment. Part B consists of a not well cemented, yellowish silty sandstone, with rare bivalve shell fragments, which upwards passes into alternations with cohesive calcareous sandstones bearing coralline algae. It is a transitional facies to pure marine conditions, represented by part C. Seven cycles were identified in C, based on the different morphological types of the coralline algae. Each cycle consists of two layers grading into each other as developing upwards. A first one, a rigid bindstone of patches of coralline algae that resemble as 'crusts' and a second one, a rhodolithic floatstone composed of various diameter of nodules (7cm-20cm). The fine- to silty sand bioclastic matrix contains bivalve shell-fragments, benthic foraminifera and echinoids. Further up-section, (top, part D) the depositional environment changes to neritic nearshore. White to sub-white, massive, highly cemented and fractured bioclastic limestones are recorded with abundant coralline algae and other macrofauna such as diverse molluscs Echinoids, and bryozoans. The Part D unconformable overlies Part C. Parts A and B represent a Transgressive System Tract, passing normally to part C, which is considered as a Highstand System Tract (HST) (compare also Kroeger *et al.*, 2005) while the limestones of part D appear strongly karstified at their base, an indicator of a sub aerial exposure pointing to a sudden sea-level drop before marine sedimentation was reactivated (SB). The data suggest that the part C deposits represent a part of a carbonate ramp that was under the sea level base at depths ranging between 40 to 100 m. Rhodoliths prevailed layers are interpreted as a moderate-energy, of low sedimentation rates setting similar to the ones that develop at a fore-reef slope (middle Ramp), while the coralline bioconstructions represent rather a shallower (upper Ramp) environment in cyclic development due to sea-level changes within a HST.

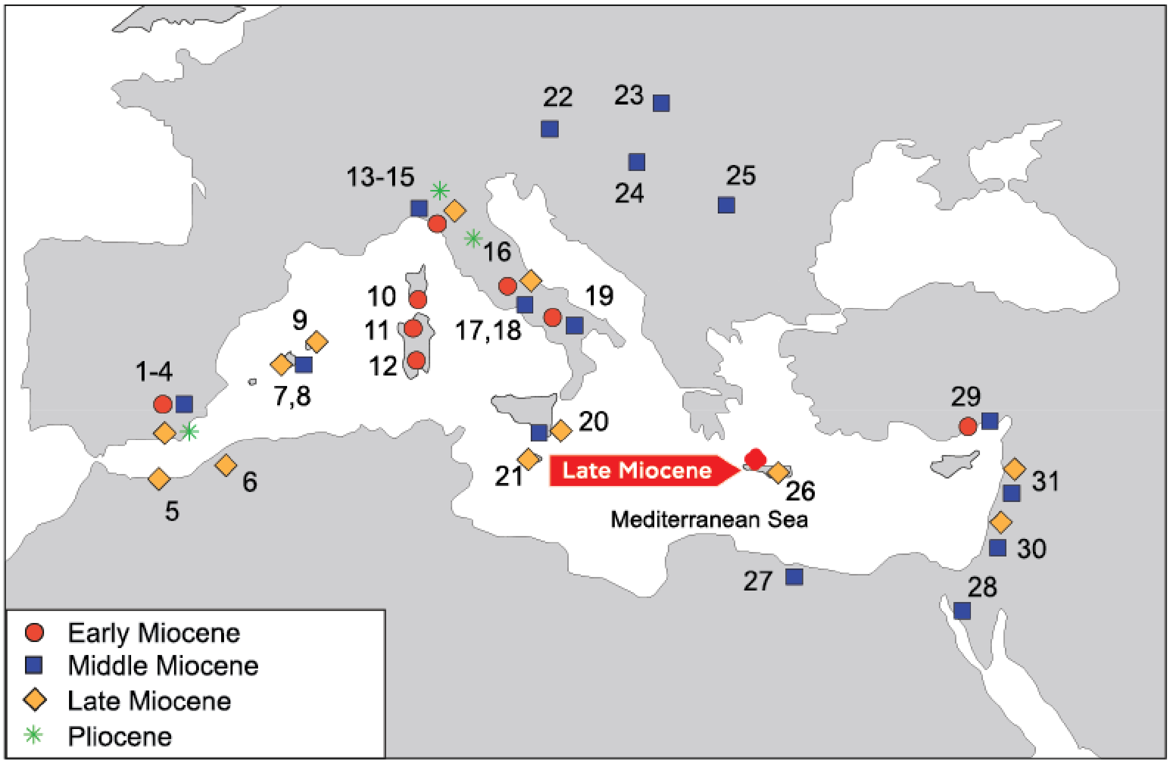


Picture 43. Schematic Model; Carbonate ramp and Coralline algae /Rhodolith of Late Miocene of Crete

These fills are very commonly found in the Mediterranean as occurrences of Neogene age; most specifically in Southern central Crete have been previously recognized as an appearance of a Tortonian age (Kroeger et al., 2006, n. 26). It is noticeable that the depositional environment in which the rhodoliths have been found are related to current events driven periodically within the fair weather wave base and the storm wave base. The Upper Miocene was characterized by massive and extensive carbonate platforms and basins all over the Mediterranean. Moreover, in the present work another example of occurrence of rhodoliths is reported from central Crete, in Rethimno region across the national roadway. (See App. Photographs)



Picture 44. Total list of occurrences of Coralline Algae in the Mediterranean, After Braga (2017)



Picture 45. Coralline Algae Distribution Map (after Braga, 2017); Red arrow points to the this work Latest Tortonian- Early Messinian Occurrence in North-Western Crete.

Analysis of rhodoliths' shape and hydrodynamic regime

According to Bosence(1976,1983) a general categorization for rhodoliths was proposed, based on the taxonomic composition (monospecific/multispecific), the external morphology, the density of their branches (I: single branch, II: open branches, III: frequent branches; IV: densely branched) and the form of algae growth (laminar, any concentric or boxwork, branching, and columnar). Rhodolith morphology, including both general shape as well as specific algal growth-forms, is dependent on a number of environmental factors including water movement, biological activity, and light levels. Although morphology has been used as an indicator of water energy (Bosence 1983a, 1991; Basso 1998), this is not always the case as shown in both recent and fossil studies on rhodoliths (Braga and Martı´n 1988; Steller and Foster 1995; Lund et al. 2000; Brandano et al. 2005; Basso et al. 2009). Biological activity, such as fish behavior, has also been shown to play a significant role in overturning and displacing rhodoliths (Marrack 1999; Gischler and Pisera 1999; Amado-Filho et al. 2012). The coralline algal taxonomic assemblage characterizing the nodules and their growthform morphologies can be used as indicators of environmental conditions such as light levels and turbulence as well as of changes of these parameters over time (e.g., Steller and Foster 1995; Basso 1998; Bassi et al. 2012; Aguirre et al. in press).

Below, a classification is reported using the method of triangular diagrams following Sneed and Folk (1958), Bosence(1976,1983), Aguirre et al. (2012) and Bracchi et al. (2022).

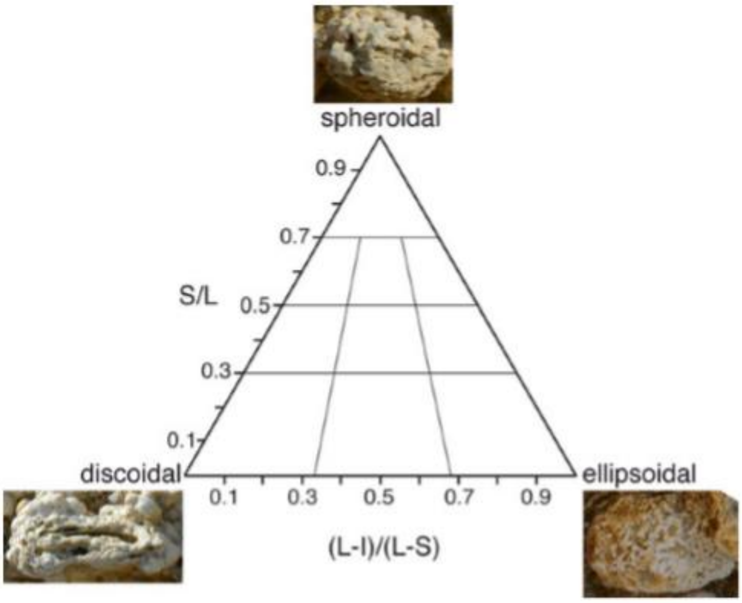


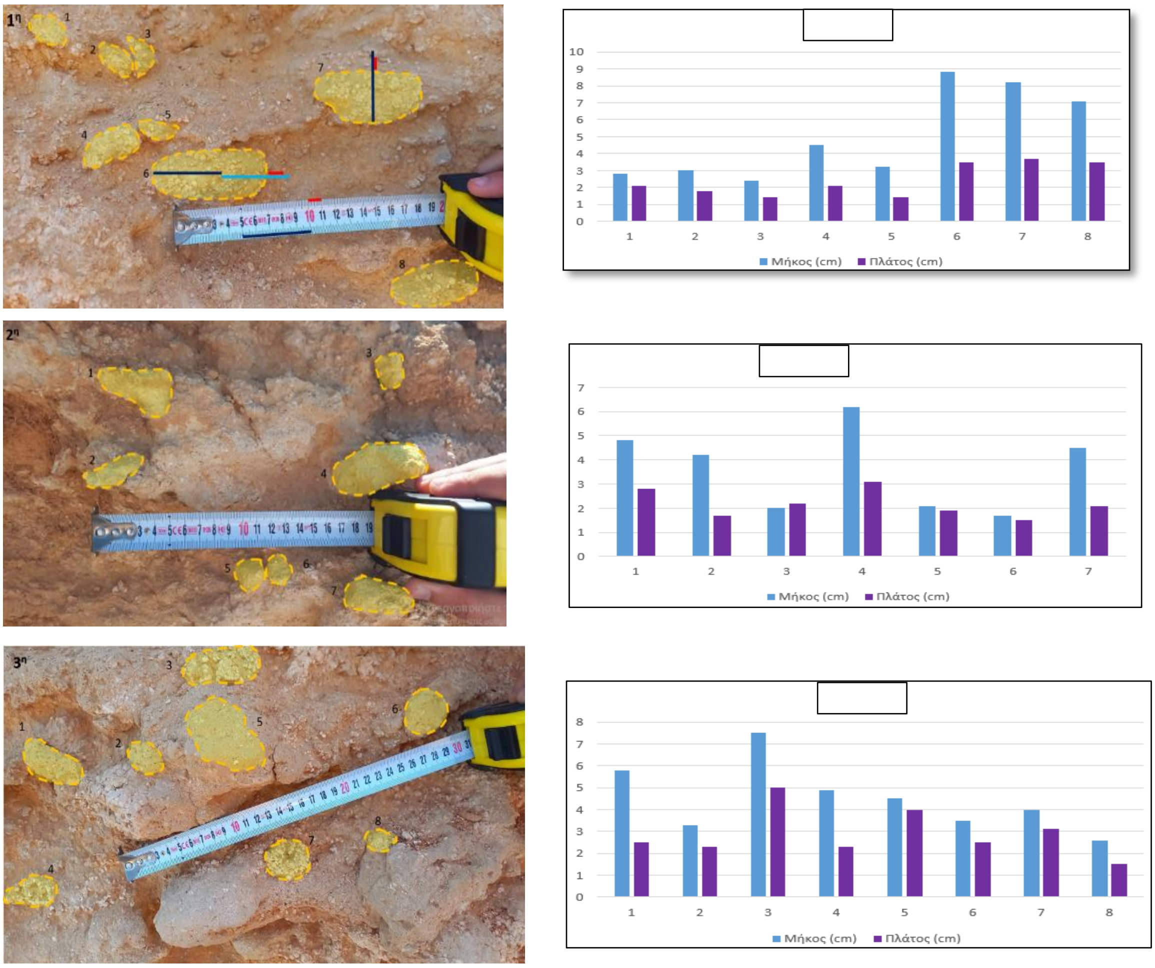
Diagram 3. Triangular diagram for the representation of the rhodolith shape. L, I and S indicate the large, intermediate and short axes, respectively of the rhodoliths—classification following Bassi et al. (2015)

Based on modern rhodoliths' observations dissimilar morphological types of rhodoliths can be associated with different temperature, salinity and current direction and velocity. From literature and observations on three different locations of southeast of Sardinia (Cape Carbonarthe) Bracchi et al. 2022, and while temperature and salinity assumed steady (due to the vicinity of the area) the measurements of the current velocities provide the conclusion that the location with the strongest hydrodynamic regime gave birth to the smallest and most spheroidal rhodoliths in shape, that is also an observation mentioned from Basso (1998). At locations based on medium hydrodynamic regimes rhodoliths are bigger, that is explained due to the steady environment that favors their development (Amado-Filho et al., 2007). This resembles the case of some of the "Koumpeli" outcrop rhodoliths, where rather medium size nodules are developed. When the hydrodynamic regime is slightly low, the sedimentation rate is subsequently higher, thus lead to the prevention of rhodolith's full development. The aim is to implement image processing software in order to determine morphological features as well as porosity patterns. Following Kartsonaki Ioanna (2022) 9 pictures were taken in the field for the identification of morphology of the fossilized rhodoliths of the succession. We were able to determine the dimensions of the shapes of rhodoliths and plot them into histograms and subsequently relate them to a specific hydrodynamic regime.

Picture 46: **Coordinates of three different locations rhodolith measurements (googlemaps.com)**

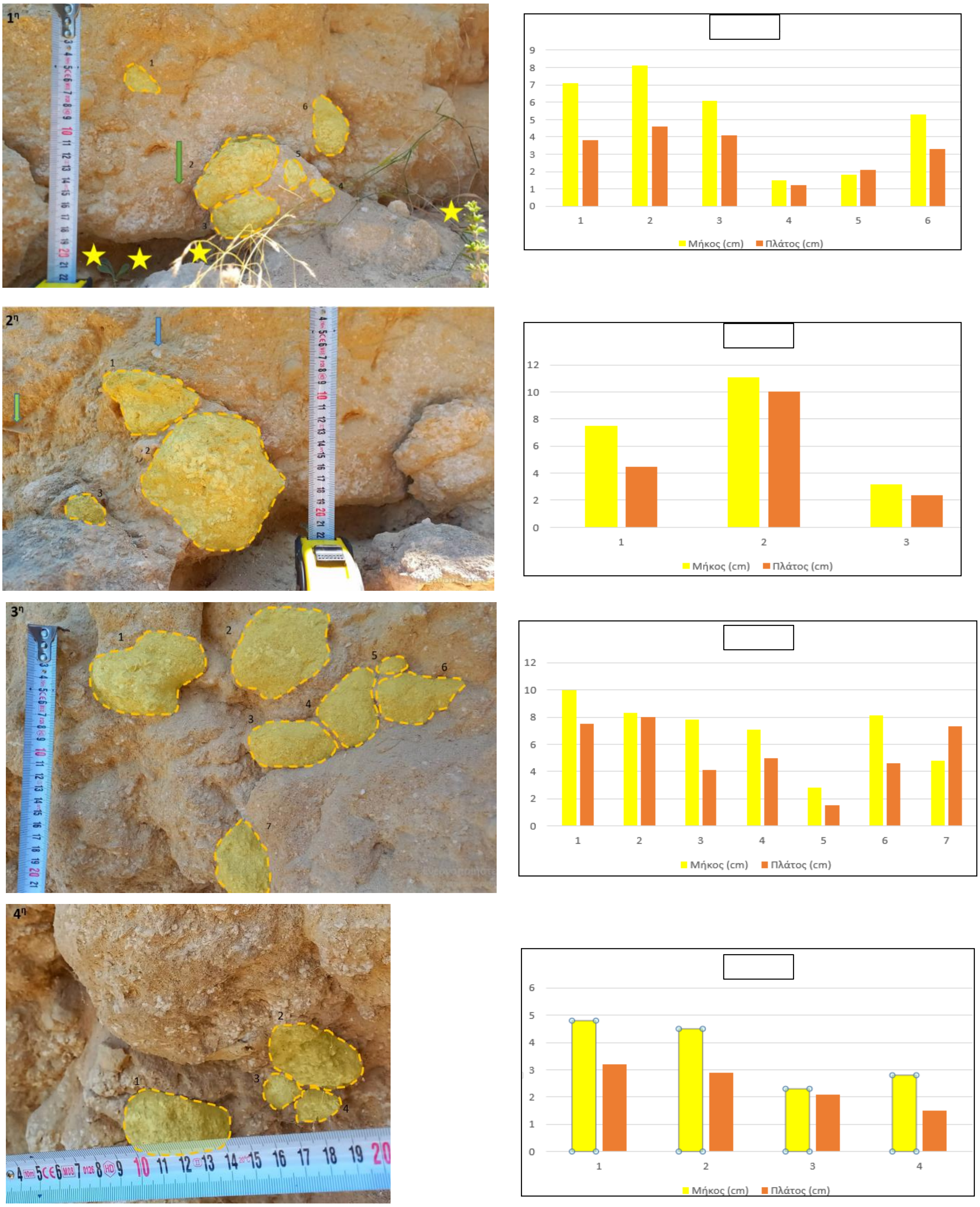
Resulting from the pictures that were observed sixty seven (67) rhodoliths in total and the necessary measurements, the below conclusions extracted regarding the hydrodynamic regime:

In the first location there are thirteen (13) spheroidal and ten (10) ellipsoidal in shape rhodoliths. Considering the average percentage that is 56,5% for the spheroidal rhodoliths, the highest in comparison to the other two localities and not taking into account the size, it reasoned that the specific location is driven by the highest hydrodynamic regime.



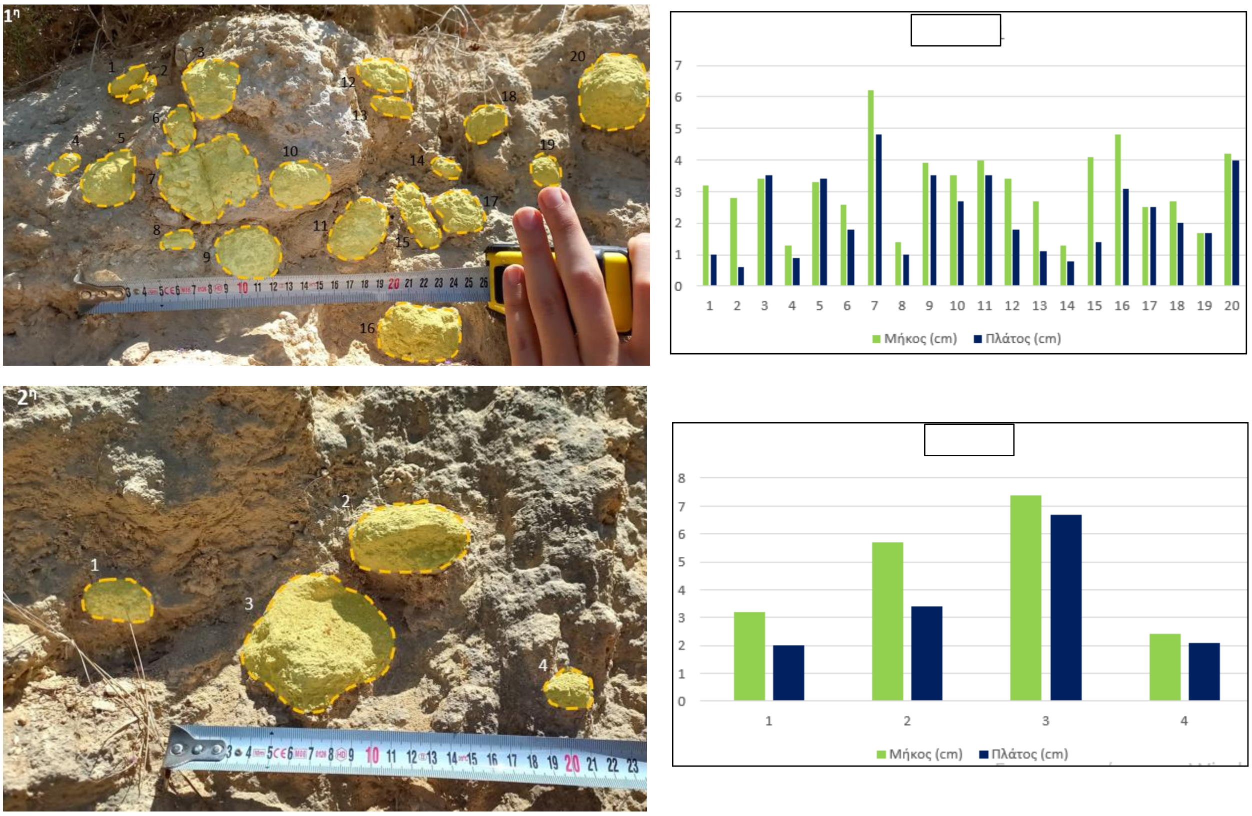
[Picture 47]: First location_Histogram on the size distribution of the studied rhodoliths; classification following Bassi et al. (2015)

In the second location which eight (8) spheroidal and twelve (12) ellipsoidal while in the third location eleven (11) spheroidal and thirteen (13) ellipsoidal rhodoliths in shape were observed. In the second location the larger size of the rhodoliths should be reported, so as the higher to medium hydrodynamic regime is assumed, a conclusion that is getting stronger by the proof of evidence of Echinodermata fossils. The relevant fossil fauna of Neogene age are also lamellibranchia and bivalve molluscs such as *Cardium* (see: Picture 48, green arrow). Also echinus possible of the genus of *Placatenella complanata* or *Abertella pirabensis* (see: Picture 48,2, green arrow) are included. It should be mentioned the strong karstification of the middle strata at the lower level of the coralline algae strata (yellow stars), that is laterally developing.



Picture 48: Second location_Histogram on the size distribution of the studied rhodoliths; classification following Bassi et al. (2015)

In the third location there was found the maximum number of rhodoliths and the analogy 1:1, points out to a discontinued hydrodynamic energy rather than a steady condition regime where an equal development of both types is described (see: Table 6).



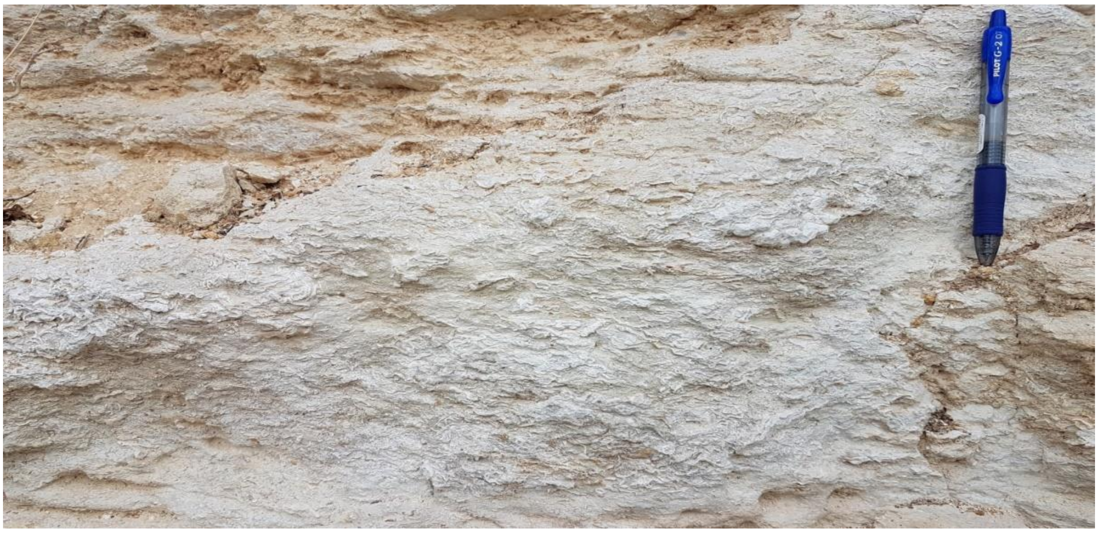
Picture 49.Third location_Histogram on the size distribution of the studied rhodoliths; classification following Bassi et al. (2015)

Table 6 : *Number of Rhodoliths' types in the location settings(after Kartsonaki I., 2022)*

Shape Classes Counts			
	1η Location	**2η Locaton**	**3η Location**
Spheroidal	13	8	12
Ellipsoidal	10	12	12

The results are of medium accuracy due to the lack of determination of the third dimension reasoning from the fossilization, the steepness and the orientation of the profile.

Other carbonate components include fragments of calcareous red algae as crusts along with other skeletal debris, molluscs and benthic foraminifers (see: Pict.50, 51, 52)



Picture 50. Fossil fauna of Neogene age, Encrusted Coralline algae

Picture 51. Fossil fauna of Neogene age, bivalve mollusk: *Pinna* double-shell macrofossil (in growth position)

Picture 52. Macrofossil fauna of Neogene age, bivalve mollusk: genus of cf. *Cardium* .

Conclusion- Discussion

An extraordinary Coralline Algae dominant outcrop is reported (both in length and thickness) as a new carbonate marine depositional occurrence near the Chania city, at the western part of Crete island in South Aegean. The outcrop was studied both stratigraphically and geochemically using detailed profiles logging. Coralline algae that were the main discovery of this study are benthic organisms that belong to the genus of Corallinaceae, having a hard outer shell composed of calcite. The different species and morphological types of coralline algae family have been previously recognized in reef flat, reef slope and in island shelf environments. A classification by shape of the rhodoliths provided valuable results for the paleoenvironmental conditions through excel and diagram analysis but further investigation is essential for the accurate prediction of paleo-depth based on the species identification and morphological appearance of them. A rough drawing model has been designed showing the mechanism of deposition, trying to simulate the sea-level fluctuations under which deposition of Rhodoliths/Coralline Algae layer alternations took place during successive Transgressive/Highstand system stratigraphic cycles. Based on the geological setting and geochemical analysis, we conclude that Koumpeli area was a shelf ramp affected by quick and numerous sea-level fluctuations during Tortonian – lower Messinian time, which influenced the changes of depositional conditions from marine to lagoon and vice versa, before the setup of the Mediterranean Messinian Crisis (MSC).

This research also examines the Koumpeli sedimentary succession under two scenarios; as a potential Source or as a Reservoir Rock. From field observations and profiles logging (geologic, paleontological and stratigraphic - sedimentological) four distinguished sedimentary packages of depositional settings were determined (A, B, C, D) and the relative relationships within them were verified. Two sets of sandstones at the base (A & B), the Coralline Algae (C) and the bioclastic limestones of Akrotiri Formation (D) at the top. The outcrop'scarbonate deposits (C and D) belong to Vrysses group and their age is within the uppermost Tortonian to early Messinian corresponding to previous published data (Freundenthal, 1969; Meulenkamp, et al., 1979; van Hinsbergen & Meulenkamp, 2006) and correlating with a single similar finding from central Crete (Kroeger, 2006). Twenty-four samples in total were collected along the outrcrop from the Coralline Algae Unit in interest (C) for rock evaluation geochemical analysis. Rock Eval pyrolysis resulted in low TOC values, possibly due to high-energy of the shallow depositional environment, in comparison to the sea-shore bioclastic limestones of Akrotiri Formation, that prove to be almost depleted in TOC. The studied sequences luck of Evaporitic facies that has been deposited in other Mediterranean basins during late Messinian. This event may had prevented the oxidization by sealing the organic content of the Red algae carbonate unit. It seems that an erosional surface (SB) is developed, at least locally, between unit C and the overlying formation (D).

Based on the previous geochemical results, the lithologic character of the unit C and the geological depositional setting we came to a conclusion that the rhythmical coralline algal deposits could better potentially serve as a reservoir rock. Therefore, as a first approach to estimate possible reserves in this individual occurrence and in the absence of well data, three different scenarios were evaluated by calculations of volume using the outcop's architecture provided by the logging and geometry terms from field work. Even the first scenario of this case study where small values of porosity were used for estimations, shows a great volume of space that potentially can be filled up with fluids/gas. This scenario is not uncommon under the hypothesis that the reservoir is also to be found in the deeper offshore area; therefore, an adequate seal would have been developed, in order to avoid escaping of hydrocarbons.

These promising results of this study could formulate the base of further investigation for the comprehending of the Neogene geology of Crete. The geometry and the reserve potentiality of the reservoir rock can be better evaluated by seismic data along with drilling exploration wells logging further in the offshore area. It is worth mentioning the large (potential) hydrocarbon gas fields to the south and southwestern of Crete that are indicated by large structures identified in the seismic data (compare picture 2). Henceforth, this study could provide a solid basis for research on equivalent reservoir rocks possible connected to those from the offshore Crete.

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Websites

{http://sepmstrata.org/page.aspx?pageid=90}

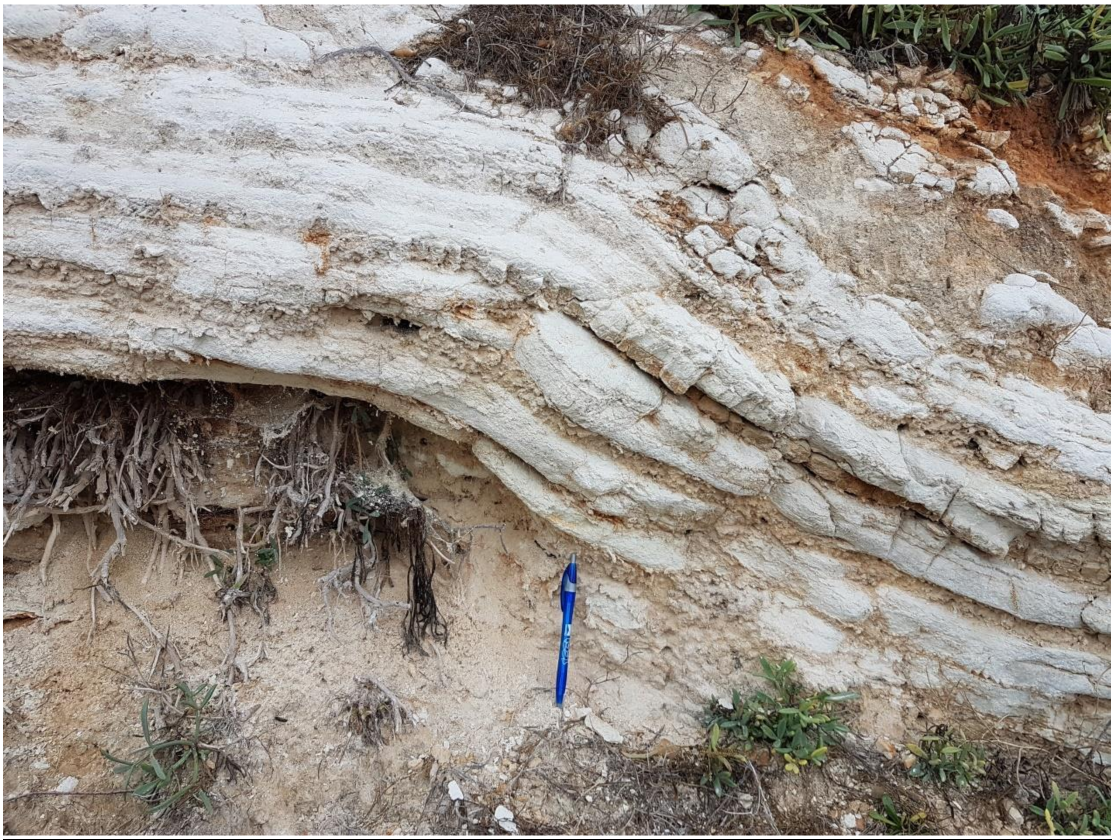
{**https://www.frontiersin.org/articles/10.3389/fmars.2019.00723/full}**

Appendix

Part 1: Photographs of FieldWork

1. **Slump phenomena in carbonates**

2. **Slump phenomena in carbonates**



3. Slump phenomena in carbonates

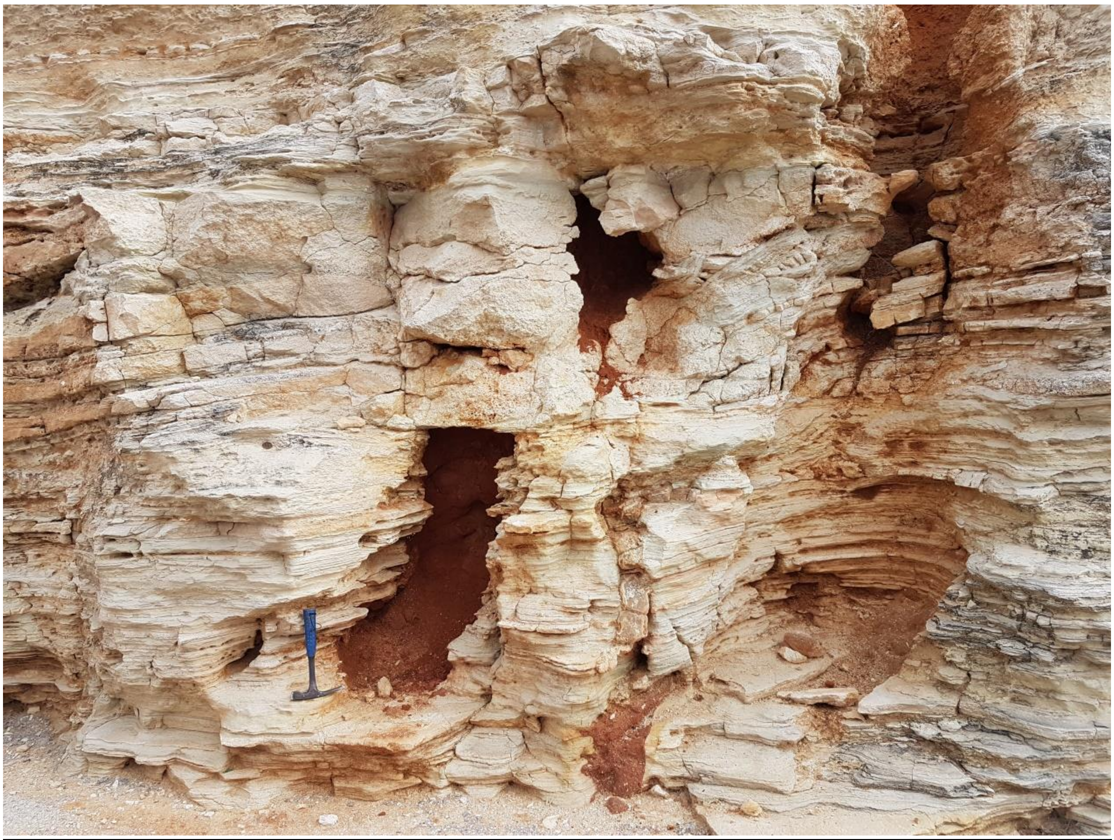
4. Slump phenomena in carbonates

5. Location of Sampling (Green -Grey layer)

6. Contact of packages C(rhodoliths) and D(Akrotiri)

7. General view of the Koumpeli Section

8. Thin layered carbonates on the top of Akrotiri Formation



9. Carstificatioon in Carbonates

10. Fossil fauna (fragments of shells)

11. Fragmented Aksotiri formation (height:3.30m)

12. Coralline algae Crusts

13. Sandstones with abundant Ostrea Shells

14. Red sandstones (probable laggonal environment)

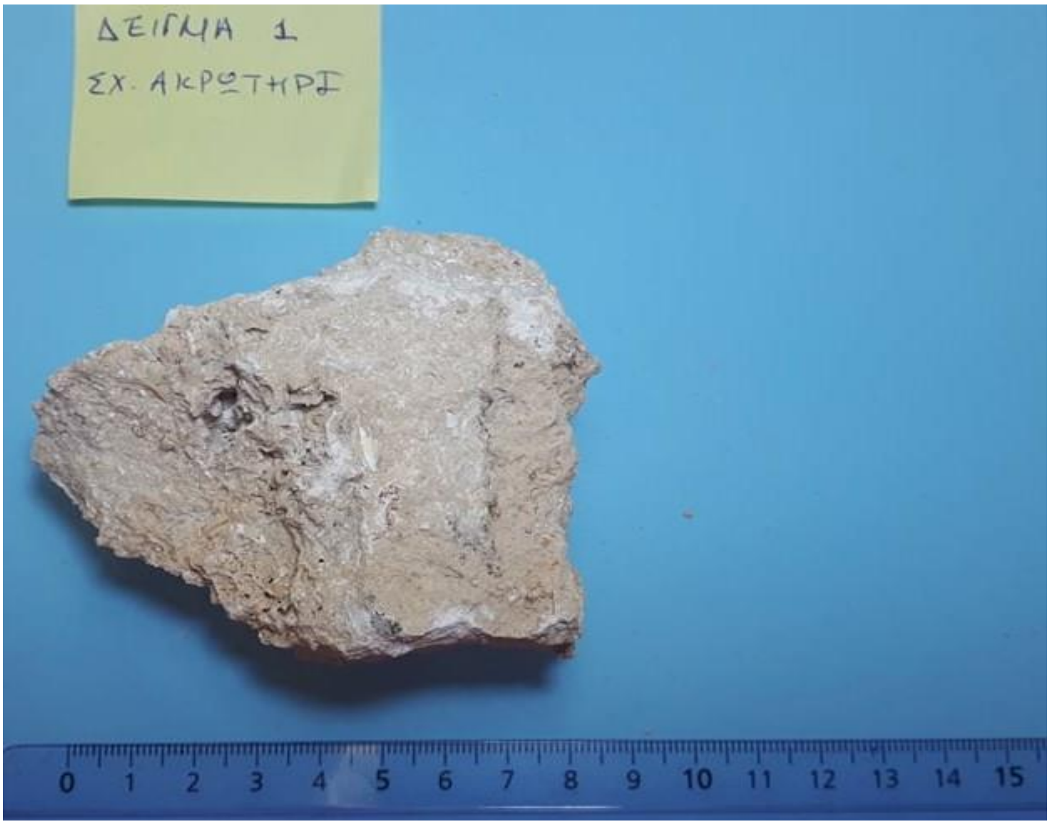
15. Fossil fauna (pr. Cardium)

16. **Rhodoliths occurrence, Rethimno region, central Crete**

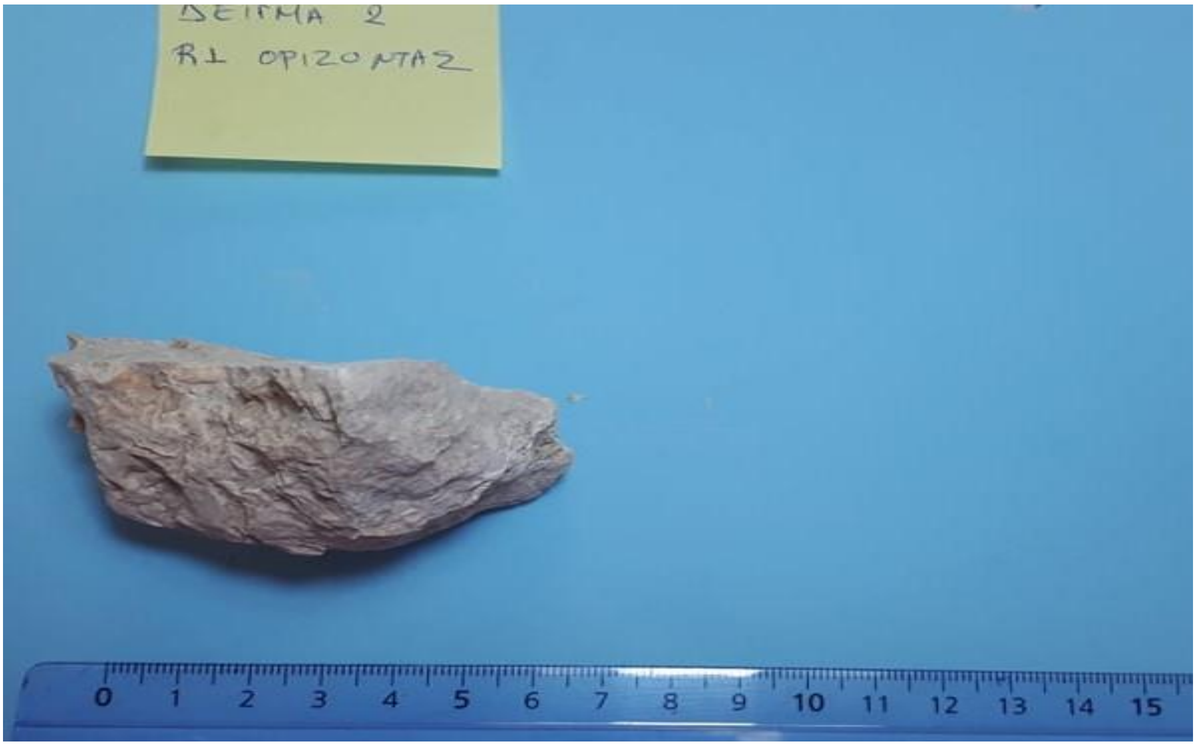
17. **Rhodoliths occurrence, close up view, Rethimno region, central Crete**

Part 2: Photographs of laboratory work

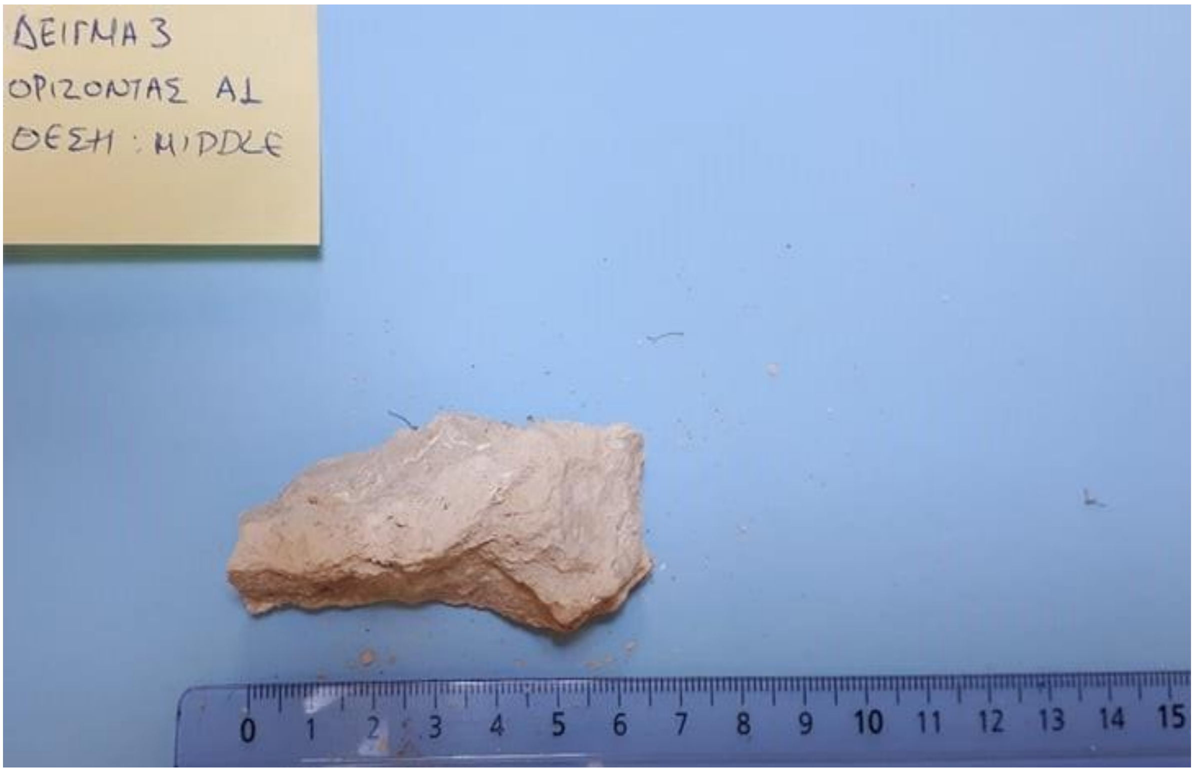
1. **Sample 1 (Akrotiri Fm)**



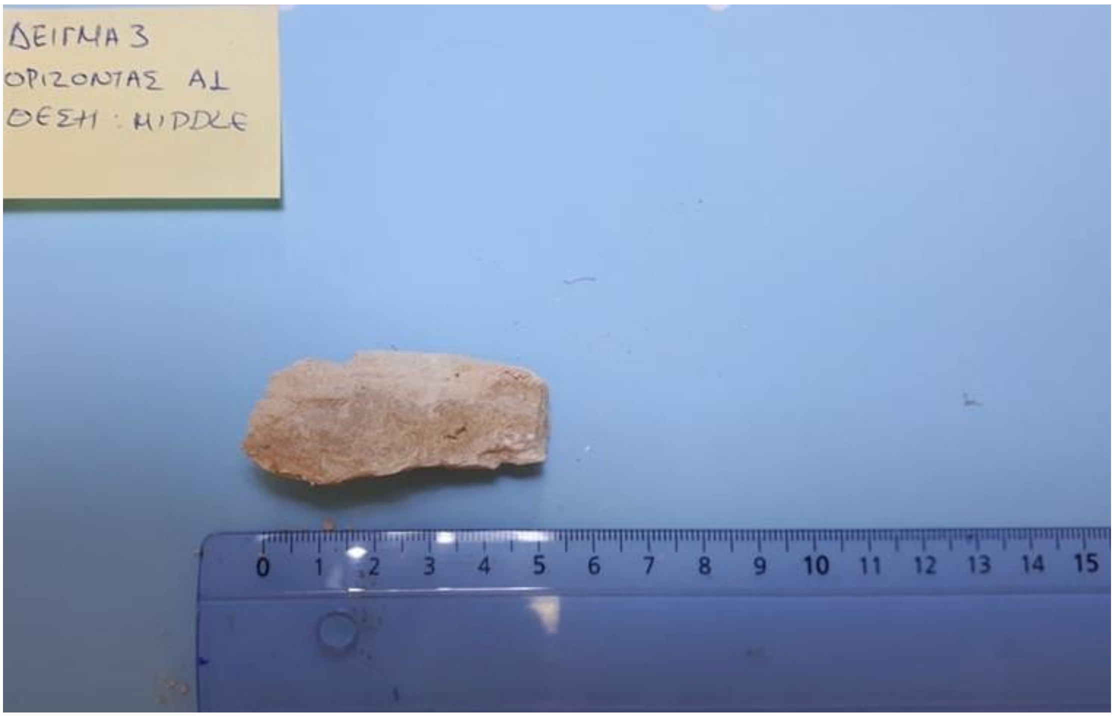
2. **Sample 1 (Akrotiri fm)**



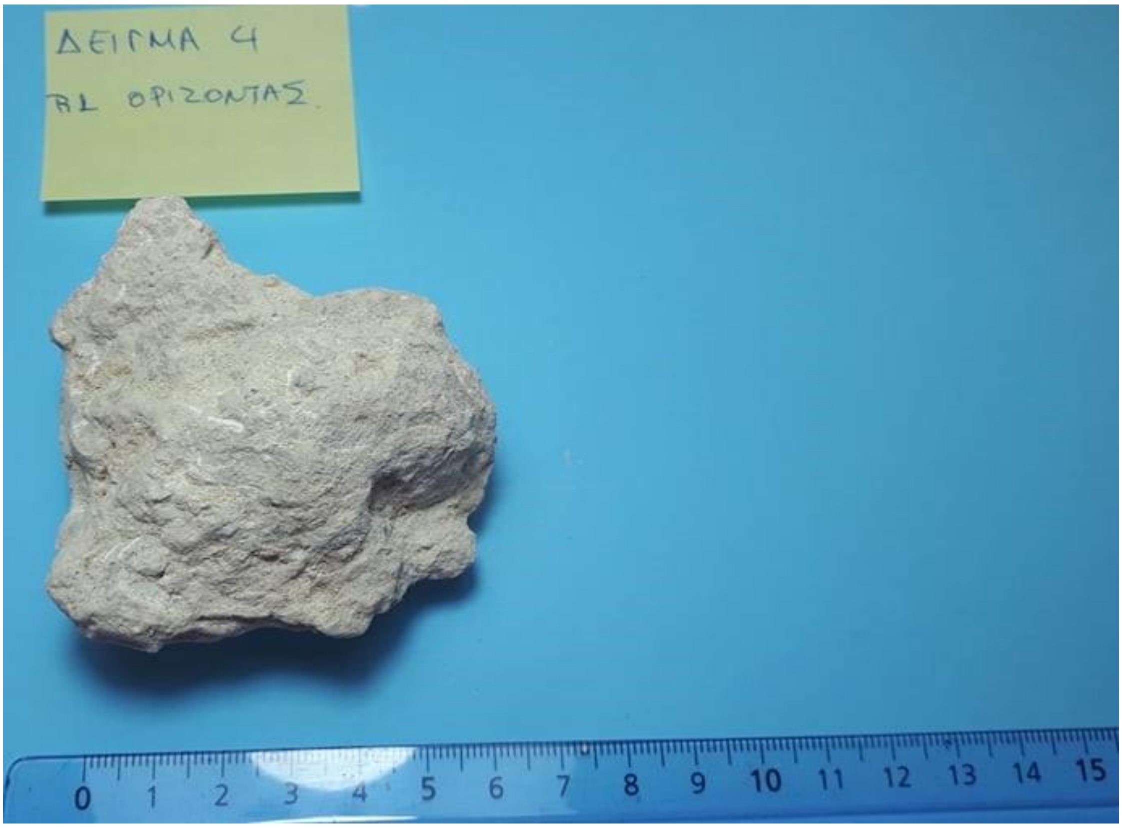
3. Sample 2 R1 Rhodoliths



4. Sample 3 A1 Coralline algae layer

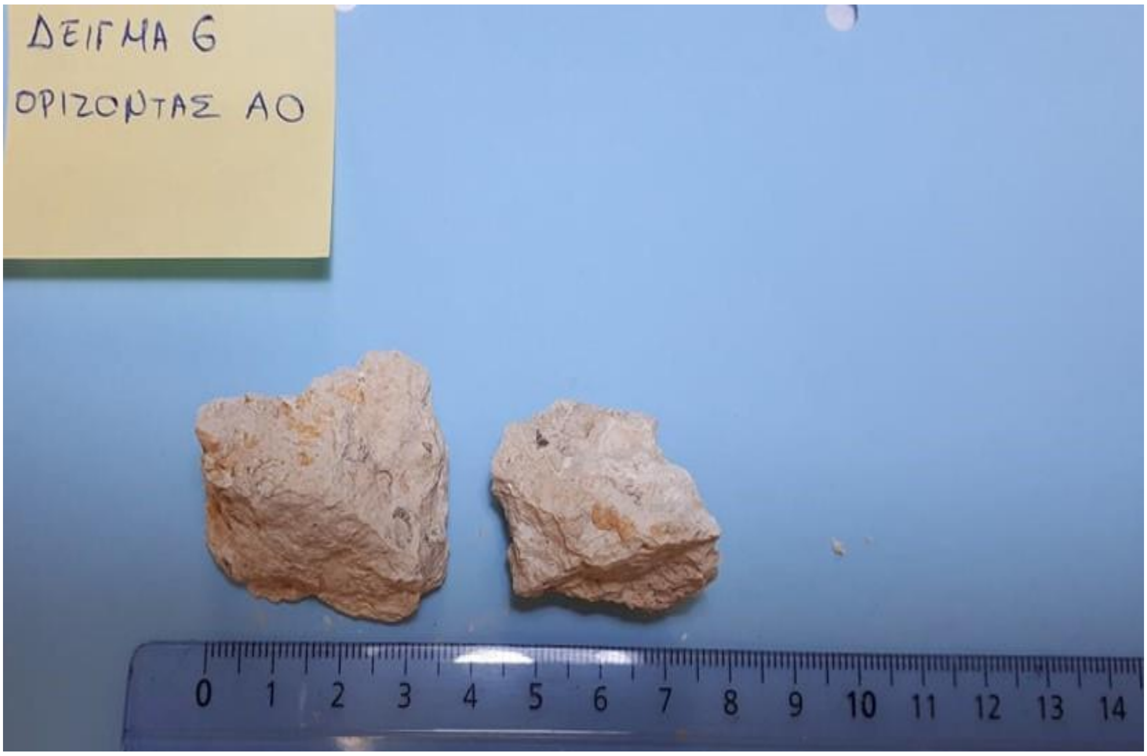


5. Sample 3 A1 Coralline algae layer



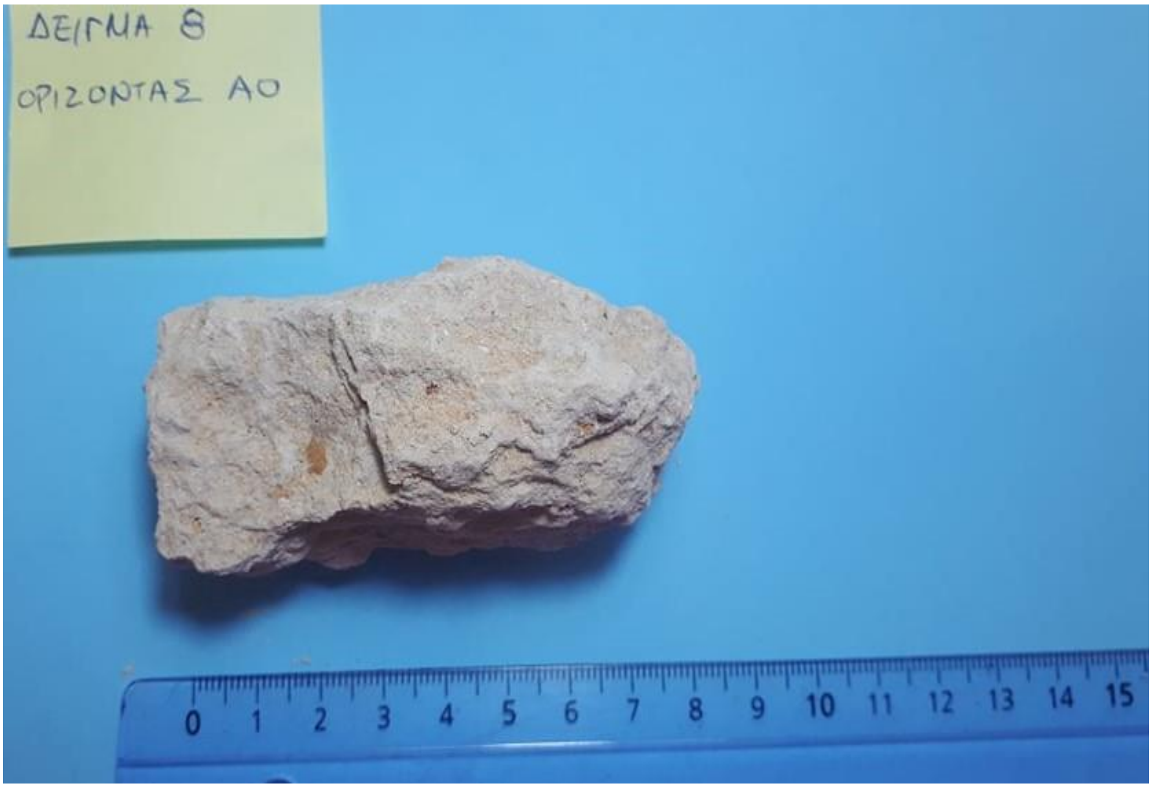
6. Sample 4 R1 Rhodoliths

7. **Sample 5 A1 Coralline algae layer**



8. **Sample 6 A0 Coralline algae layer**

9. Sample 7 A0 Coralline algae layer



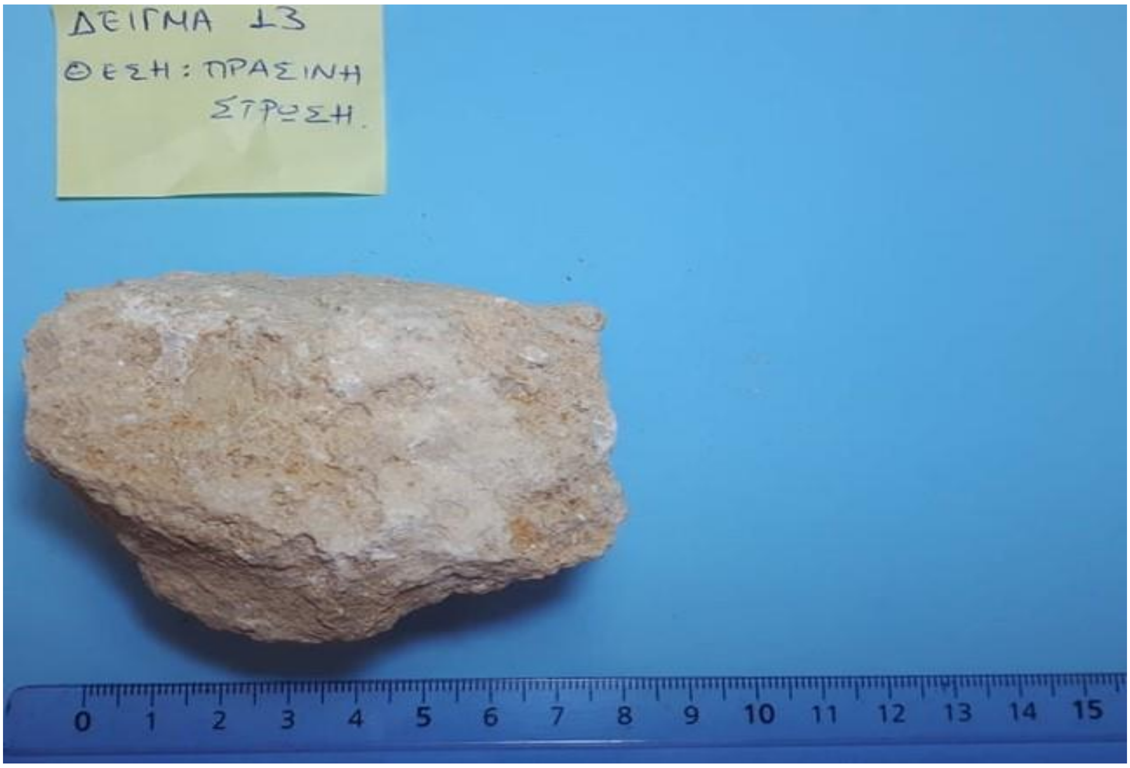
10. Sample 8 A0 Coralline algae layer

11. **Sample 9 A0 Coralline algae layer**

12. **Sample 10 Rhodolits**

13. **Sample 11 Rhodoliths**

14. **Sample 12 Coralline algae layer**



15. Sample 13 Coralline algae layer

16. Sample 14 Coralline algae layer

17. Sample 15 Sands

18. Sample 16 Transition layer, Coralline algae -Sands

19. Sample 17 Carbonate layer

20. Sample 18 Rhodoliths, kalyves

21. **Sample 19 Coralline algae layer**

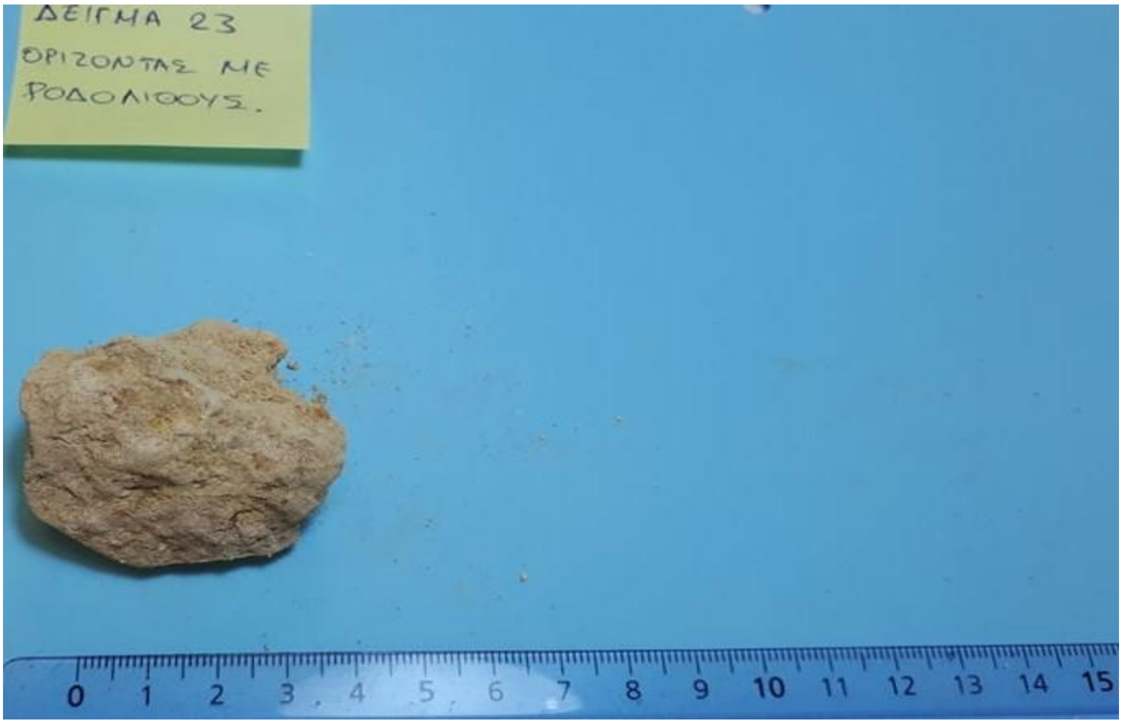
22. **Sample 20 Coralline algae layer**

23. Sample 21 Transition layer Sandstone - rhodoliths

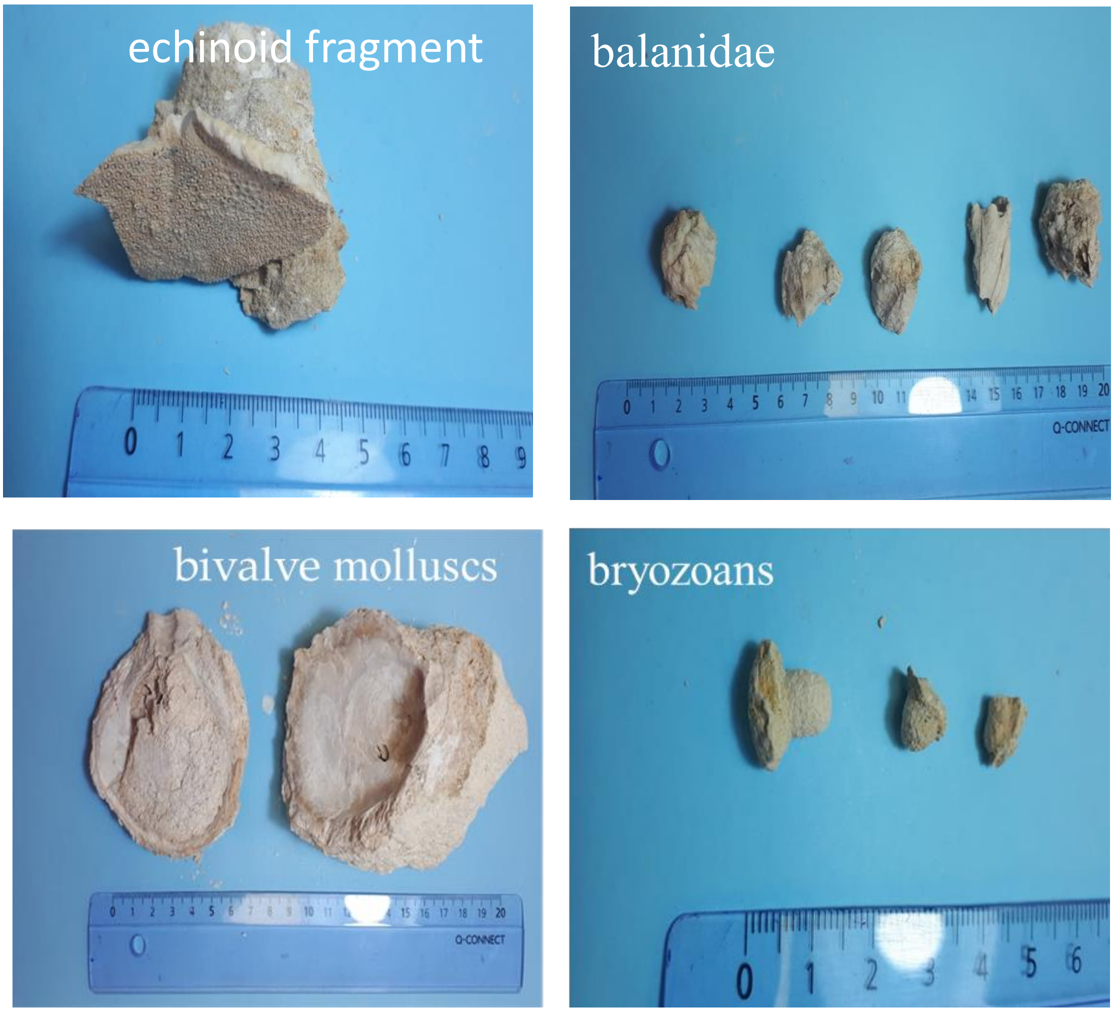
24. Sample 21 Transition layer Sandstone - rhodoliths

25. **Sample 22 Coralline algae layer**

26. **Sample 22 Coralline algae layer**



27. Sample 23 Rhodoliths



28. **Fossil fauna of Neogene Age**