Sedimentology of the Apostoli Basin – A Transition from Continental to Marine Conditions

Aerial view of the Potsami table top mountain looking Northwest. The Potamon Lake, which is a fresh water dam, is visible on the left-hand side in the background. Reef limestone caps the top of the mountain. In the valley yellowy conglomerate sediments indicated continental conditions. They grade upwards into coastal lagoonal and subtidal limestones. Light grey marls near the top of the mountain were deposited in a protected marine shelf environment. [Source of image: Google Maps]

By George Lindemann, MSc.

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Content

Appendix

1 Introduction to Sedimentary Concepts

1.1 The Transgressive-Regressive Sequence

A transition from continental to marine conditions that may be observed in vertical section often represents a transgression**,** where sea level rises relative to the land. It is a progression of facies moving from terrestrial deposits such as fluvial sands or paleosols to more marine sediments for example tidal flat or shallow marine deposits.

Alternating energy levels within the section are typical of tidal flats and related environments. For example, low-energy mudflat deposits displaying a laminated structure may be interbedded with higher-energy sand layers from storm or tidal channels. This variability may also reflect tidal cycles (e.g., spring vs. neap tides) or shifts between lagoonal, intertidal, and subtidal zones.

Tectonic activity, such as subsidence or uplift, is often a key driver of transgressive-regressive cycles. Subsidence can enhance accommodation space, promoting transgression, while uplift can reduce it, driving regression. Evidence of tectonics can include unconformities, syn-sedimentary faulting, or abrupt facies changes within the succession.

The term sedimentary "facies" describes a specific depositional environment, which may be determined from a set of sedimentary features such as grain size, composition, and structures. When examining an outcrop, the vertical arrangement of facies provides clues about the lateral changes in environments during deposition.

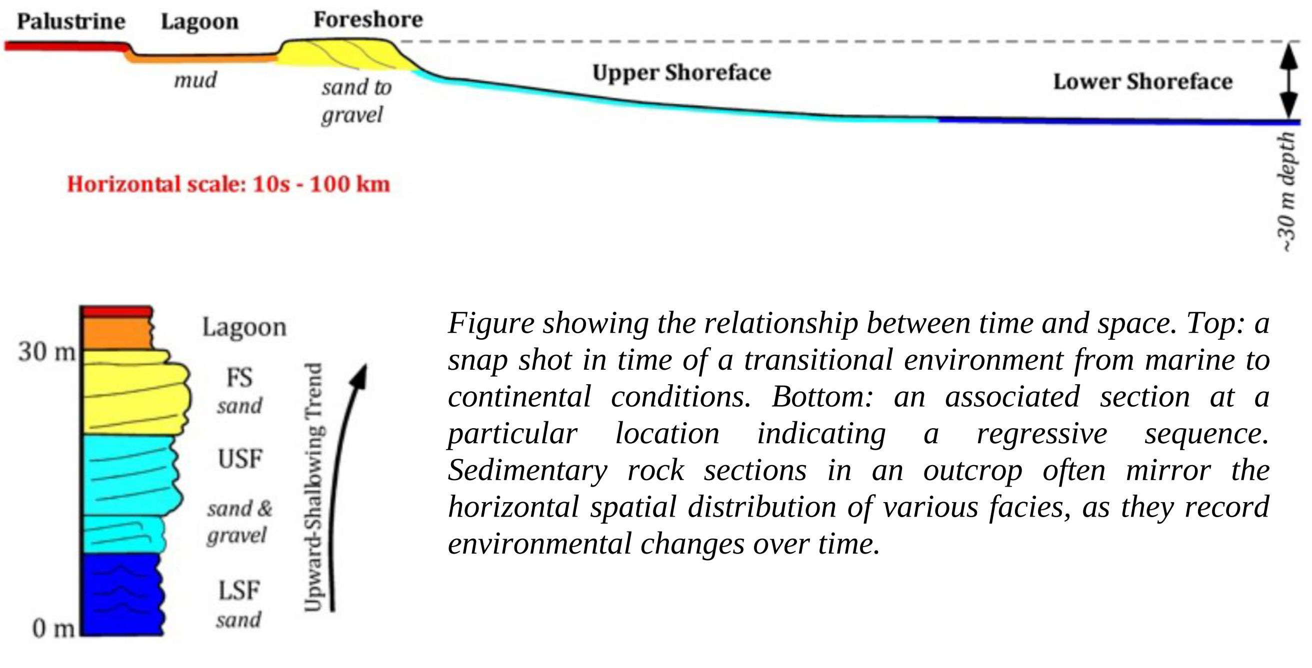
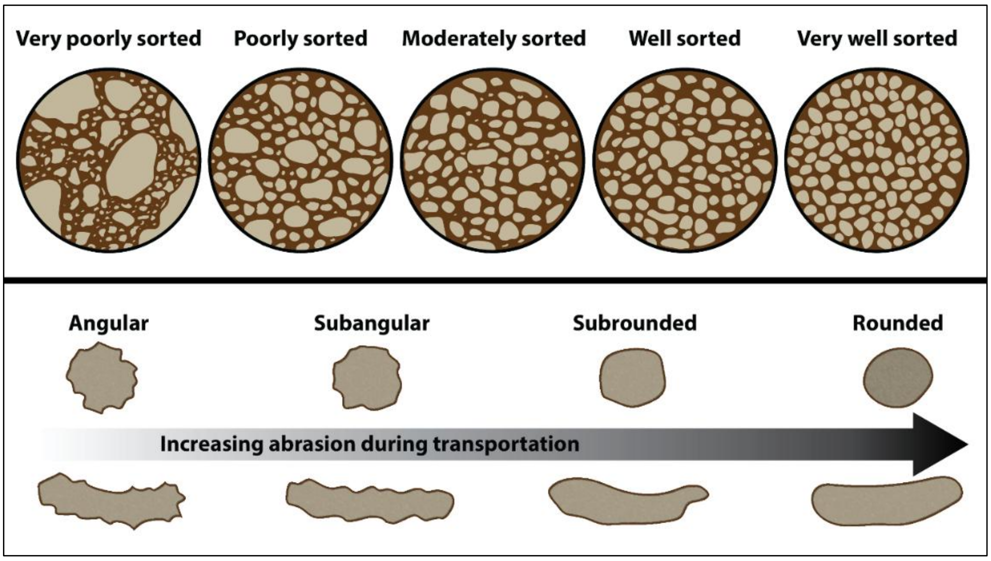


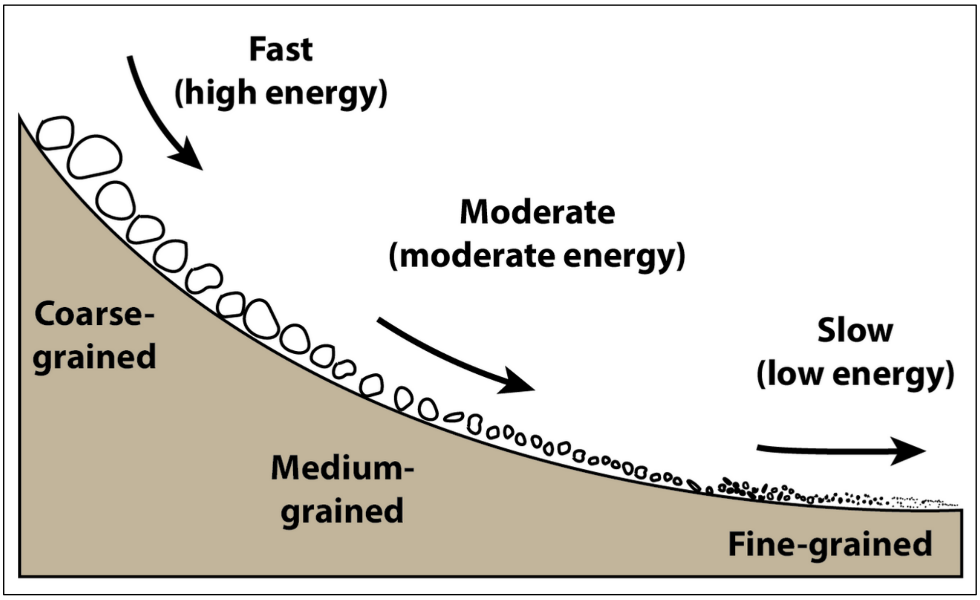
Figure showing the relationship between time and space. Top: a snap shot in time of a transitional environment from marine to continental conditions. Bottom: an associated section at a particular location indicating a regressive sequence. Sedimentary rock sections in an outcrop often mirror the horizontal spatial distribution of various facies, as they record environmental changes over time.

The above figure shows a regressive sequence, which is characterized from the base upwards by a gradual shallowing upwards trend - the different facies related to a marine shelf and coastline. Palustrine wetlands include any inland wetland that contains ocean-derived salts in concentrations of less than 0.5 parts per thousand, and is non-tidal. Wetlands within this category include inland marshes and swamps as well as bogs, fens, pocosins, tundra and floodplains. Lagoon muds can be deposited either under freshwater, marine or hypersaline conditions (Wikipedia). Depending on the various facies a regressive sequence typically involves a coarsening upwards trend. The last sediments being of continental nature are normally fluvial or alluvial conglomerates.

1.1.1 Description of Clastic Sediments

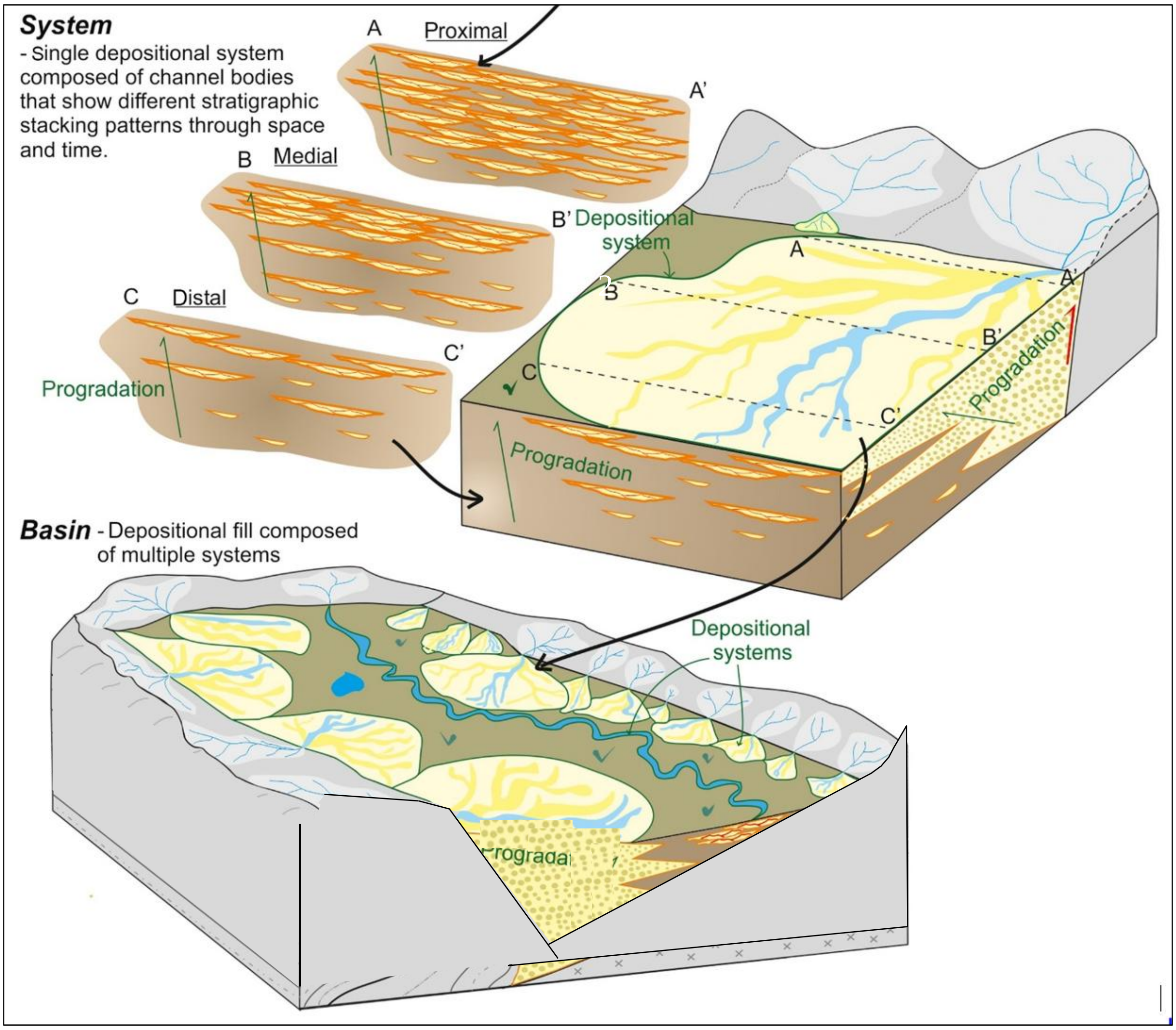


A visual reference for descriptions of sorting (top) and roundness (bottom) of sediments and grains in clastic sedimentary rocks. Note that rounded grains are not necessarily spherical in shape. Grain shapes are controlled by both the extent of transportation (and abrasion) and by the physical properties of the grain. [Source: A Practical Guide to Introductory Geology, Author: Siobhan McGoldrick]



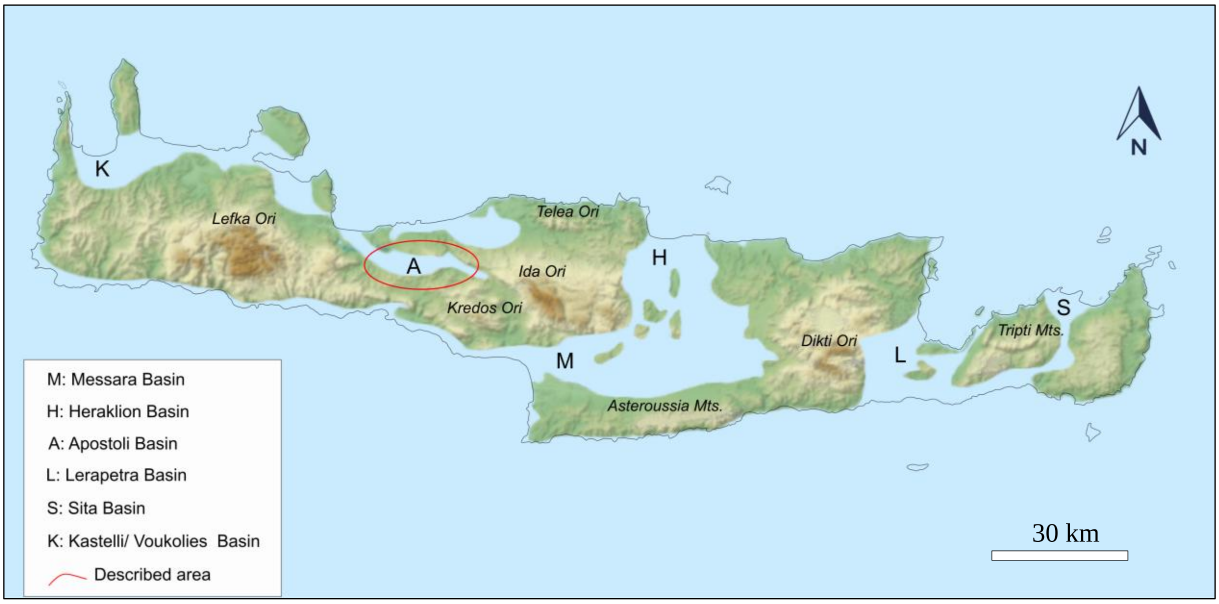
Schematic relationship between flow velocity (fast, moderate, slow), energy, and clast size. [Source: A Practical Guide to Introductory Geology, Author: Siobhan McGoldrick]

1.1.2 Continental Basin Fill Systems



Source: Owen, A. et al., 2017, See Appendix

2 The Apostoli Basin



Cretian archipelago during the Tortonian (approx.7 ma). Land areas and the Heraklion, Messara, Ierapetra, Sitia and Apostoli basins (based on the map of Zachariasse et al., 2011) [Psarras C. et al., 2023]

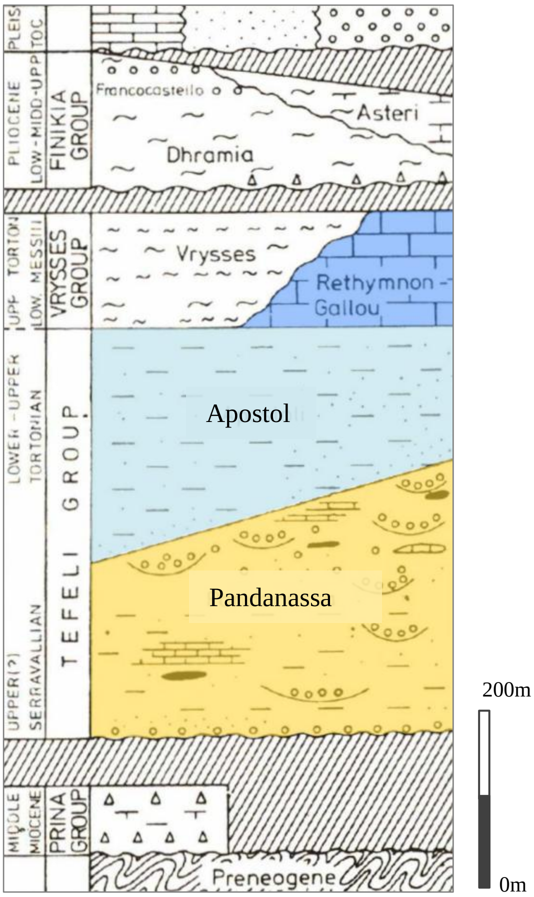
As part of the alpine orogeny Crete is located near a subduction zone at the southern edge of the Aegean Plate. The subduction of the African plate took place initially under convergent conditions resulting in the stacking of various nappes and thickening of the continental crust in the forearc region during the Late Oligocene/Early Miocene (Seidel et al.,1982; Bonneau, 1984). In Middle Miocene southward directed rollback of the subduction zone coupled with the southward migration of the Aegean plate resulted in extensional faulting and the denudation of a progressively thinning crust. This resulted in the formation of the first Neogene basins (Kilias et al., 1993; Fassoulas et al., 1994).

The extension of the area, resulted in N-S and E-W normal faulting. However, extension was also accompanied by buoyancy related uplifting of Pre-Neogene Units, which provided the source rocks for sedimentation within the Neogene basins. During the Tortonian, many parts of the island were submerged, resulting in the creation of an archipelago of small islands. The figure above shows the archipelago of Crete and its six different basins during the Tortonian. These were:

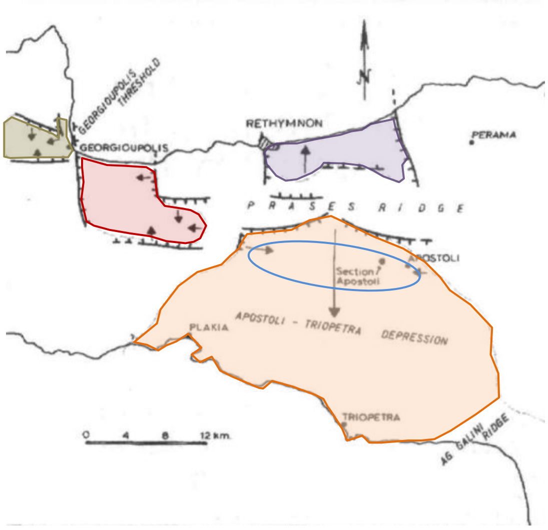
- the Messara Basin divided from the Heraklion Basin by a E-W striking Normal Fault (Central Heraklion Normal Fault, CHNF) active between 9.7 and 7.36 Ma (Zachariasse et al., 2011),
- the Ierapetra Basin,
- the Sitia Basin,
- the Apostoli Basin, and the
- Kastelli/ Voukolies Basin (Keupp H. et. al, 2000)

The major mountain ranges Psiloritis, Dikti, Asterousia and Lefka Ori had already been uplifted at that time *[Psarras C. et al., 2023]*.

View of the western part of the Apostoli Basin. The escarpment in the background is topped by marine bioclastic limestones. The valley is characterized by yellowy continental conglomerates. The mountain side in the foreground consists of metamorphic pre-neogene rocks.



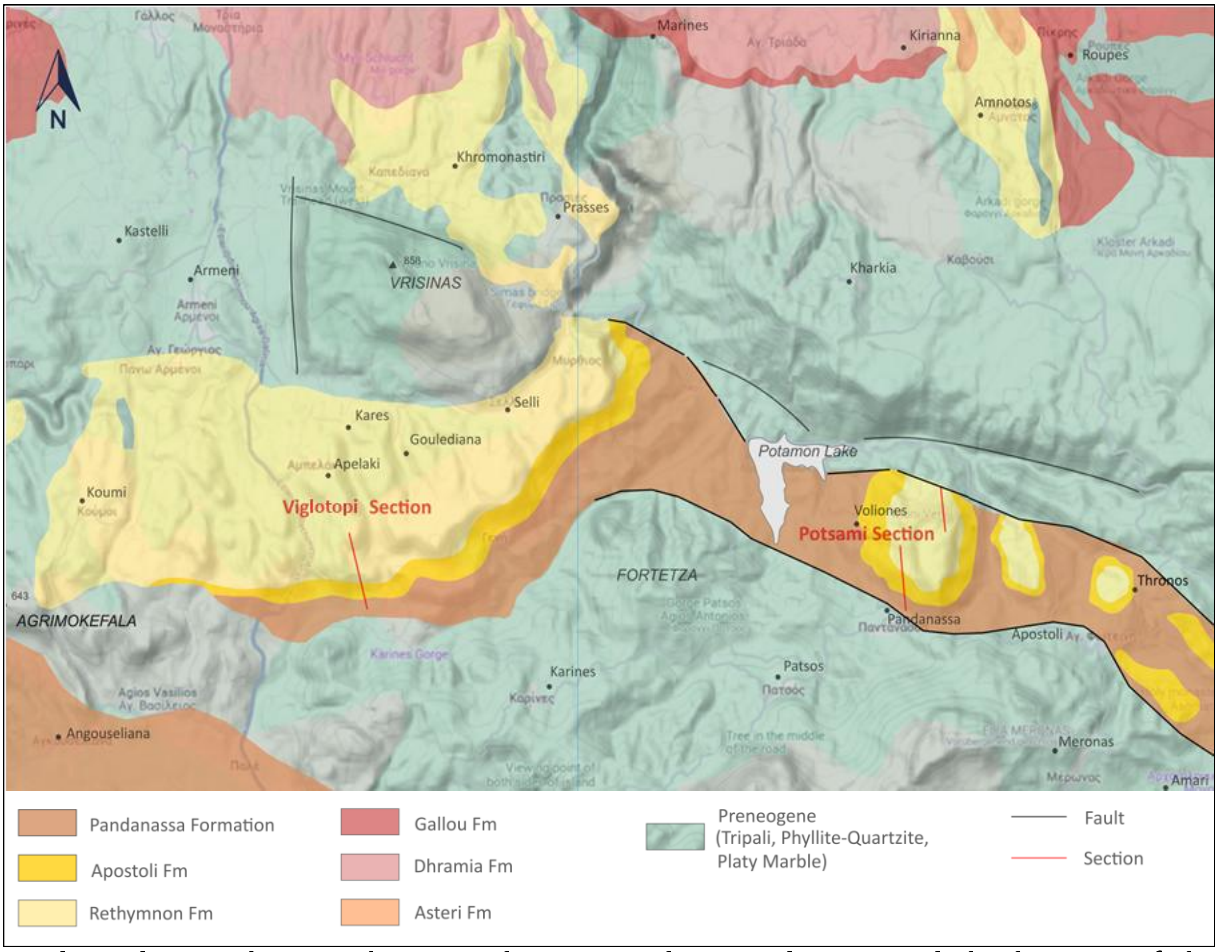
The eight Neogene Formations of the Rethymnon region (Rethymnon to Plakias) determined by Meulenkamp, 1969.



Location of Central Crete's Neogene basins after Meulenkamp, 1969

Apostoli Basin *

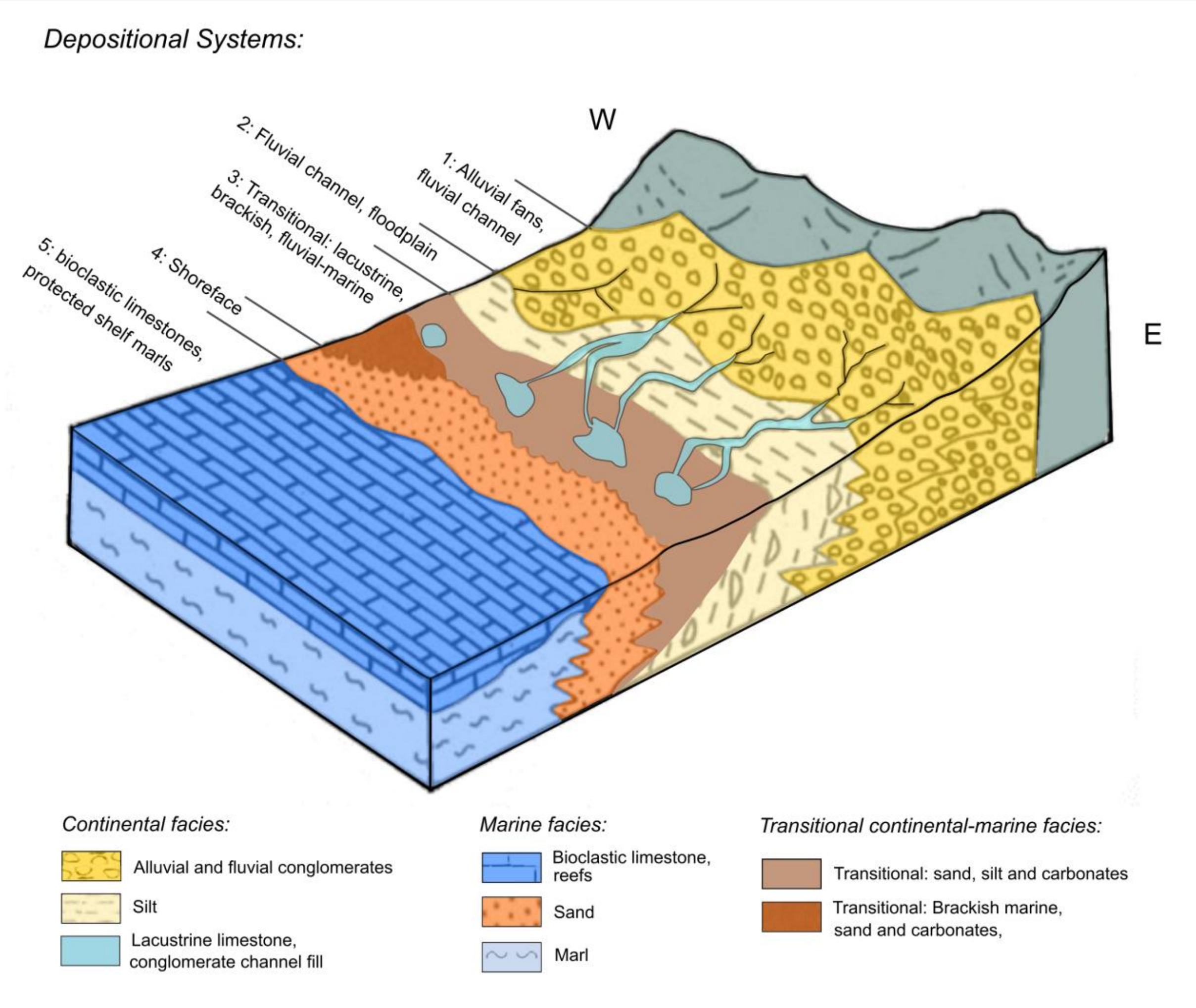
The lithostratigraphical extent of Central Crete's Neogene basins was established by Meulenkamp (1969), who subdivided the various basin fillings of Central Crete's Neogene basins into eight formations, each one corresponding to different environmental conditions. The Neogene succession includes marine as well as brackish and fresh-water sediments. Eight formations are recognized, several of which have to be regarded as lateral equivalents. From the sediment types and their distribution along the north coast of Crete it may be concluded that today's topography still reflects the paleogeographic conditions existing during the Neogene. *[Meulenkamp, 1969]*



Geological map showing the Apostoli Neogene basin sediments and the location of the Viglotopi and Potsami sections. Facies boundaries are based on Meulenkamp, 1969. Large amounts of red conglomerates and reddish-grey sands, thought to be of Quaternary age, unconformably overlie the Pandanassa Formation at several places in the Apostoli basin. They are not shown the map. [relief image: Google Maps]

2.1 Depositional Model

The depositional model put forward by Drina (1998) for the Neogene Apostoli Basin describes two different modes of sedimentation formed in continental and marine environments. The continental conditions gave rise to clastic sedimentation issuing from alluvial fans and predominantly braided-delta systems. During a transitional phase to a marine environment brackish fluvial-marine and supra-tidal flat deposits were formed. Sedimentation under marine conditions involved coastal deposits associated with sandy shoreface conditions, succeeded by a carbonate shelf environment. The marine limestone shelf environment can be divided into shallow shelf and deep marine shelf conditions. Based on the investigation of several sections within the Apostoli Basin, Drina (1998) envisages five main sedimentary facies or systems.



Schematic depositional model of the Apostoli basin after Drina, 1998.

2.2 Evolution of the Apostoli Basin

The evolution of the sedimentary fill of Apostoli Basin started when subsidence of the basin took place and coarse-grained clastic sediments originating from the elevated pre-Neogene basement were transported and deposited forming continental alluvial fan deposits and stream-flow sediments associated with a floodplain system (see Figure 1 and 2).

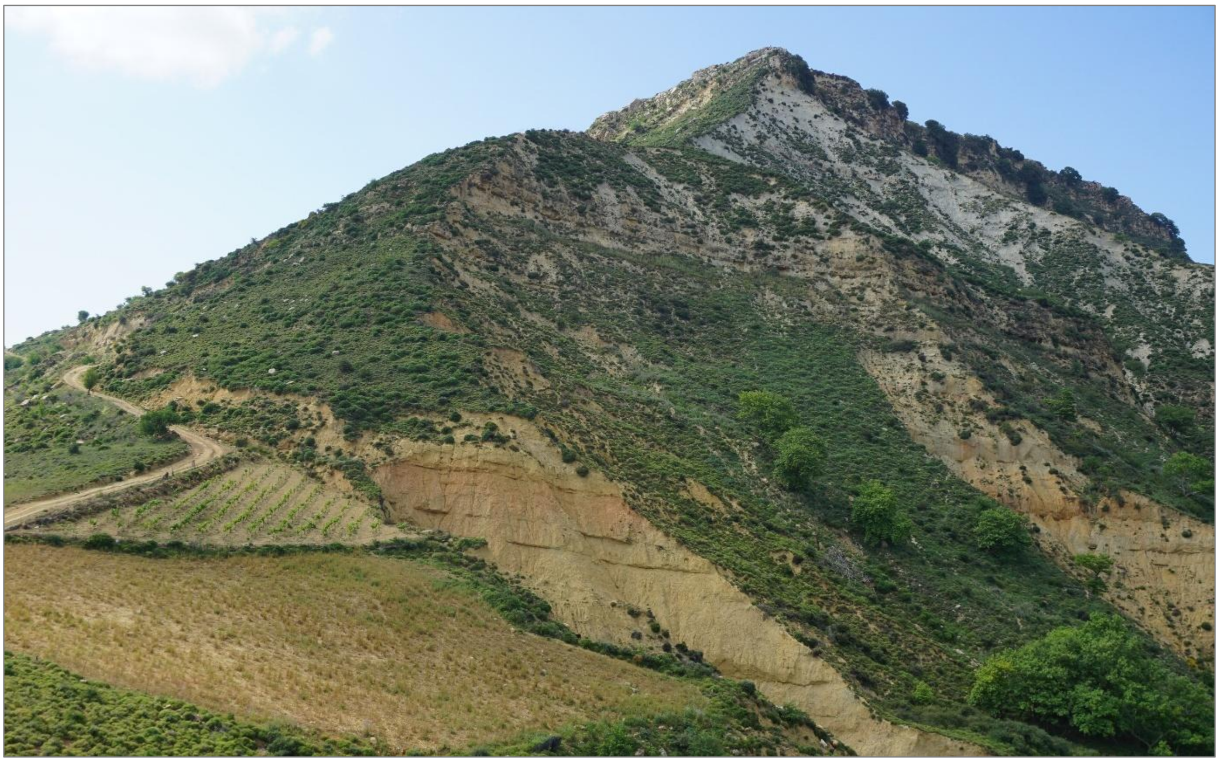
The encroachment of the sea from the south and the gradual decrease of the clastic sediment supply from the northeast, resulted in the deposition of the transitional sediments such as brackish-lacustrine deposits to the west and supra-tidal flat sediments to the east (depositional system 3). The first marine sediments are indicated by a shoreface system (dp 4).

An erosional decline in the paleorelief and a climatic transition towards warmer conditions are thought to be responsible for the change in the sedimentation regime from clastic to carbonate. These factors ultimately resulted in the formation of marls and bioclastic limestones that gradually spread across the Apostoli Basin (dp 5).

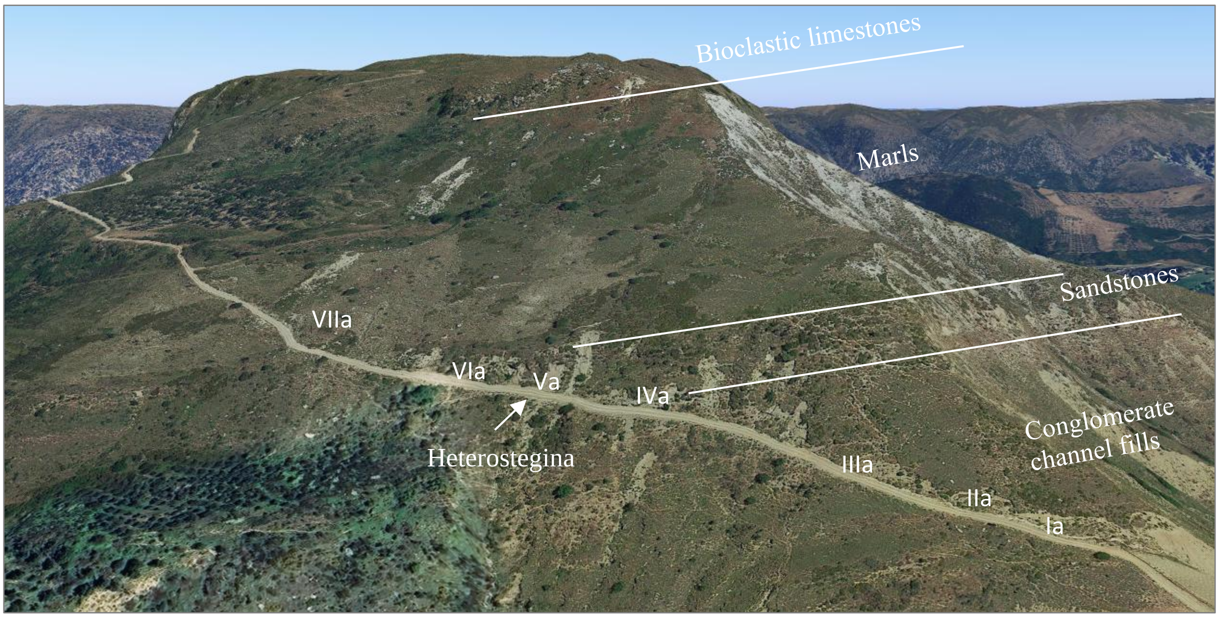
Tectonic uplift played a primary role in the erosional and sedimentary processes. It was responsible for the preservation of the paleorelief and the continuous clastic sediment supply. During increased tectonic activity, increased gravel and sand supply from the elevated paleorelief northwards of the basin, caused the deposition of coarse-grained continental deposits. During periods of low tectonic activity, the transport and deposition of finer-grained sediments was more prominent.

The following paragraphs describe two sections of the Apostoli Basin. The Potami Section represents the eastern part of the basin and the Viglotopi Section is located at the western side of the basin. The Potami Section presents a full sequence of continental sediments but has no transitional fluvial-marine deposits. The Viglotopi Section on the other hand has well developed thick fluvial-marine sediments, but has less continental alluvial deposits exposed. The description of each stratigraphic section starts at the base of an appropriately exposed sequence and works its way upwards through the various depositional units.

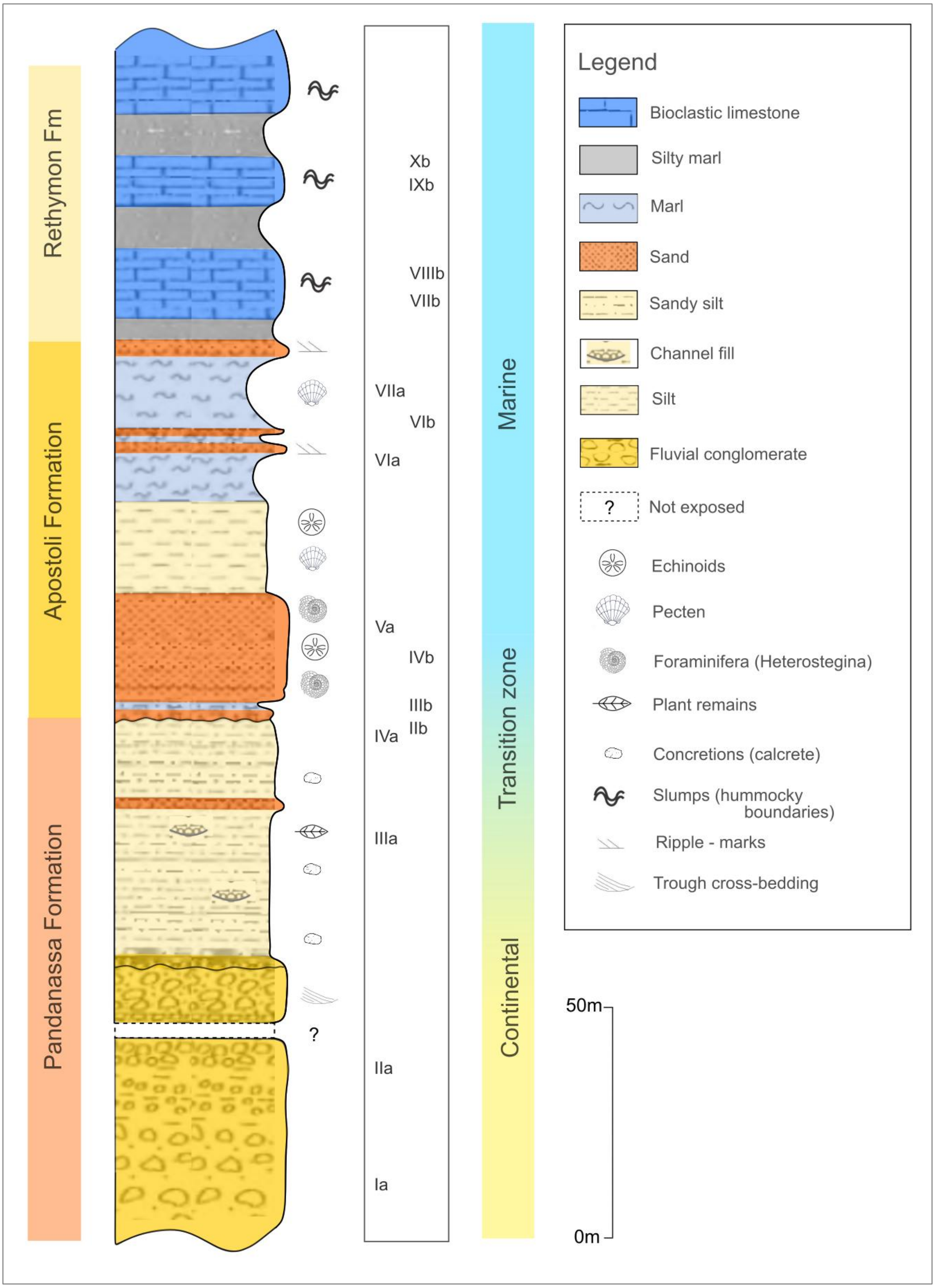
3 The Southern Potami Section



Overview of the south side of the Potami mountain. The dirt road on the left gives good access to the Southern Section described in the following text.



Bioclastic reef limestone caps the top of the mountain. Light grey marls underlying the reef limestone were deposited in a low energy protected shelf environment. Further down in the section coastal lagoonal and subtidal sands indicate a gradual transition to continental conditions. In the valley yellowy conglomerate sediments represent a fluvial continental environment. [Source of image: Google Maps]



Part of the Potami section showing the transition from continental to marine facies. Outcrop numbers are shown in roman numerals. This part of the section overlies an additional 100m-200m of continental conglomerates (after Drina, 1996).

3.1 Continental, Alluvial Fan System

Note that the bottom part of the continental sequence representing the alluvial system (see depositional model) is not referred to here, owing to poor accessibility. Drina (1998) describes them as coarse, poorly sorted, angular and matrix-supported fanglomeratic deposits often classifying them as debris flows. The sediments may either be loose or cemented. The deposits may be characteristically followed along the depositional strike, but rapidly thin out downdip indicating the shape of an alluvial fan. The pre-Neogene basement on top of which the sediments lie is eroded and partly shows pronounced paleorelief.

3.2 Continental Fluvial, Floodplain System

The fluvial deposits are composed of laterally consistent, subangular to subrounded, partly stratified, stream-flow conglomerates and channel conglomerates that are interbedded with silty-sandy flood plain-overbank deposits. The sediments that are mainly clast-supported are generally poorly to moderately sorted and their composition varies between Phyllite-Quartzite Unit and calcareous components. Sorting and roundness improve in the higher levels of the Unit. Imbrication structures, where visible, indicate that the paleocurrent direction was towards the south and southwest.

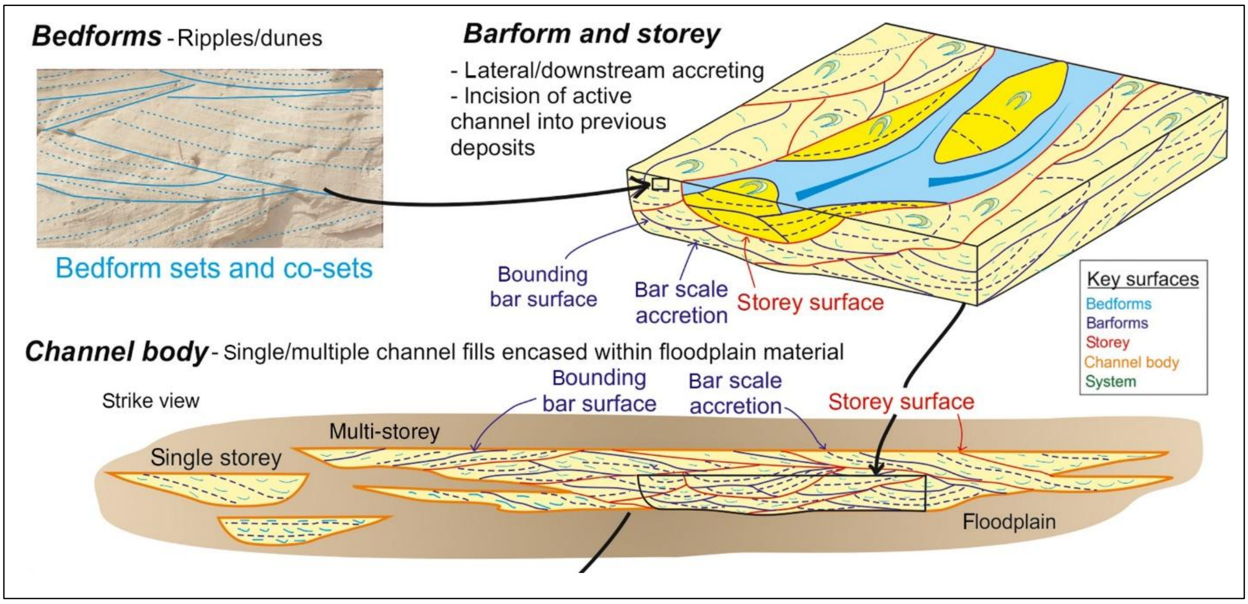


Figure showing the architecture of fluvial deposits after Owen, A. et al., 2017: Classification of fluvial textures: an example from the Palaeocene-Eocene Bighorn Basin, Wyoming.

Outcrop Ia, continental facies: Overview showing stream-flow conglomerates at the Potami section. The conglomerate bed is approx. 3-4 m thick and has fine silty and sandy overbank deposits at its base and top.

Outcrop Ia, continental facies: The clasts composed of pre-neogene rock are moderately well sorted and rounded. The size of the clasts appears to be bimodal (i.e. large clasts in a matrix of smaller rounded gravel). The composition of both sized clasts is highly varied reflecting a wide range of metamorphic rocks from the pre-neogene alpine basement.

This facies consists of clast-supported conglomerates with minor interbedded sandstones and pebbly sandstones. Basal surfaces of the beds are sharp and irregular with relief of up to 0.3 m. Intercalations of sandstone and mudstone are often lenticular. The conglomerates are commonly capped by medium to coarse grained sandstones up to 0.3 m thick which are usually parallel laminated or display low angle planar cross-stratification.

Outcrop IIa, continental facies: Overview of a gravel sized conglomerate alternating with silty, sandy overbank deposits.

Outcrop IIa, continental facies: Closeup showing mainly subrounded gravel sized clasts in a sandy matrix with distinct parallel bedding.

3.3 Transitional Deposits - Fluvial to Marine

This depositional system belongs to the upper part of Pandanassa Formation and has been corelated with brackish-lacustrine sediments in the western part of the Apostoli Basin (Viglotopi Section). At this location, which lies at the eastern part of the basin the transitional zone is not so prominent and is composed of silty carbonate sand and marl beds that alternate with conglomerate channel flow sediments. Thin sandy layers within the silty marl beds occasionally contain peat remains indicating former vegetation that has been reworked after diagenesis. Palustrine and lagoonal muds are thought to indicate a transitional stage between the continental and the shallow-marine environments.

Outcrop IIIa: fluvial-marine transition zone. Picture showing an excerpt from several meters of silty sand beds with occasional sand layers. This sequence is interpreted to have been a lagoon or supratidal flat indicating the transition to marine conditions.

Outcrop IIIa, fluvial-marine transition zone. Closeup of a sand layer within the sequence of silty sand beds. The black particles are plant remnants, which could have been peat transported by a stream.

Outcrop IIIa, fluvial-marine transition zone. Sample from one of the sand layers containing plants remnants.

Outcrop IVa: fluvial-marine transition zone. 1: Silty carbonate fine sand bed with concretions at base. 2: hardground indicating former erosional surfaces 3: conglomerate channel fill, 4: overbank silty sediments.

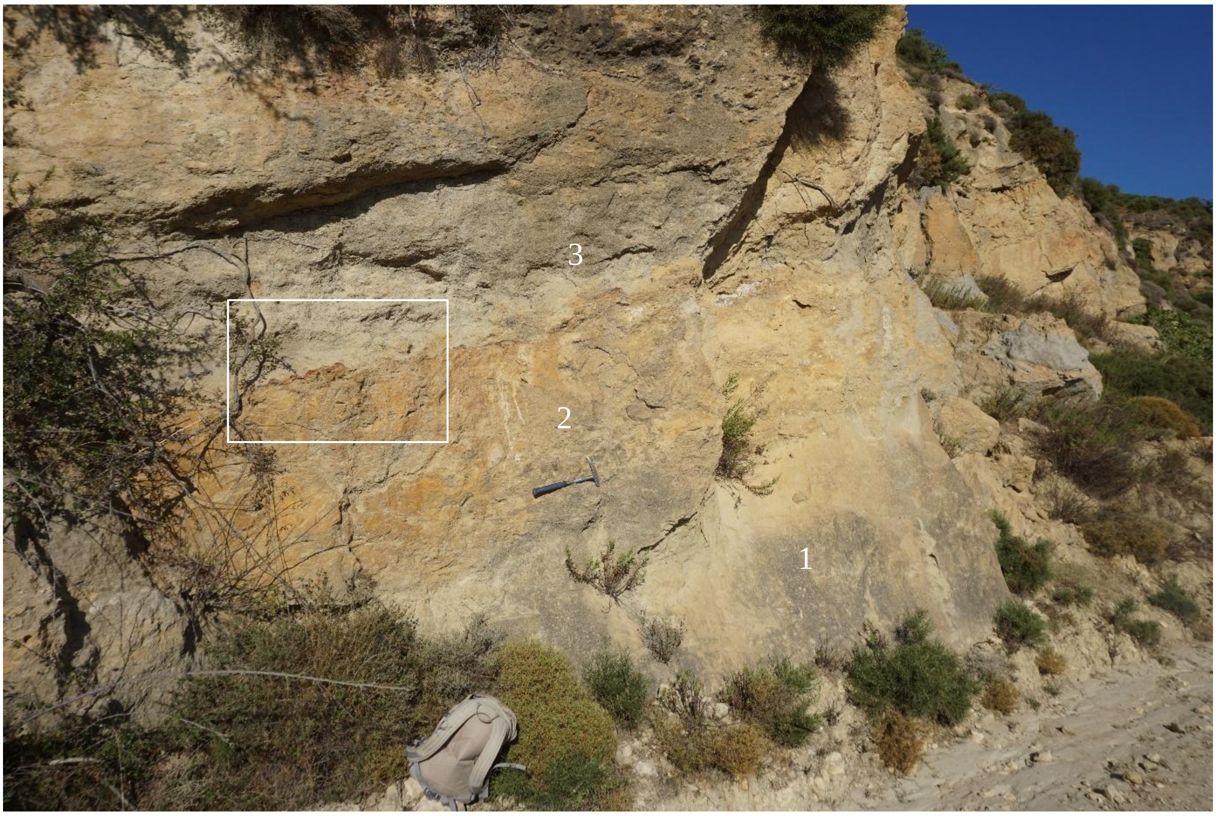
Outcrop IVa: fluvial-marine transition zone. Closeup of previous picture (see box). 6: wavy surface texture is thought to be the result of weathering – during heavy rainfall flowing water winnows and transports fine partials from the exposed surface. Note that the silty carbonate sand beds are fairly soft. 5: concretions, 7: underlying dark grey marl bed could be a lagoonal deposit.

Outcrop IVa, fluvial-marine transition zone. 1: sample from the outcrop displaying carbonate fine sand.

Outcrop Iva, fluvial-marine transition zone. The overlying conglomerate channel fills document a temporary return to fluvial continental conditions.

3.4 Marine Facies - Sandy Shoreface, Shelf Deposits and Subtidal Flats

The marine deposits consist of a sequence of beach conglomerates, shoreface sandstones, and shelf deposits. The bluish sandy beds contain horizons with abundant Heterostegina. These beds can be traced laterally throughout the basin and therefore represent a key horizon for corelation among the marine deposits. The marine deposits belong to Apostoli Formation.



Outcrop Va, marine facies, overview, 1: marine fine sand, 2: sandy Heterogestina bed, 3: Silt bed with occasional Pecten

Outcrop Va, marine facies. 1: marine shoreface fine sand

Outcrop Va, marine facies. 2: sandy Heterogestina bed, 3: echinoid rest

Outcrop Va, marine facies. Closeup of previous picture. Weathered surface reveals bioclastic structure. 2: sandy Heterogestina bed. 1: Heterogestina, 2: Pecten, 3: echinoid rest (see arrow previous picture).

Outcrop Va, marine facies. Transition between two beds (see box in outcrop overview above) 2: sandy Heterostegina bed, 3: Silt bed. 4: brown concretions (iron oxides) forming a hardground, 5: Heterostegina and Pecten.

3.4.1 Heterogestina

Heterostegina, a genus of larger benthic foraminifera, is typically found in shallow marine carbonate facies (generally 10 to 100 meters) such as in middle to distal ramp settings. These environments are often associated with reefs and carbonate platforms, where warm water, good light penetration, and low turbidity conditions prevail. Heterostegina hosts photosynthetic microalgae within its test (shell), relying on them for nutrients produced through photosynthesis. This symbiosis restricted it to well-lit environments. In addition to photosynthesis, it supplemented its diet by capturing organic particles from the water column using pseudopodia. *[Wikipedia]*

3.4.2 Hardgrounds

Hardgrounds are surfaces of synsedimentarily cemented layers that have been exposed on the seafloor (Wilson and Palmer, 1992). A hardground is essentially, then, a lithified seafloor. Ancient hardgrounds can be distinguished from later-lithified sediments by evidence of exposure to normal marine waters. This evidence can consist of encrusting marine organisms, borings of organisms produced through bioerosion, early marine calcite cements, or extensive surfaces mineralized by iron oxides or calcium phosphates. *[Wikipedia]*

3.4.3 Pecten

Outcrop Va, marine facies: close up of the Heterostegina bed from a different angle

Outcrop Va, marine facies, 3: Silt bed with occasional Pecten (see arrow). The silt bed is likely to have been deposited in a protected shelf environment.

Outcrop Va, marine facies: closeup of the silt bed with wavy surface probably due to weathering. 1: Pecten, 2: Heterostegina. The presents of Pecten and Heterostegina confirm the marine facies. However, as Pecten prefer sandy or gravely substate the presents of Pecten in a silty environment indicates that the Pecten are not "in situ". They have therefore been reworked, transported and deposited alongside with other fossils such as Heterogestina.

	*Pecten also known as Scallops are usually found in waters ranging from approximately 5°C to 20°C. They prefer normal marine salinity (around 30–35 ppt). Drastic fluctuations, such as those caused by freshwater input from rivers or heavy rainfall, can stress them and limit their distribution to regions with consistent salinity levels. Like all marine organisms, Scallops depend on sufficient dissolved oxygen in the water. Poor oxygenation, often caused by pollution or algal blooms, can lead to hypoxic conditions, making certain areas uninhabitable for Pecten populations. [Wikipedia]*

Fossil Pecten species, such as *Pecten benedictus* and *Pecten cristatus*, are commonly associated with Tortonian sediments in the Mediterranean region, including Crete.

Pecten are filter feeders. They draw in water through their gills, where they trap and consume plankton. This feeding process is facilitated by the constant flow of water over their gills. They therefore rely on moderate water currents for nutrients. Most Pecten live on sandy or gravelly sea beds, where they can either rest or slightly bury themselves. Areas with excessive mud or silt may smother their feeding apparatus or limit their ability to remain mobile, reducing their presence in such environments.

Unlike many bivalves, Pecten are capable of movement. They "swim" by rapidly clapping their shell valves together, which forces water out and propels them through the water. This behaviour is often used to escape predators such as starfish. Another unusual feature is that they have primitive eyes located along the edge of their mantle. *[OpenAl]*

3.4.4 Shoreface Sediments

Typical shoreface sediments consist of medium to fine sands, as wave energy normally sorts and removes finer particles like silt and clay. Shoreface sediments are also usually well-sorted, reflecting the consistent wave action and currents in this high-energy environment. Sedimentary structures include parallel lamination, cross-bedding, and wave ripple marks, indicative of wave and current influence.

Well-sorted fine sand often accumulates in the lower shoreface, where energy levels are somewhat lower compared to the upper shoreface, but waves still play a significant role in sediment transport and deposition. Beach conglomerates may also be found in an upper shoreface environment.

Outcrop Va, marine facies. Several meters of marine fine sand thought to have been deposited in a lower shoreface environment, where energy levels are somewhat lower compared to the upper shoreface.

Outcrop Via, marine facies. Close up of previous picture. Shoreface sediments generally consist of medium to fine sands. The sand contains numerous minute broken shell particles that could be associated with wave action.

3.5 Marine Shelf Deposits - Subtidal Protected Shelf Deposits

Outcrop VIIa, marine facies. Succession of marl beds

Outcrop VIIa, marine facies. Closeup of previous picture

4 The Northern Potami Section

Overview of the northern Potami Section [source of image Google Maps]

Outcrop Ib: underlying Pre-neogene metamorphic rock indicated on the geological map 1: 200 000 to belong to the Phyllite-Quartzite unit.

4.1 Marine Facies - Sandy Shoreface, Shallow Shelf and Subtidal Flat Deposits

Outcrop IIb, marine facies. Carbonate sands

Outcrop IIb, marine facies. Closeup of previous picture displaying fairly porous carbonate sand

Outcrop IIIb, marine facies. Marl bed interpreted to be a subtidal protected shelf or lagoonal deposit

Outcrop IVb, marine facies. Heterostegina limestone with reef debris

Outcrop IVb, marine facies. Closeup of Heterostegina limestone

Location Vb: View of Potamon Lake looking westwards. In the central background other Neogene tabletop mountains. The highest mountain in the background consists of Pre-Neogene metamorphic rock.

Outcrop VIb, marine facies. Marl bed representing a protected shelf environment, that may have been in a back reef location.

Outcrop VIb, marine facies, closeup of previous picture: marl

4.2 Marine Inner and Outer Shelf System

4.2.1 Marine Inner Shelf System - Rear of Barrier Reef

These carbonate deposits have been allocated to the Rethymnon Formation and are composed of two main lithological types: a) bioclastic limestones alternating with marls and b) reefs. The bioclastic limestones are thought to represent a carbonate platform, on which the occasional reef was able to form within the submerged basin.

Outcrop VIIb, marine inner shelf: coralline red algae limestone

Rhodoliths are calcareous nodules composed of more than 50% of coralline red algal material, which can consist of one to several coralline species growing together. Coralline red algae are organisms that deposit calcium carbonate within their cell walls to form hard structures or nodules that resemble beds of coral. Rhodoliths produce energy solely through photosynthesis and can only grow and survive in the photic zone of the ocean. Rhodoliths are thought to have been present in the world's oceans since at least the Eocene (55 million years ago).

Outcrop VIIb, marine inner shelf, closeup of previous picture: coralline red algae limestone

Outcrop VIIIb, marine inner shelf. Limestone

Outcrop IXb, marine inner shelf: bioclastic limestone with coral and bivalves.

Outcrop IXb, marine inner shelf: closeup of previous picture showing fresh surface of sample. 1: bivalve clast

Outcrop IXb, marine inner shelf. Closeup of previous picture showing fresh surface of sample on the left and possible borings of marine organisms on the weathered surface on the right (see arrow)

Outcrop Xb, marine inner shelf. Bioclastic limestone. 1: reworked red algae clasts

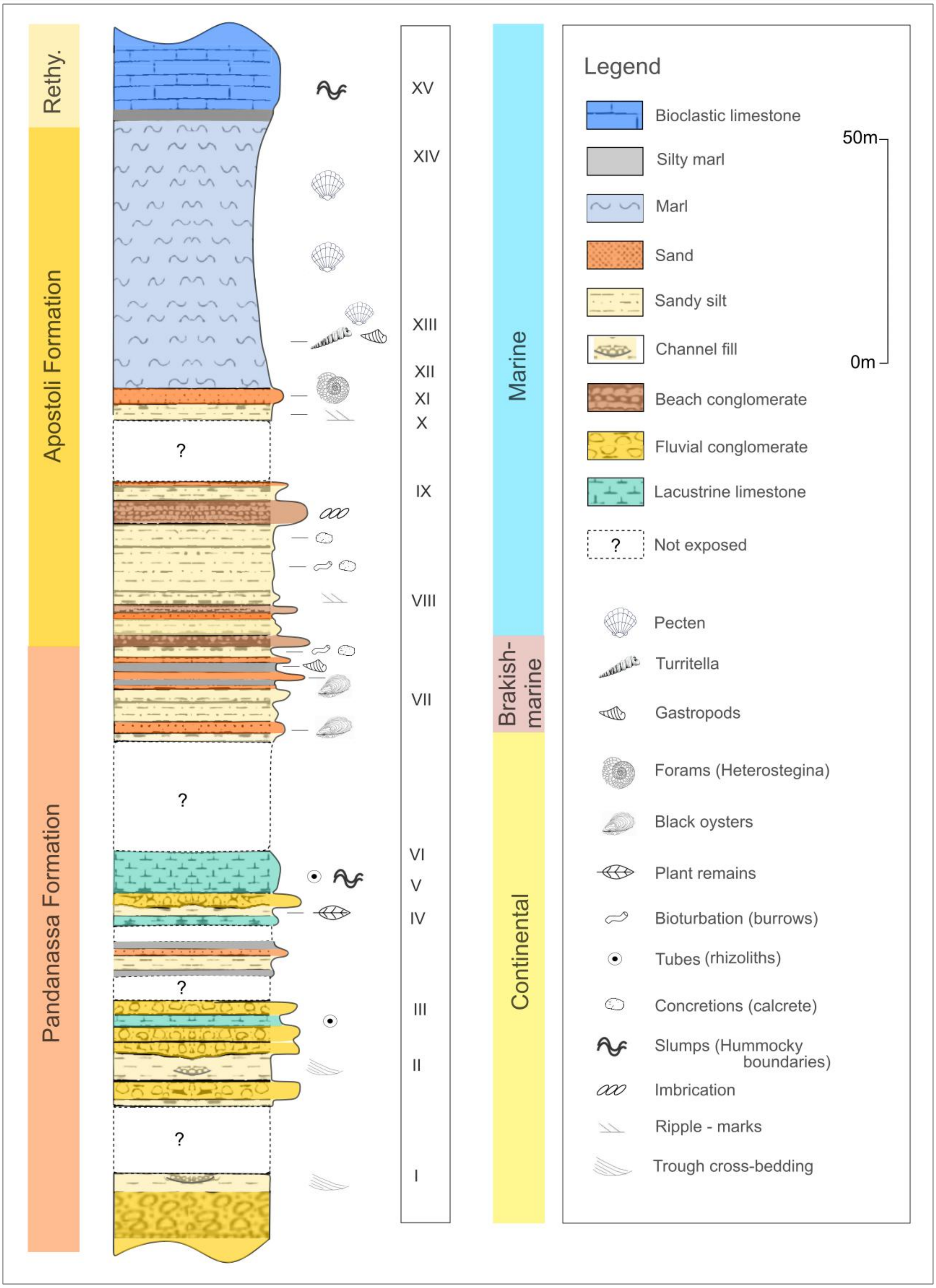
Outcrop Xb, marine inner shelf, closeup of previous picture. Bioclastic limestone. 1: reworked red algae clast, 2: echinoid spine, 3: bivalve

5 Viglotopi Section

Arrows indicate the base and top of the Vigiolopti Section

Overview of the Vigiolopti Section showing the various studied outcrops [GoogleMaps]

Continental sediments belonging to the Pandanassa Formation form the lower part of the Viglotopi Section and underlie the Apostoli Formation. The thickness of the continental sediments consisting mostly of conglomerates and silty overbank deposits is about 120-150 m. The contact with the Pre-Neogene within the area often runs along faults. Lacustrine limestones can be observed at the upper levels of the continental sediments. The limestones are often platy or laminated and contain thin conglomerate intercalations and, locally, abundant calcified tubes that are thought to be Rhizoliths (i.e. tubes formed by the interaction of plant roots with sediment). At the top part of the Pandanassa Formation brackish intercalations characteristic of the Viglotopi Section represent a transition to marine conditions. The uppermost 10 meters of the brackish carbonates contain intercalations of dark silty clays with gastropods (*Cerithium)* and oyster (*Crassostrea)* beds of variable thickness. The *Crassostrea* beds are composed of closely packed oysters, up to half a meter in length, which lie more or less parallel to the bedding plane. Eastwards within the Apostoli Basin, the brackish intercalations are no longer found and the marine sediments of the Apostoli Formation directly overlie the fresh-water deposits. The brackish deposits of Viglotopi Section can therefore be regarded as a lateral equivalent of the uppermost fresh-water deposits that occur eastwards. The overlying Apostoli Formation represents marine facies as it consists of shoreface sediments with sandy silty parallel stratified beds and conglomerates as well as shoreface deposits with hummocky cross-stratification. Further up, the section reveals *Heterostegina* sands and marly protected shelf deposits. The overlying Rethymnon Formation is characterized by bioclastic limestone and reef bodies *[Meulenkamp,1969]*.



Lithostratigraphical column of the Viglotopi Section. (Based on Drina, 1998)

5.1 Continental Facies, Stream-flow and Channel Fill Conglomerates

This facies consists of conglomerates with minor interbedded sandstones and pebbly sandstones. The conglomerates are moderately to well sorted, comprising subrounded to subangular pebbles and cobbles. Invariably, they are clast-supported and tightly packed. The beds are mainly ungraded. The clast supported conglomerates generally show clear evidence of erosion at the base. Intercalations of sandstone and mudstone are often lenticular. Many of the sandstones are plane-stratified and form graded cappings of the conglomerate beds. The texture- and stratification of the clast-supported conglomerates strongly suggest a braided stream-flow origin. The small-scale lenticular sandstone intercalations may simply represent deposition due to slight fluctuations in stream velocity (Harms et al., 1975) *[Drina, 1998]*.

Outcrop I, continental facies: base of section displaying braided-stream deposits. The outcrop consists mainly of light grey conglomerates with occasional light grey silty interbeds and yellowy silty lenses.

Outcrop I, continental facies: close up of previous picture. The conglomerates are moderately to well sorted, comprising subrounded to subangular pebbles and cobbles. They are clast-supported and tightly packed. Beds are generally ungraded.

Outcrop I, continental facies: yellowy silty lens within one of the conglomerate beds.

Outcrop II, continental facies, overview: 1: light grey braided stream deposits, 2: Yellowy conglomerate fluvial channel fill deposits.

Outcrop II, continental facies: closeup of previous picture. 3: a sandy layer separates the lower and upper channel fill. The lower channel fill (2a) displays fining upwards of the clasts indicating reduction in stream flow energy.

Outcrop II, continental facies: close up of the previous picture showing the upper channel fill (2b). The conglomerate shows some signs of cross bedding. The lower sandy layer was probably eroded by the stream prior to deposition of the conglomerate.

According to the description given by Dina, 1998 channel fill conglomerates differ from the braided stream conglomerates by greater clast roundness, better sorting and by the presence of distinct sedimentary structures. Both planar and trough cross bedding are conspicuous in transverse and longitudinal sections, and plane bedded units commonly show clast imbrication and occasional local fining upwards.

5.2 Calcrete Limestones - Paleosols

Outcrop III, continental facies: fine-grained river floodplain deposits with caliche interbeds and tubes

Outcrop III, continental facies: close up of the previous picture showing caliche nodules and tubes (rhizoliths). 4: caliche nodules, 5: rhizoliths

Calcrete, which is also known as caliche is typically seen in river floodplain sediments. It occurs in several forms, from nodules to continuous layers, with massive, laminated and pisolitic textures. Calcrete is generally thought to be a soil building process whereby carbonate in the upper, A-horizon of the soil profile is washed out and precipitated lower down in the B-horizon (Goudie, 1973). It consists of calcareous nodules ranging from 0.5 to 4 cm in diameter. The presence of calcareous palaeosols suggests a relatively dry, probably semiarid palaeoclimate (Reeves, 1970; Cerling, 1984) *[Drina, 1998]*.

Rhizoliths are organosedimentary structures formed in soils or fossil soils (paleosols) by plant roots. They include root moulds, casts, and tubules. Rhizoliths, and other distinctive modifications of carbonate soil texture by plant roots, are important for identifying paleosols (fossil soils) in the geologic record. Plant roots normally remove calcium from soil while lowering its pH, by exchanging H^+ ions for Ca^{2+}, Mg^{2+}, K^+, and other cations. This contributes to the ability of roots to bore through rock, but it works against precipitation of calcite around roots. Several explanations have been offered for how rhizoliths are formed. One possibility is that some plant roots take up more anions than cations, maintaining charge balance by secreting HCO_3^- ions rather than H^+ ions. In so doing, the pH of the surrounding soil is raised, rather than lowered. This may trigger precipitation of calcium carbonate around roots.

Outcrop III, continental facies: close up of the previous picture: 4: caliche nodules, 5: rhizoliths

Outcrop III, continental facies. 6: yellowy matrix supported gravel bed with subrounded to subangular clasts, thought to represent distal alluvial fan or braided stream deposits. Owing to the sub-angular clasts the material source is likely to have been closer than that of the lower conglomerate beds. 4: Limestone with caliche nodules

5.3 Fresh-Water Limestones

Outcrop III, continental facies. Overview of previous picture. 7: Fresh-water limestone probably originating from a lake, 6: Matrix supported gravel bed with subrounded to subangular clasts.

Outcrop IV, continental facies, 7: fresh-water limestone overlying the limestone shown in the previous picture. The well stratified limestone has an irregular erosional surface at the top of the bed indicating the presents of an unconformity (i.e. a time gab in the geological record). 8: a gravel bed with caliche that also displays an irregular erosional surface.

Outcrop IV, continental facies, 7: fresh-water limestone

Outcrop IV, continental facies, closeup of previous picture

Outcrop IV, continental facies, 7: fresh-water limestone, 8: Gravel bed possibly with flat caliche nodules

Outcrop IV, continental facies, 8: gravel bed possibly with flat caliche nodules

5.3.1 Nodular and Rhizolithic Lacustrine Limestones

Outcrop V, continental facies, 9: intensely stratified nodular fresh-water limestone

Outcrop V, continental facies, closeup of previous picture displaying thin nodular carbonate layers

Outcrop V, continental facies, 10: rhizoliths (calcified tubes) in lacustrine (fresh-water) limestone

Outcrop V, continental facies, closeup of rhizoliths in nodular lacustrine limestone

The deposition of lacustrine lime muds has several possible chemical and biological explanations. Inorganic precipitation of carbonate may for example be due to evaporation. CO_2 loss through plant photosynthesis and/or degradation of microbial substances are other process causing the precipitation of carbonate mud. Alternatively, a change in water chemistry may also arise from mixing of fresh stream water with brackish/saline lake water causing carbonate precipitation *[Drina, 1998]*.

CO_2 loss through plant photosynthesis can contribute to carbonate precipitation in lacustrine (lake) environments, especially in the microenvironments around plant roots. When aquatic plants photosynthesize, they consume dissolved CO_2 from the surrounding water. This reduces the concentration of carbonic acid, shifting the carbonate equilibrium toward the formation of carbonate ions (CO_3^{2-}). If calcium ions (Ca^{2+}) are also present in sufficient quantities, this can lead to precipitation of calcium carbonate ($CaCO_3$) - the main component of carbonate mud.

This process is particularly effective in shallow, well-lit waters where photosynthesis is intense. Around plant roots, localized zones of high pH and altered CO_2 concentrations can create ideal conditions for micrite (fine-grained carbonate) formation. While other mechanisms like microbial degradation of organic matter and whiting events[1] also play a role, biologically induced precipitation via photosynthesis is a well-supported contributor.

[1] A whiting event is a natural phenomenon where fine-grained calcium carbonate ($CaCO_3$) suddenly precipitates out of the water column, creating a cloudy, milky appearance - hence the name "whiting." These events can occur in both marine and freshwater environments, and they're often visible from the air as pale patches in otherwise clear water.

5.4 Transitional Fluvial-Marin Facies

5.4.1 Laminated Lacustrine Limestones

The limestones in this part of the Viglotopi B section are the result of complex combination of fluvial and shallow-marine processes indicating the beginnings of transgression.

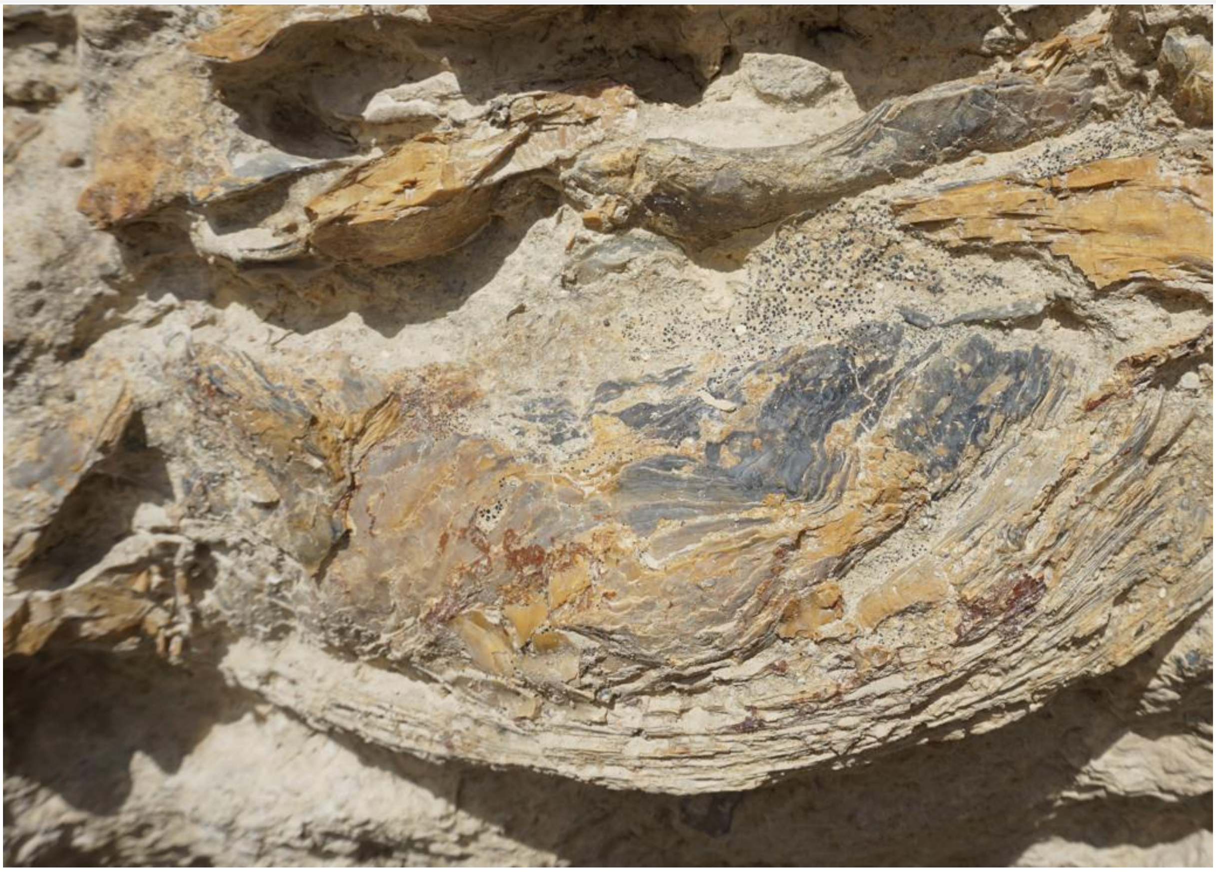
Outcrop VI, transitional fluvial-marine facies. 11: well stratified lacustrine limestone beds.

Outcrop VI. Closeup of previous picture

5.4.2 Oyster Banks

The sandy oyster beds are composed of closely packed oysters, more or less parallel to the bedding plane. The oysters are often very big (up to 40 cm length) and are stacked upon each other with a silty matrix in between. According to Demarcq & Demarcq (1989) the development of these oyster banks are related to brackish paleoenvironmental conditions.

Outcrop VII, transitional fluvial-marine facies, 12: oyster bank

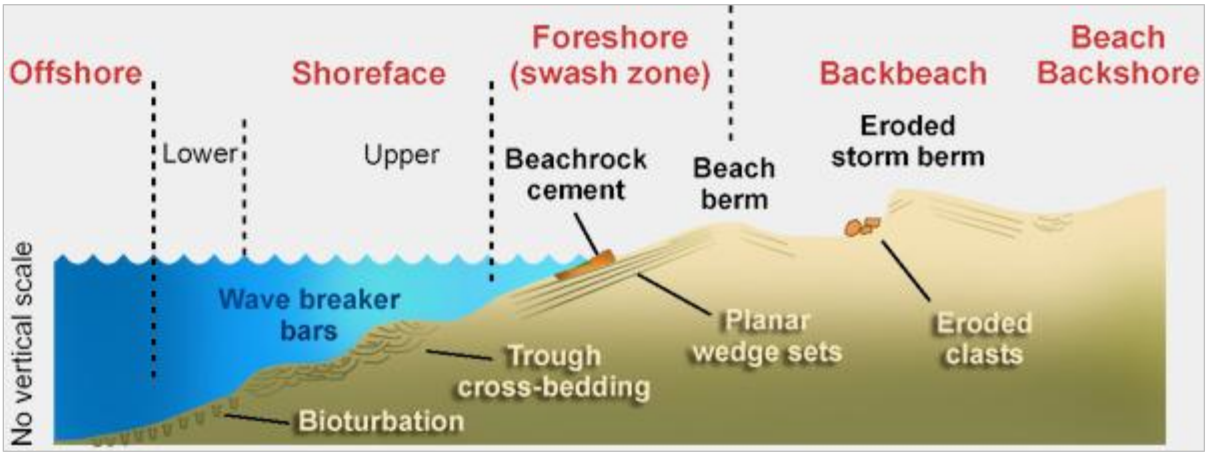


Outcrop VII, transitional fluvial-marine facies, oyster from the transitional marine-fluvial facies. Oysters are reported to have existed under brackish water conditions.

Outcrop VII, transitional fluvial-marine facies. Dark marly deposits with freshwater/brackish gastropods. 13: gastropod, 14: oyster

5.5 Marine Shore Facies

5.5.1 Shore Facies Terms



Backshore: Back sides of beaches can be dominated by several environments including eroded storm berms, eolian dunes, washover fans, supratidal flats, and pond sediments.

Backbeach: Composed of bankward tilted planar wedge sets with some trough crossbeds where water is funneled along the trough of the back beach.

Foreshore: Forms in the swash zone and is composed of seaward dipping planar wedge sets of thin, even laminae where the sediment is sand sized. Keystone vugs created by trapped air are a commonly characteristic of this facies. Beaches can be composed of gravel to boulder-sized material where they are located landward of a source of coral.

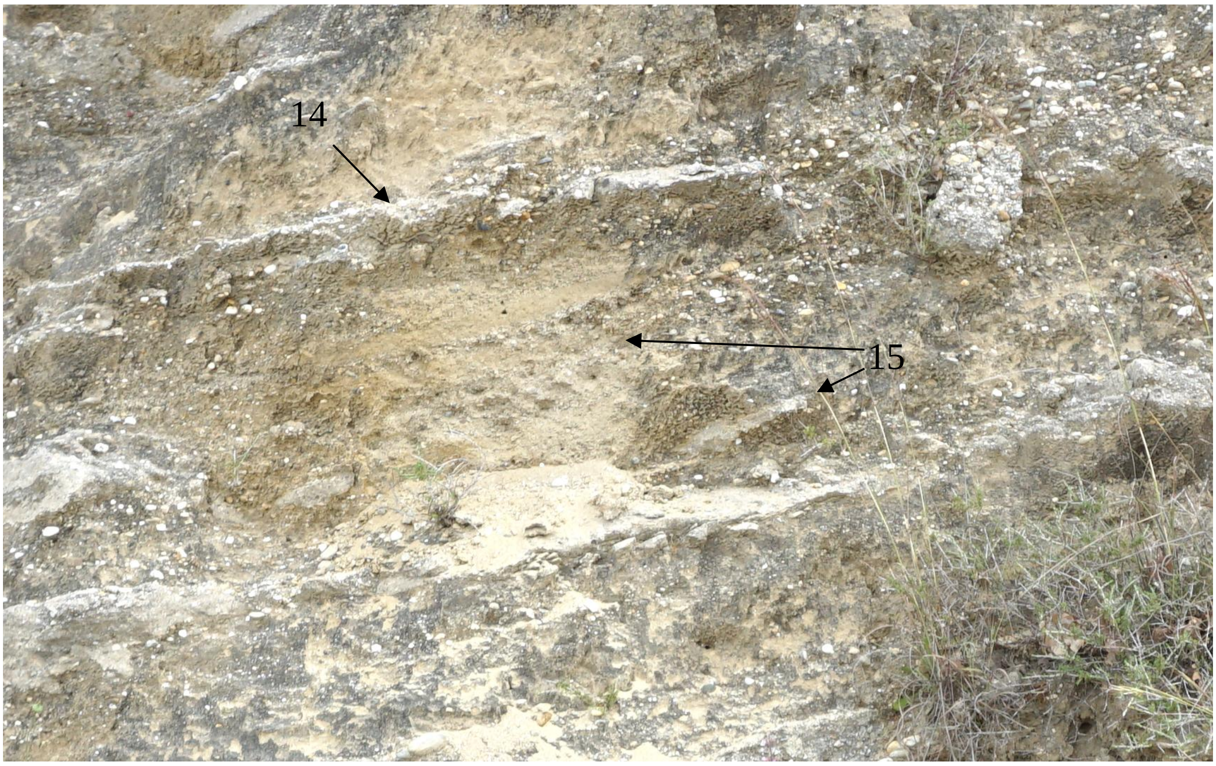
Shoreface: Forms in the surf zone producing wave-breaker bars that are oriented obliquely to the shoreline and generate medium-scale, trough crossbeds.

Offshore: This is a lower energy environment where biological processes become more important than physical processes. Bioturbated sands to muddy sands are deposited.

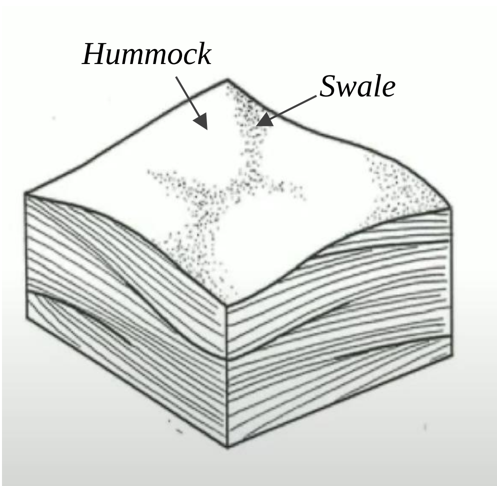
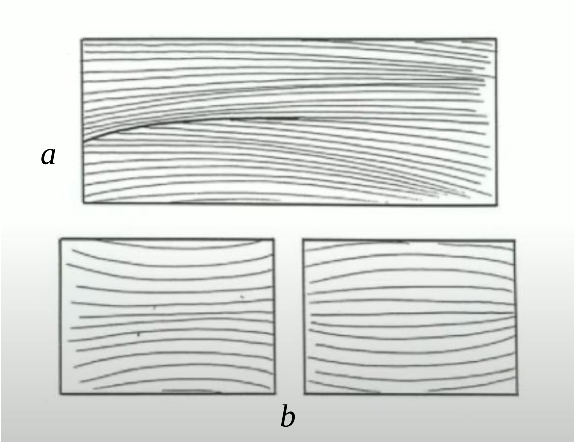
5.5.2 Shoreface Sandstones and Conglomerates

Shoreface sandstones are represented by fine-to coarse-grained beds with horizontal to low-angle stratification and swalley or hummocky cross stratification. The individual beds are lenticular, showing flat or slightly irregular, erosive bases and low-relief undulatory tops. Periodic high energy oscillatory currents, associated with storm conditions, are reflected by the presence of swalley or hummocky-cross-stratification. Low angle truncation of lamina and swelling and pinching lamina structures characterize hummocky-cross-stratification.

Outcrop VIII, marine shore facies. Shoreface gravely sandstones indicating marine environmental conditions. Characteristic features are low-angle hummocky cross stratification. 14: Bedding plane

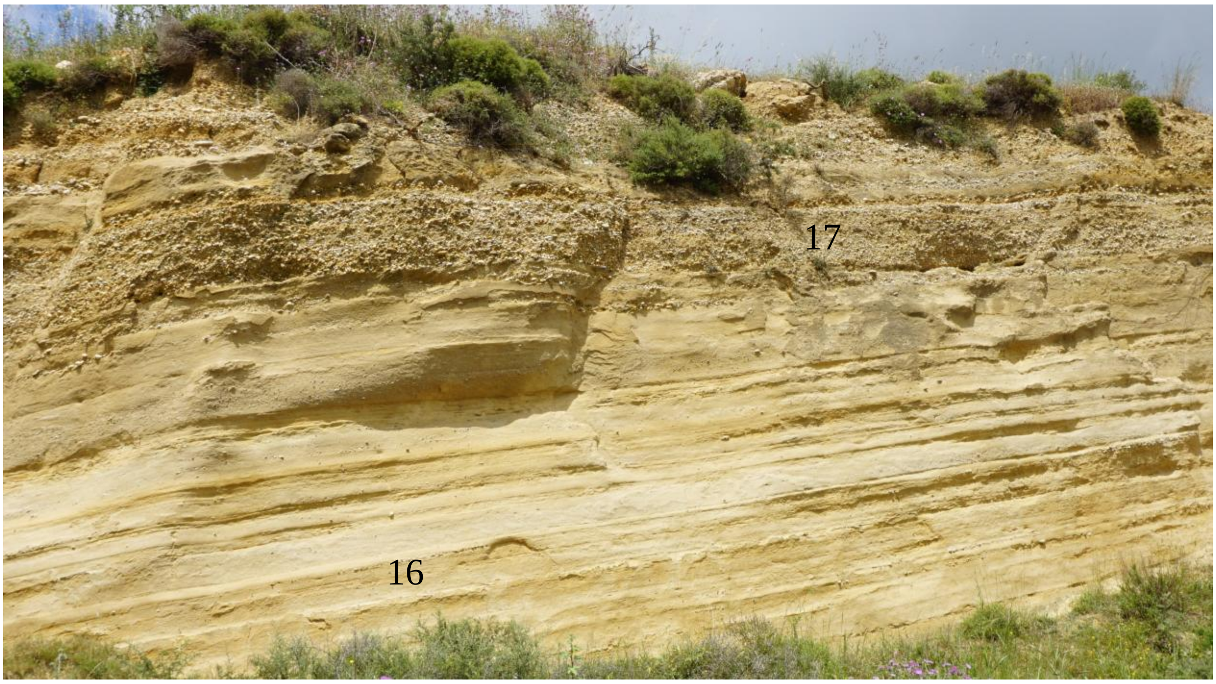


Outcrop VIII, marine shore facies. Closeup of the previous picture. 14: Bedding plane; 15: Low angle crossbedding of gravel and sand as well as truncation of lamina.

	
Hummocky cross-stratification (HCS) indicating high energy conditions at a shoreface. HCS typically forms between the fair-weather wave base and the storm-weather wave base.	*Lamina display low angle truncation (a) and swelling and pinching of lamina (b). Structures are created by the combined action of unidirectional and oscillatory flows, often during storm events.*

5.5.3 Foreshore Sandstones and Conglomerates

The foreshore sandstones and conglomerates are well-defined, gently inclined, seaward dipping layers of alternating sandstones and conglomerates. The bedding pattern is known as planar wedge sets. The sandstones and conglomerate beds are well-sorted and are either horizontal or low-angle parallel laminatied. Skolithos burrows are reportedly common. Conglomerates occur as laterally persistent, one-clast thick layers as well as thicker sharply based tabular units. Most of the thicker, tabular units have an ungraded clast-supported framework of spherical to rod-shaped pebbles and cobbles, with a matrix of sand and small pebbles *[Drina, 1998]*.



Outcrop IX, marine shore facies. Foreshore facies displaying silty-sand beds (16) and conglomerate layers (17). Stratification represents seaward dipping planar wedge sets.

Outcrop IX, marine shore facies. Closeup of the previous picture showing planar stratified clasts that indicate deposition in a beach environment.

Outcrop IX, marine shore facies. Two possible transgressional sequences indicated by a fining upwards *trend. Conglomerates at the base become progressively finer grained, ending in fine sand at the top of each cycle.*

Outcrop IX, marine shore facies. The larger sized clasts are more rounded whereas the gravel sized clasts are less rounded.

5.6 Marine Inner and Outer Shelf System

Outcrop X, marine inner shelf facies. Predominantly loose sand beds with occasional gravelly layers.

Outcrop X, marine inner shelf facies. Loose sand beds

Outcrop X, marine inner shelf facies. Closeup of soft sandstone sample

5.6.1 Heterostegina Sands

Marine inner shelf facies. Photo of a piece of slope debris containing Heterostegina. In-situ Heterostegina sands were not encountered during field work.

Figure showing Heterostegina, depressa. Heterostegina is a large foraminifer, belonging to the family of Nummulitida: (Source Wikispecies).

Owing to its lateral continuity, the Heterogestina Sands represent a key horizon that can be used to correlate the shallow marine deposits of the Apostoli Basin. Within the Heterostegina beds there are scattered Echinoids (Clypeaster) and Pectinidae bivalves. The high skeletal concentration within the Heterostegina sands could be due to a mass-mortality event caused for example by a storm or Tsunami. Alternatively, the high shell content could be attributed to episodes of low net sedimentation, winnowing or erosional reworking (Kidwell (1989, 1991) *[Drina, 1998]*.

Outcrop XI, marine inner shelf facies. Pebbly sandstone beds

5.6.2 Grey-bluish Fossiliferous Marine Marls

The grey-bluish marls and clays overlying the Heterostegina sands display occasional lenses or layers of fine to very fine-grained sandstones. Some levels within the marls yield a rich mollusc fauna. Amongst the genera are *Conus, Murex, Area, Ancilla, Dentalium, Natica, Vermetus, Turritella, Chlamys, Corbula, Ostrea and Pecten*. Specimens of *Pecten latissima* may reach a diameter of up to 30 cm. In particular, *Ancilla glandiformis*, is an “index fossil” of the Tortonian. Echinids are represented by *Clypeaster* and *Scutella*. Brachiopods of small dimensions, like *Argyrotheca cf. dertomutinensis, Megerlia oblita, Terebratula sinuosa*, have been found in the lower strata of the clayey marls.

The fine grained marls indicate quiet sea floor conditions such as in a slightly deeper protected marine shelf environment. Occasional lenses or layers of fine to very fine grained sandstones are thought to be due to waning sand laden traction currents *[Drina, 1998]*.

Outcrop XII, marine inner shelf facies. Grey-bluish fossiliferous marine marls

Outcrop XIII, marine inner shelf facies. Turritellids in the grey-blueish marly deposits

Outcrop XIII, marine inner shelf facies. Closeup of previous picture

Outcrop XIII, marine inner shelf facies. Pecten valve

Dorsal view, damaged	**Apertural view, damaged**
 *Clavatula.sp ?, displaying borehole*	
 *Family Busyconidae*	
 *Conus.sp (antiquus* Lamarck*?)*	

Turritella.sp

Cerithium.sp ?

Ancilla.sp ?

Aspa.sp (marginate?)

Lunatia.sp ? / Natica.sp (Nacca) ?

Gastropod fossils found in the grey-bluish marly beds at the Viglotopi Section [Literature: (Symeonides (1968), Georgiades - Dikeoulia (1974), Gergiades - Dikeoulia (1979)]

5.7 Bioclastic Limestones and Marls

The bioclastic limestones and marls are characterized by the presence of alternating marls and bioclastic limestones, which are partly stratified and often resemble reef deposits. The limestones contain abundant disarticulated and reworked gastropods, bivalves, corals and algae. Heterostegina may be still present. Textural characteristics reflect deposition under low energy conditions, in a protected marine environment such as in a shallow protected shelf, “bay-like”, environment, where scattered patch-reefs consisted of coralline algae and bryozoans develop.

There are several factors controlling the deposition of carbonate limestone of which the most important are temperature, salinity, water depth and siliciclastic input (Lees, 1975). Many carbonate skeletal organisms, such as the reef-building corals and many calcareous green algae, require warm waters in which to flourish. The majority of carbonate sediments therefore occur during tropical-subtropical climatic conditions. Many carbonate skeletal organisms are affected by salinity and water depth and occur preferentially in the shallow agitated part of the photic zone in seawater of normal salinity. One of the overriding controls of carbonate deposition is a lack of terrigenous detritus. The influx of much siliciclastic material will inhibit the formation of limestones *[Drina, 1998]*.

Outcrop XIV. Marine marl deposits representing the deeper shelf environment.

Outcrop XV. Reef limestone and/or bioclastic limestone capping the top of the Viglotopi Section. The carbonate sediments are characterized by Coralline Algal-Bryozoan facies. Abundant echinoderms and in a lesser amount benthonic and planktonic foraminifera have been observed within the bioclastic limestones of the Apostoli Basin.

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6 Appendix

Stratigraphic Table of the Cenozoic

Eonothem/ Eon	Erathem/ Era	System/ Period	Series/ Epoch	Stage/ Age	mya[1]
Phanerozoic	Cenozoic	Quaternary	Anthropocene[5]		1950 CE
			Holocene		0.0117
			Pleistocene	Upper	0.126
				Middle	0.781
				Calabrian	1.80
				Gelasian	2.58
		Neogene	Pliocene	Piacenzian	3.600
				Zanclean	5.333
			Miocene	Messinian	7.246
				Tortonian	11.63
				Serravallian	13.82
				Langhian	15.97
				Burdigalian	20.44
				Aquitanian	23.03
		Paleogene	Oligocene	Chattian	27.82
				Rupelian	33.9
			Eocene	Priabonian	37.8
				Bartonian	41.2
				Lutetian	47.8
				Ypresian	56.0
			Paleocene	Thanetian	59.2
				Selandian	61.6
				Danian	66.0

[1] Millions of years ago

Paleogeography of Crete

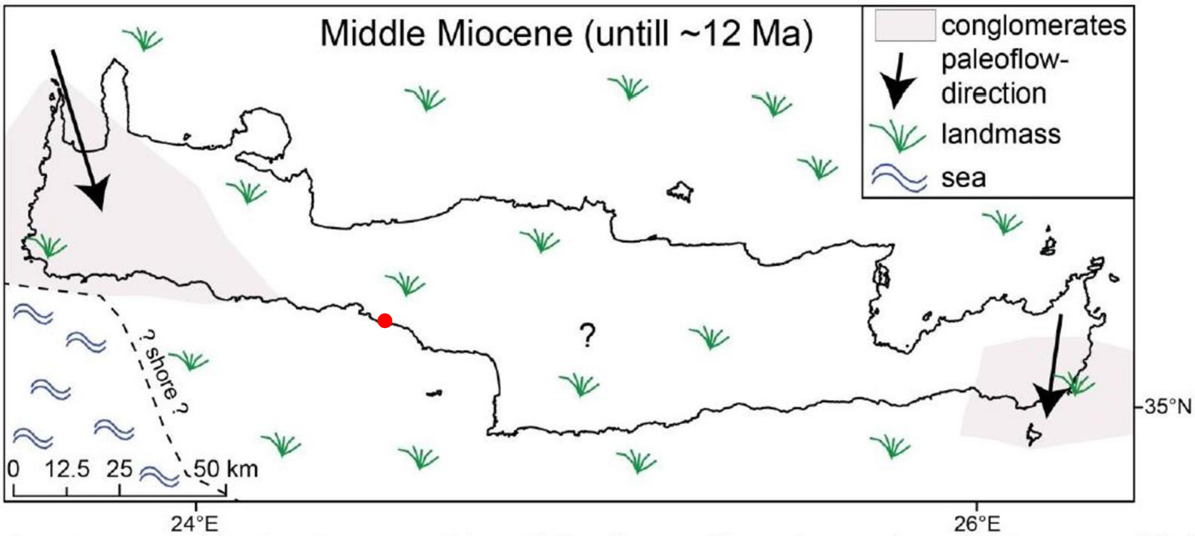
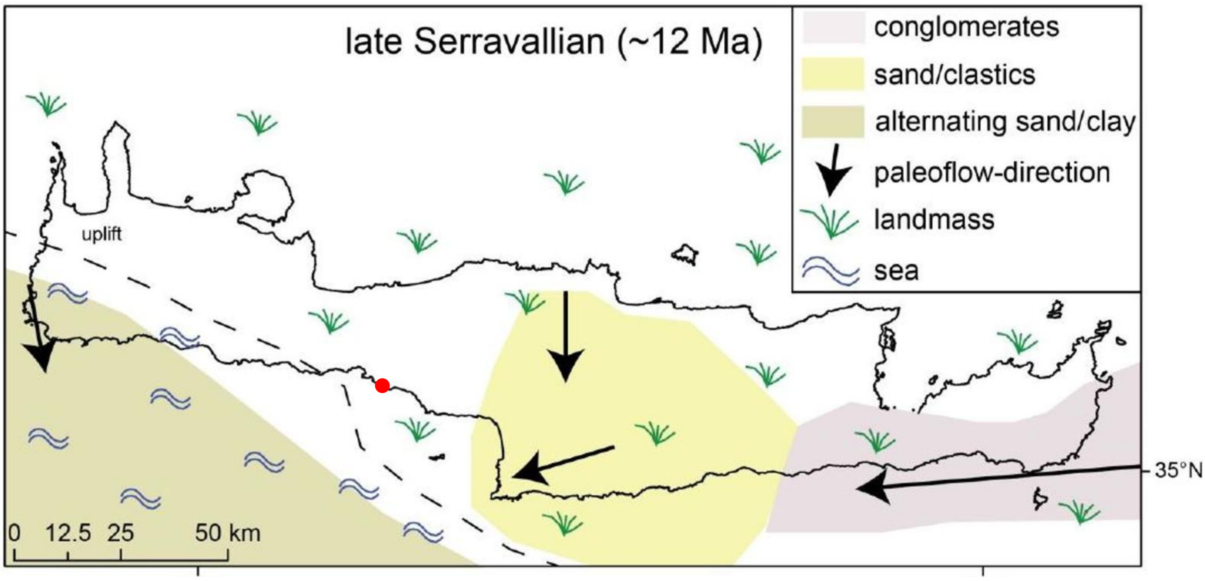


Figure 5.3: Depositional environment of the Middle Miocene of lacustrine-continental sediments modified after van Hinsbergen et al. (2006).



Dispositional Environments Serravalian van Hisbergen. JPG

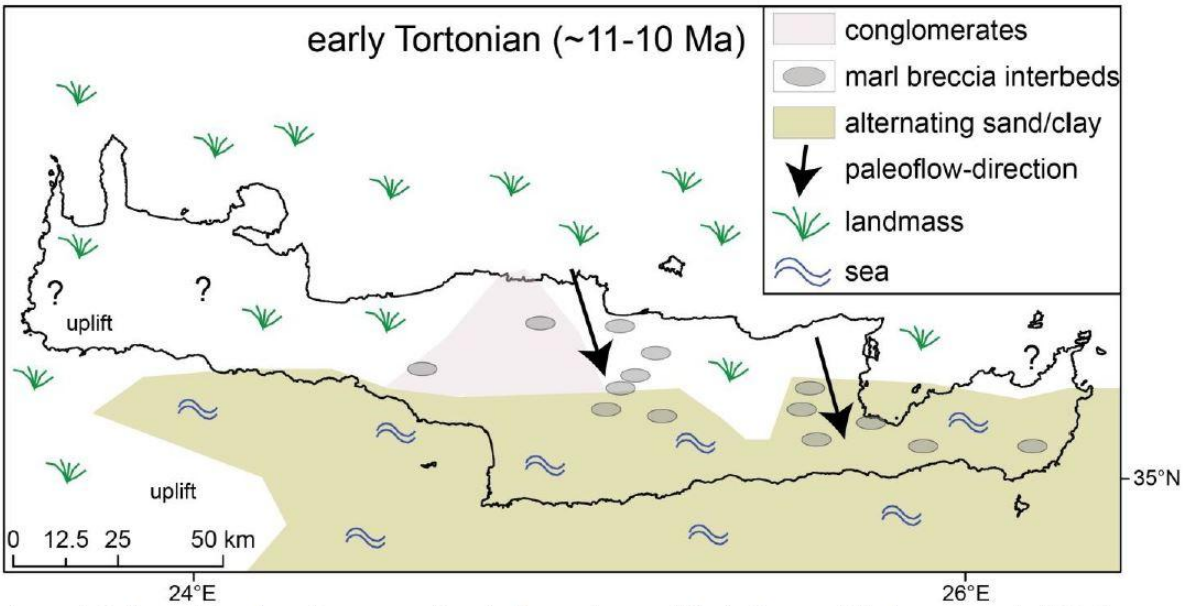


Figure 5.5: Depositional environment of early Tortonian modified after van Hinsbergen et al. (2006).

Introduction to Carbonate Facies

[Carbonate Facies - SEPM Strata](#)

Platform Interior

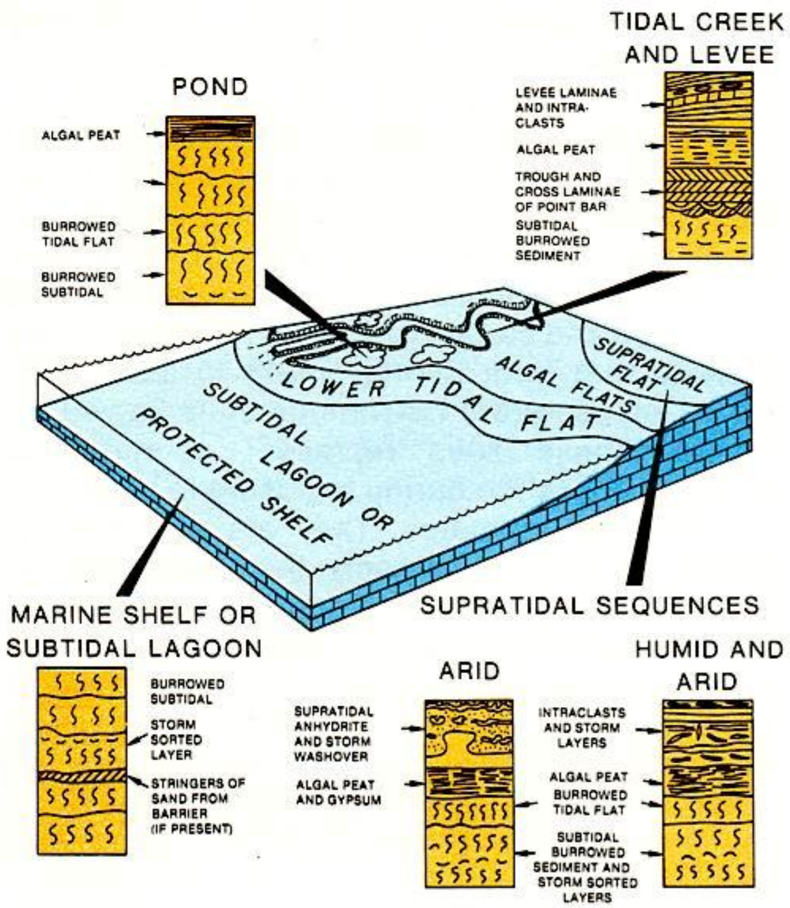
Epeiric Sea, Lagoon or Bay

This depositional setting, protected by a wide shallow sea, reefs, or mobile carbonate sand barriers, is characterized by continuous wide sheets of poorly-sorted sediments which are commonly extensively burrowed. The sediments either formed in situ or were transported from a seaward barrier by the winnowing action of waves and currents. In the normal marine setting the faunal remains are abundant but not diverse. However, when the setting is some tens of kilometers from the open sea, as in epeiric seas, faunas steadily decrease in species diversity as a response to elevated salinity. At the landward margins of epeiric seas, where salinities are frequently at their highest, the only evidence of life may be subtidal blue-green algal stromatolite heads and mats.

The principal facies in shallow water are clean carbonate sands, muddy skeletal sands, and lime muds, whereas in deeper water marls and shales are common. The sands in shallow water form on stable flats where current energy is sufficient to winnow lime mud but not grains. Grains may be oolitic but are more commonly pellets, grapestones or oncolites. Lime muds form in areas with restricted circulation. Along the land-ward margins of epeiric seas, the muddy sediment is usually dolomitic and stromatolitic. These sediments are well bedded and have wide lateral distribution. In subtidal areas, faunal abundance is low but diversity is high. In contrast, in intertidal areas faunal abundance may be high but diversity is low. Again the cyclic character of these shoaling Sequences is a response to constant cyclic changes in Base level

Tidal Flats

Tidal flat sediments include those forming in the intertidal zone (flooded by daily tides) and the supratidal zone (flooded by wind and spring tides) (figure below). Sediments range from carbonate sands to muds and commonly contain algal stromatolites. Tidal flat sediments occur as widespread sheets that are often dissected by channels. Bedding is thin and even and contacts are sharp; but evaporites show irregular Bedding and may be nodular. Collapse breccias of angular fragments tend to parallel depositional strike and are local.



Traced landward the principal fades belts are: sandy tidal flats, muddy tidal flats, mangrove/algal flats and supratidal flats. The sandy flats, commonly cross-bedded and winnowed, reflect storm wave and current movement. The muddy tidal flats are burrowed and homogenized; Bedding Planes may be irregular, in part a result of the burrowing. Mangroves, algae and other plants bind and trap transported lime mud and may also aid its precipitation. Algae produce a variety of structures in response to desiccation and erosion; lamellar birdseye fabrics and dome heads are the most significant. Tidal creeks rework the tidal flat sediments, developing sandy or muddy point bars. The channel margins may be marked by levees. If the levees are made of lime mud, they generally exhibit a variety of Laminations, mud cracks and Intraclasts. The levees may pond water in the over-bank areas, where sediments are highly burrowed.

Supratidal flat sediments vary according to their climatic setting. For instance, with high salinities and magnesium concentrations Dolomite replaces calcium carbonate and forms a cement. In arid regions gypsum and anhydrite may precipitate directly within the sediment. Simultaneously halite may precipitate locally on the sediment surface, but wind or marine flooding usually removes it.

Reservoir and Source Potential

Tidal flat muds and pelleted sands have low porosities due to dewatering and compaction. However, dolomitization of these deposits forms reservoirs by creating higher porosity and permeability. Tidal flat carbonates commonly are associated with evaporites that act as seals to the reservoirs. Examples of production from tidal flat Sequences include the Ordovician Ellenburger Formation, the Ordovician Red River of the Williston Basin, Permian Basin carbonates of Texas and the Cretaceous offshore of West Africa. The cyclic character of these tidal flat Sequences is again a response to constant cyclic changes in Base level

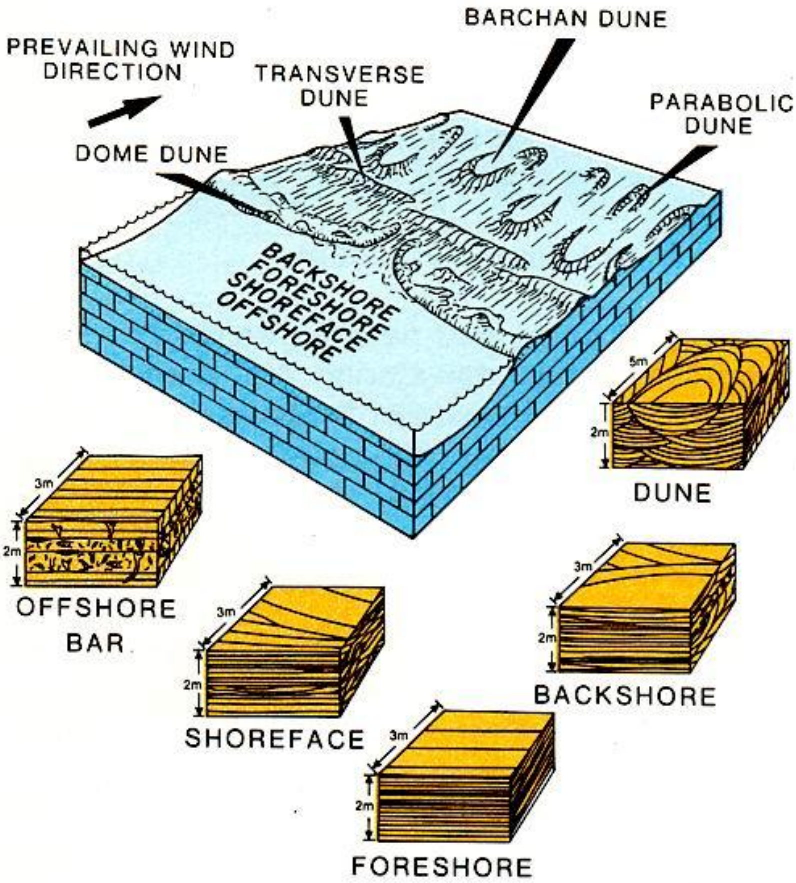
Tidal flat carbonates have abundant algal organic matter mixed into them. Although there may be ample opportunity for the organic matter to be oxidized and come in contact with fresh waters, there is evidence that some tidal flat Sequences were deposited quickly enough to maintain a relatively high percentage of organic matter. In addition, there is a growing belief that evaporites may have a sufficiently high organic content to serve as a hydrocarbon source.

Terrestrial

Dunes, Lakes, Cave Deposits, Soils, Fanglomerates

Dunes of carbonate form where there is a source of loose carbonate sand, usually landward of a marine setting or on sand cays (figure below). These fine, well-sorted dune sands exhibit large-scale cross beds that are several meters heigh. The dunes commonly have irregular lower contacts and immediately overlie beach deposits with sharp, upper contacts. Root casts and soil horizons may occur. Dunes form long, linear localized deposits. They have not been recognized very often in subsurface studies, probably because they have been eroded by winds during sea level lows or in a few cases have been misinterpreted.

Lakes may be present in fault-block intermontane basins or on delta plains. Here if terrigenous influx is low, carbonates may accumulate in the lakes. Algal heads, pisolites and beach deposits composed of rock rubble or cross-bedded oolite sand typify Shoreline sediments of lakes. Lake floor deposits consist of alternating light carbonate laminae and dark organic laminae, although terrigenous clays may replace the carbonate muds. The deposits vary from localized thin sheets of individual lake origin to widespread and complex sequences of beds related to stacked lakes. They can be distinguished from marine deposits by the lack of marine fauna, presence of tufa, and association with other non-marine sediments. Modern examples include the Dead Sea and Great Salt Lake, and ancient examples include the Eocene Green River Formation of the Uinta Basin and Pennsylvanian-Permian Coal Measures of the Illinois and Appalachian Basins.



Cave deposits include travertines, stalagmites, and stalactites, cave pearls and carbonate sands. These carbonates are precipitated during exposure above sea level as waters supersaturated with respect to calcium carbonate are evaporated and carbon dioxide is released. Other deposits that form during breaks in deposition due to exposure are calcareous soils known as caliches. These soils represent a stage of substrate alteration during exposure in semi-arid Mediterranean climates. They are also termed calcrete or nan. Commonly the soil profile is characterized by thin, irregular to continuous layers and pisolites. Laminated soil zones are difficult to distinguish from algal stromatolites. Soil zones are important to recognize in ancient Sequences because they indicate breaks in deposition during which surrounding carbonates may have been exposed to fresh waters and leached.

Fanglomerates are recycled Limestone fragments (lithoclasts) usually found on the down-thrown side of faults in arid regions. The deposits are fan-shaped wedges formed of braided stream and sheet-flow deposits. Braided stream deposits exhibit large-scale festoon cross-Beds and low-angle coarse planar beds that may show fining-upward grading. Channel-fill deposits within the fan are graded beds that fine upwards and show low-angle cross-Beds. The sheet-flow sediments are alternating coarse and fine units with faint grading and some debris-flow boulder layers. Ancient fanglomerates include the Triassic in the Newark Basin and the Tertiary Overton Formation of southern Nevada.

Hardgrounds

Carbonate hardgrounds - Wikipedia

Wikipedia The Free Encyclopedia

Carbonate hardgrounds are surfaces of synsedimentarily cemented carbonate layers that have been exposed on the seafloor (Wilson and Palmer, 1992). A hardground is essentially, then, a lithified seafloor. Ancient hardgrounds are found in limestone sequences and distinguished from later-lithified sediments by evidence of exposure to normal marine waters. This evidence can consist of encrusting marine organisms (especially bryozoans, oysters, barnacles, cornulitids, hederelloids, microconchids and crinoids), borings of organisms produced through bioerosion, early marine calcite cements, or extensive surfaces mineralized by iron oxides or calcium phosphates (Palmer, 1982; Bodenbender et al., 1989; Vinn and Wilson, 2010; Vinn and Toom, 2015). Modern hardgrounds are usually detected by sounding in shallow water or through remote sensing techniques like side-scan sonar.

Carbonate hardgrounds often host a unique fauna and flora adapted to the hard surface. Organisms usually cement themselves to the substrate and live as sessile filter-feeders (Brett and Liddell, 1982). Some bore into the cemented carbonate to make protective domiciles (borings) for filter-feeding. Sometimes hardgrounds are undermined by currents which remove the soft sediment below them, producing shallow cavities and caves which host a cryptic fauna (Palmer and Fürsich, 1974). The evolution of hardground faunas can be traced through the Phanerozoic, from the Cambrian Period to today (Taylor and Wilson, 2003).

Middle Jurassic hardground (Carmel Formation) with encrusting oysters and borings.

University of Saskatchewan

Weathering and Erosion

https://openpress.usask.ca/physicalgeology/chapter/8-2-chemical-weathering-2/

Weathering occurs when rock is exposed to the "weather" — to the forces and conditions that exist at Earth's surface. Rocks that form deep within Earth experience relatively constant temperature, high pressure, and little or no interaction with moving water. Once overlying layers are eroded away and a rock is exposed to the atmosphere conditions change dramatically. Temperatures vary widely, and pressure is much lower. Reactive gases like oxygen and carbon dioxide are plentiful, and in many climates, water is abundant.

Weathering can be characterized as mechanical (or physical), and chemical. In mechanical weathering, physical processes break rock into smaller pieces. In chemical weathering, chemical reactions change minerals into other more stable forms that are less affected by the condition at the Earth's surface. Mechanical and chemical weathering reinforce each other, because mechanical weathering provides new fresh surfaces for attack by chemical processes, and chemical weathering weakens the rock so that it is more susceptible to mechanical weathering. Together, these processes create the particles and ions that can eventually become either sedimentary rock or soil.

Intrusive igneous rocks form at depths of 100s of metres to 10s of kilometres. Most metamorphic rocks are formed at depths of kilometres to 10s of kilometres. Loose sediments are turned into sedimentary rocks only when they are buried by other sediments to depths in excess of several 100s of metres.

Rate of erosion

Tectonically stable areas erode at only a few meters per million years, regardless of whether they are in a tropical region such as Sri Lanka, a temperate region such as Kentucky in the southeastern United States, or in an arid region such as central Australia or South Africa. In tectonically active areas such as the Himalaya or the Andes, erosion rates are kilometers per million years. *[Granger D.E., 2007]*

One example where erosion rates have been quantitatively compared to known uplift rates is in Italy (Cyr and Granger, 2008; Cyr et al., 2010). Uplift rates have been quantified from well-dated marine terraces that ring the Italian peninsula and islands, and range from 0.2 mm year−1 in the north to 1.6 mm year−1 near the Straits of Messina in the south. *[Granger D.E., 2007]*

Texture

https://www.geological-digressions.com/atlas-of-sediments-and-sedimentary-structures-textures-and-fabrics/

Texture in a rock describes the relationship of its components – grains, minerals, other chunks of rock – to one another. In detrital sediments and sedimentary rocks, a distinction is made between clasts that form the framework (silt, sand, grit, pebble, cobble, boulder), and detrital sediment that is the matrix – matrix resides in the spaces between grains and usually consists of very fine-grained sediment, such as clays and silt. Detailed description of the matrix usually requires a microscope.

We can describe the framework in terms of the size (sand, cobble etc.) and shape of individual clasts (spherical, oblate, angular versus rounded), the proportions of different clast sizes (e.g. sorting), and the proportion of framework to matrix. These are all useful descriptors of a sediment, but they can also provide valuable information on depositional processes, such as:

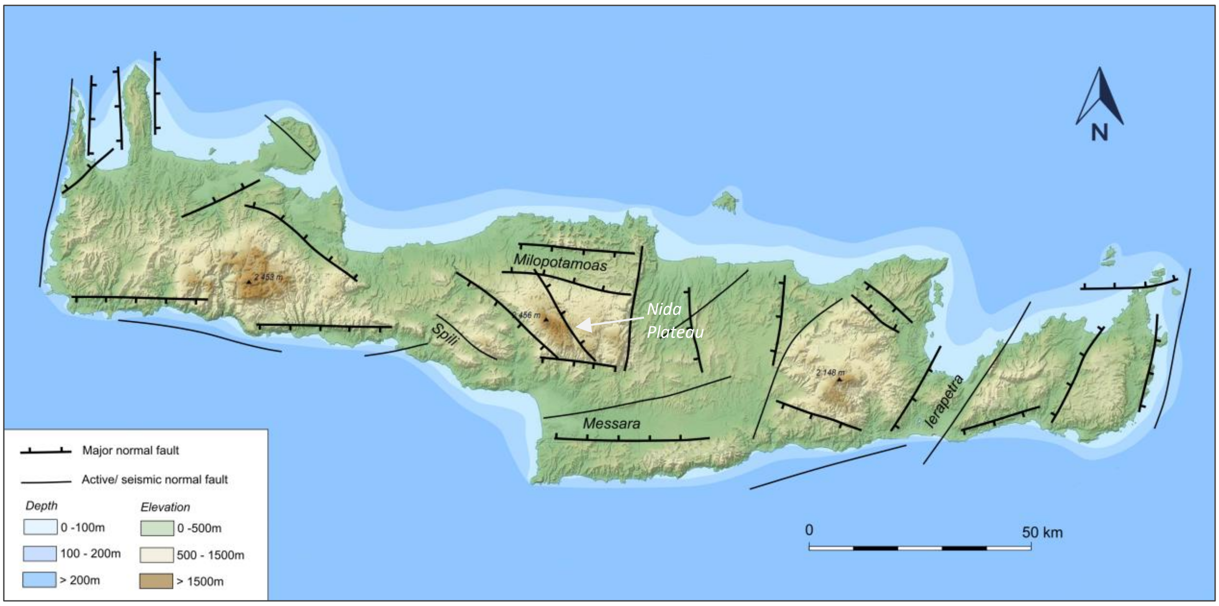
- the degree of sediment reworking during transport (e.g. beach versus glacial diamictite),
- depositional energy (e.g. river channel versus floodplain, beach versus estuary),
- the removal, or winnowing of lighter, or hydraulically more buoyant mineral grains (e.g. micas), or
- removal of mechanically less stable grains or minerals – for example quartz is mechanically more stable than feldspar because the latter usually has good cleavage.

Sedimentary fabric refers to detrital components that impart some kind of directionality to rock and sediment. It can be thought of as a vector**,** that has both magnitude (size, shape) and direction (texture only has qualities like size, shape, proportion and so on). Thus, the alignment of clasts or fossils imparts a fabric (e.g. pebble imbrication in a channel, or current-aligned fossils).

Neogene Tectonics and the formation of Basins

The island of Crete is a prominent horst structure in the forearc of the Hellenic subduction zone, which is governed by roll back of the African tectonic plate. The evolution of the plate boundary between Eurasia and Africa during the last 35 Ma is recorded in the geology of Crete. The structure of Crete is characterized by a pile of nappes derived from different paleogeographic zones. The upper units (Uppermost Unit, Pindos Unit, Tripolitza Unit) are separated from the lower units (Phyllite-Quartzite Unit, Plattenkalk Unit) by a low-angle normal fault (detachment fault) of lower to middle Miocene age. *[Seidel, 2003]*

The subduction of the African plate took place initially under convergent conditions resulting in the stacking of various nappes and thickening of the continental crust in the forearc region by the Late Oligocene/Early Miocene (Seidel et al.,1982; Bonneau, 1984). In Middle Miocene southward directed rollback of the subduction zone coupled with the southward migration of the Aegean plate resulted in extensional faulting and the denudation of a progressively thinning crust as well as the formation of the first Neogene basins (Kilias et al., 1993; Fassoulas et al., 1994).



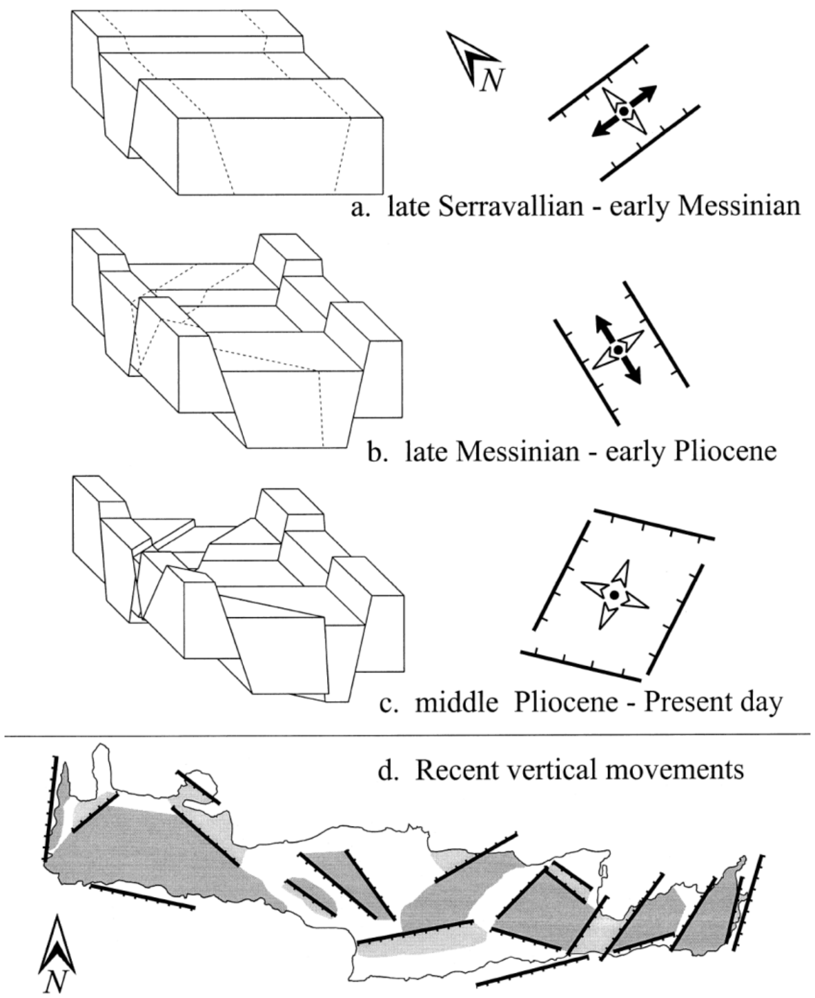
The major Neogene and Recent fault zones and geomorphological features of Crete. Data are after Creutzburg et al. (1977), Delibasis et al. (1982, 1999), Papoulia et al. (1996) and Pirazzoli et al. (1982).. Image modified after Fassoulas C., 2000

Study of the Heraklion basin in northern central part of Crete indicates that from the Middle Miocene onwards tectonic deformation has been largely due to three successive generations of faulting *[Fassoulas C., 2000]*.

The established north-south extensional regime is responsible for the first east-west trending basins in the area of Crete. The first generation of faults consisting of East-West trending faults was probably initiated during Early Miocene and culminated during the Middle/Late Miocene to early Messinian as a result of the southwards roll-back of the subduction zone. In addition, the slip along the North Anatolian fault and the resulting Anatolian extrusion beginning late Messinian (5 Ma) had a major effect on the regional stress Aegean plate (see following Figure).

During the late Messinian to middle Pliocene (13 Ma) north-south trending Second Generation faults were formed. These caused significant uplift of several regions and the simultaneous formation of the present Heraklion and other new basins such as the Apostoli basin. The east-west orientated extensional field, which can be attributed to arc-parallel stretching is thought to be associated with the southwestwards escape of the Anatolian plate *[Fassoulas C., 2000]*.

A possible increase in the roll-back rate of the subduction zone and the continuous extrusion of the Anatolian plate resulted in Third Generation faulting with multi-directional symmetry. New basins trending northeast-southwest and northwest-southeast were formed, while uplift of culminations continued at high rates. Earlier Second Generation faults group were possibly reactivated during this period. The present topography of central and eastern Crete is governed by the development of large scale, sometimes still active, normal faults of the Third group *[Fassoulas C., 2000]*.



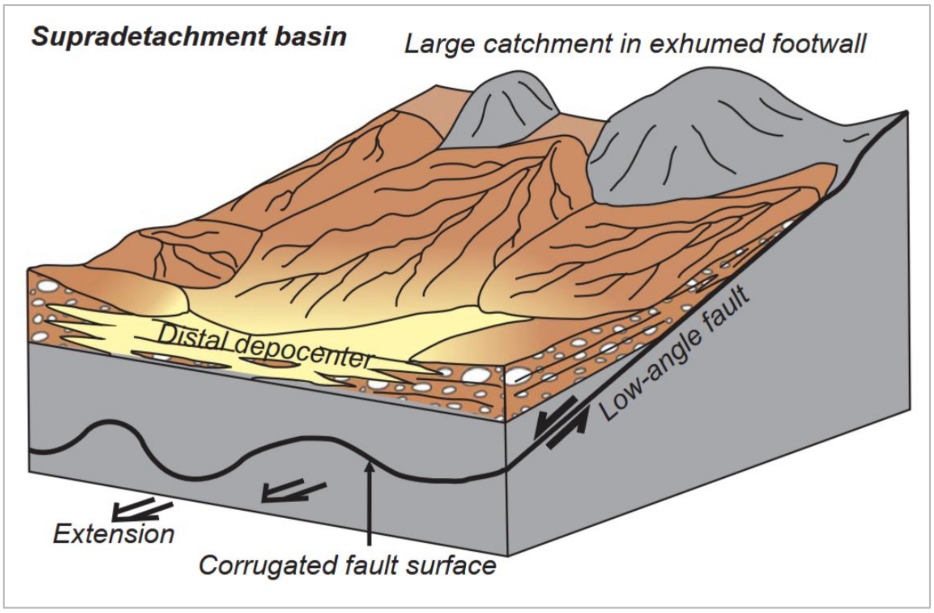
The development of the Cretan Neogene basins due to extensional tectonics. Three generations of faults arising from different force fields have been determined (Fassoulas, 2001)

Recent vertical movements.

Dark grey: Mountain ranges

Light grey: Basin sediments.

Isostatic uplift and detachment movements produce large sediment source areas and basin fill dominated by alluvial fan deposits resulting from extension-parallel (detachment-transverse) transport of sediments. Basin fill in many cases may record transgressive development from alluvial fans via braided streams to fan deltas and carbonate ramps reflecting a setting of mixed shallow marine carbonate-siliciclastic depositional systems that may prevail in low-latitude areas with arid climatic conditions and elevated drainage catchments. Arid conditions favour ephemeral runoff from hinterland catchments, leading to deposition of continental to marginal marine coarse clastic sediments. Down depositional dip, the coarse clastic sediments can grade into marine carbonates given favourable conditions *[Christopher Sæbø Serck]*



Supradetachment basin displaying continental marine deposition; [Christopher Sæbø Serck]