Plakias Graben, Young faults and Neogene Continental Sediments

View of Plakias Bay looking eastwards. In the background the Paligremnos Korifi and the conspicuous normal fault forming one edge of the Plakias Graben. The half graben stretches of eastwards (to the left) forming a basin for Neogene continental sediments.

By George Lindemann, MSc.

Berlin, December 2024

Contents

Appendix

1 Introduction

The evolution of the plate boundary between Eurasia and Africa during the last 35 Ma is recorded in the geology of Crete. A primary feature of Crete's structure is a subduction zone located at the southern edge of the Aegean plate, under which the African plate is being pushed and gradually being consumed within the Earth's mantle. 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).

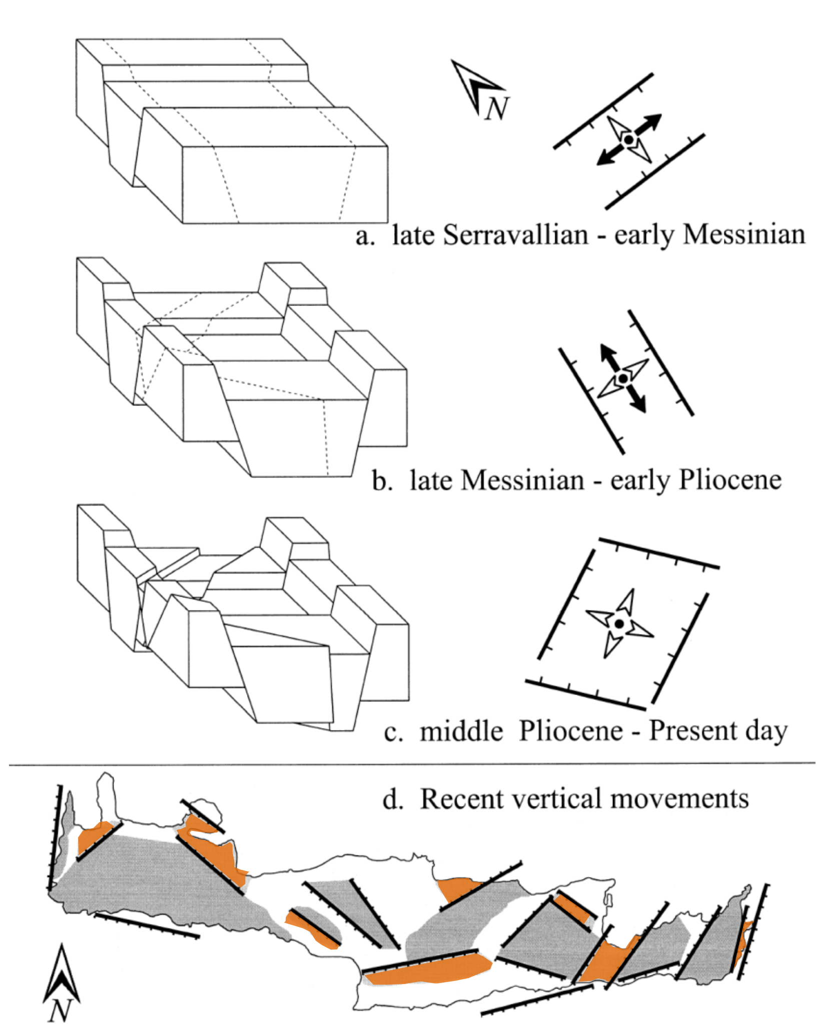
The pile of nappes characterizing the geological structure of Crete are derived from different paleogeographic zones and accommodate certain positions within the nappe stack. As a rule, the upper units (Uppermost Unit, Pindos Unit, Tripolitza Unit) differ substantially from the lower units (Phyllite-Quartzite Unit, Plattenkalk Unit) as they are mostly not metamorphic. The lower units have undergone high temperature low pressure (HP/LT) metamorphism and are separated from the upper units by a low-angle normal fault (detachment fault), which is thought to be of middle Miocene age. *[Seidel, 2003]*

Since the Upper Miocene or Lower Pliocene, the palaeostress field changed from N-S to NNE-SSW owing to westward movement of the neighbouring Anatolian plate. This movement is often referred to as the extrusion of the Anatolian plate (Dewey et al., 1986; Le Pichon et al., 1995).

The first land in the Cretan area emerged at the beginning of Lower Miocene, as a continuous landmass covering the current Aegean area (Dermitzakis and Papanikolaou, 1981). The Neogene basins on Crete were formed during the Middle Miocene by numerous multi-directional, normal faults related to crustal extension in the Aegean region and the lateral extrusion of the Anatolian plate (Fassoulas, 2001; Meulankamp and Sissingh, 2003). During the upper Serravallian (uppermost Middle Miocene) a transition in the sedimentation process on the island from terrigenous to marine deposits took place, indicating an influx of the sea from the south (Meulenkamp et al. 1979; Peters et al., 1985). It was probably the first time during the post-mountain building period that the area was directly affected by marine conditions. The absence of marine sediments of Serravallian (Middle Miocene) age north of Crete in the Aegean Sea suggests that there was continental land towards the north (Ten Veen and Postma, 1999). The Cretan Sea was probably formed later, in upper Tortonian (lower Upper Miocene) as part of the Aegean Sea by extensional forces in the backarc area of the subduction zone. Ultimately, the land bridges between Crete and the Greek mainland as well as the connection to Asia Minor were submerged, which had consequences for the paleontological evolution of the island. During the Upper Miocene and Pliocene pronounced uplift of tectonic blocks consisting of pre-Neogene rocks contributed to the shaping of today's mountains on Crete (Meulenkamp et al. 1994; Ten Veen and Postma, 1999). Due to significant sea level fluctuations that subsequently took place the uplifted blocks became islands forming an archipelago in the Cretan area. [*Zidianakis Ioannis, 2018]*

2 Basins of Crete – Graben and Half Graben Tectonics

Investigations of the Heraklion basin in the northern central part of Crete have shown that from the Middle Miocene onwards tectonic deformation was largely due to three successive generations of faulting *[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)

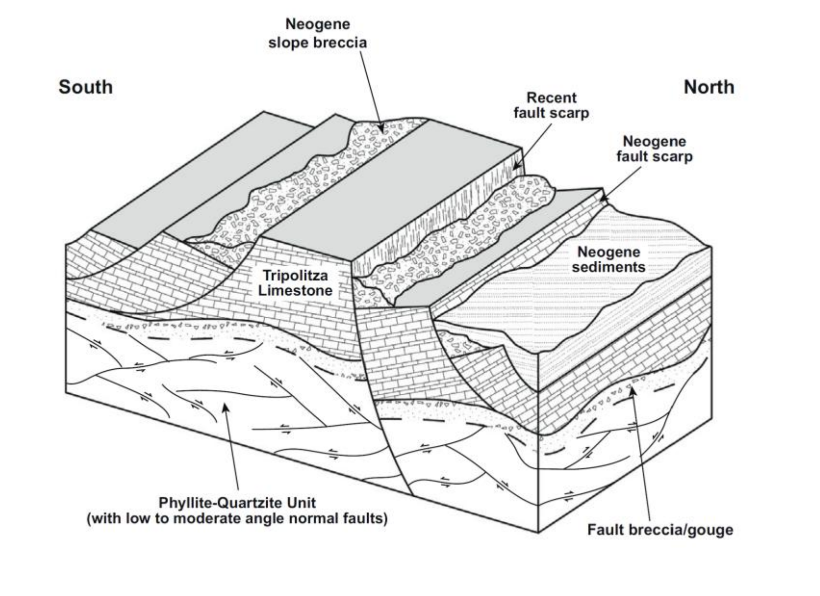
Recent vertical movements.

Basin sediments
Mountain ranges

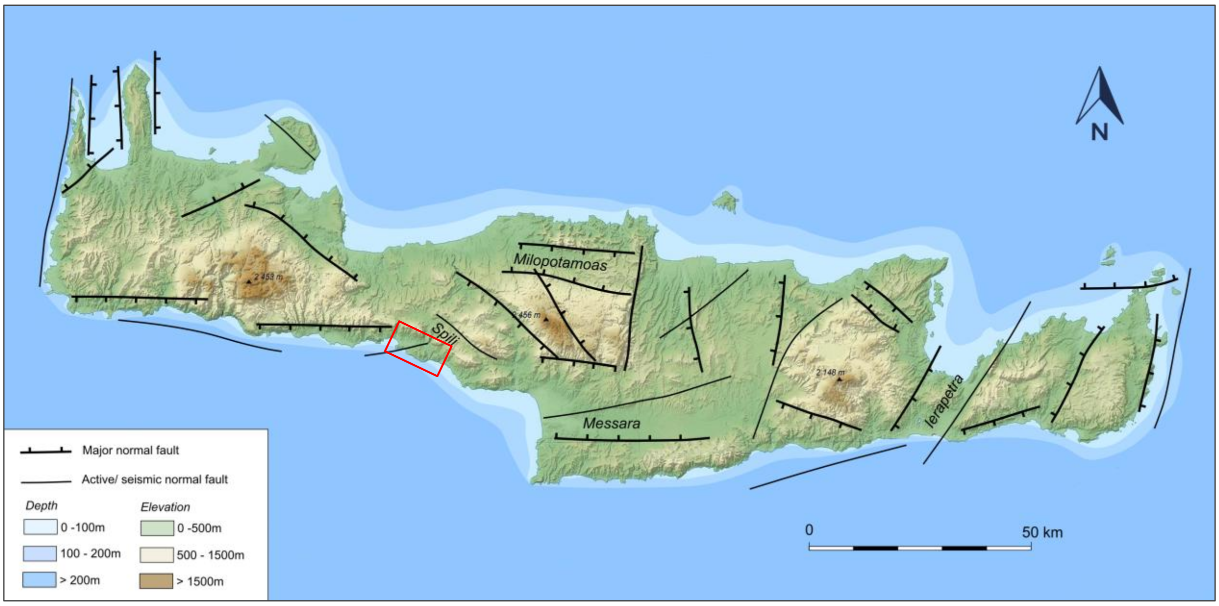
The established north-south extensional regime is responsible for the first east-west trending basins in the area of Crete. The first generation of faults consisting of East-West trending faults was probably initiated during Early Miocene and culminated during the Middle/Late Miocene to early Messinian 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 field of the Aegean plate.

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 Plakias and Apostoli basins. 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.

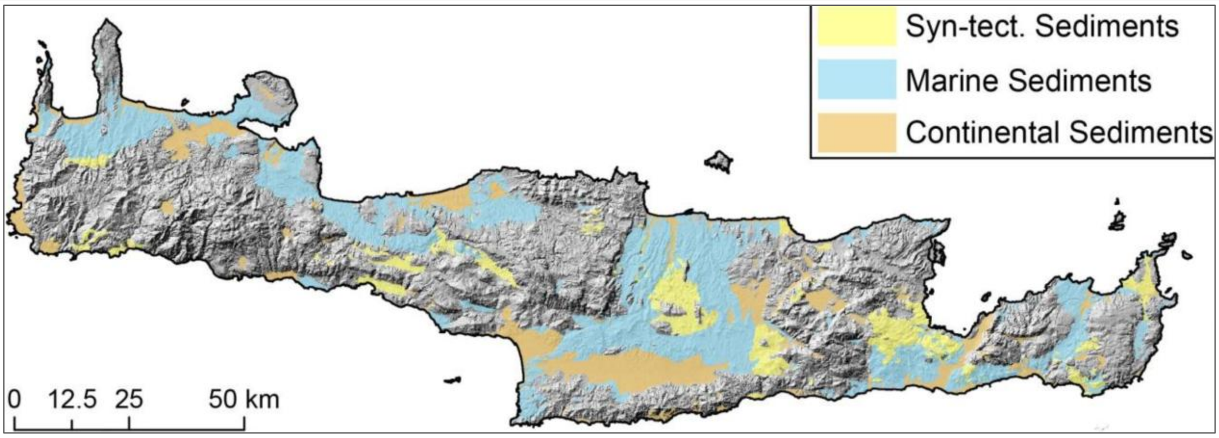
A possible increase in the roll-back rate of the subduction zone and the continuous extrusion of the Anatolian plate resulted in Third Generation faulting with multi-directional symmetry. New basins trending northeast-southwest and northwest-southeast were formed, while uplift of culminations continued at high rates. Earlier Second Generation faults 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]*



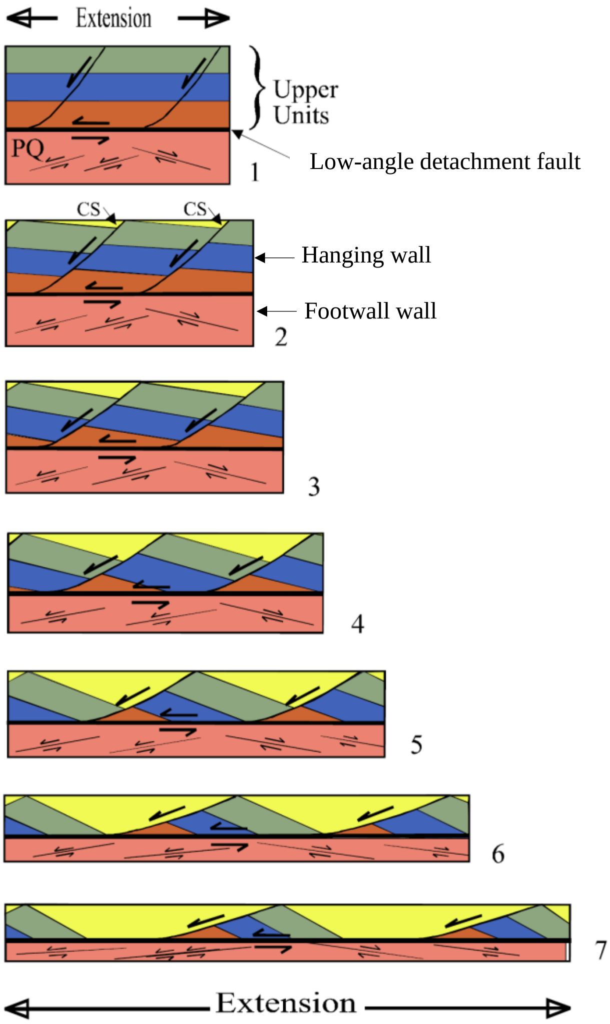
Highly simplified and interpretative sketch showing the extensional character of the Neogene tectonics on Crete involving the formation of half grabens along a low-angled detachment fault. [Alves, T. Cupkovic T., 2018 modified from Thomson S.N].



The major 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). The red rectangle shows the Plakias Basin. Image modified after Fassoulas C., 2000



Distribution of Neogene sediments on Crete (after Papanikolaou and Vassilakis, 2010) superimposed on the DEM [Rieger S., 2015]

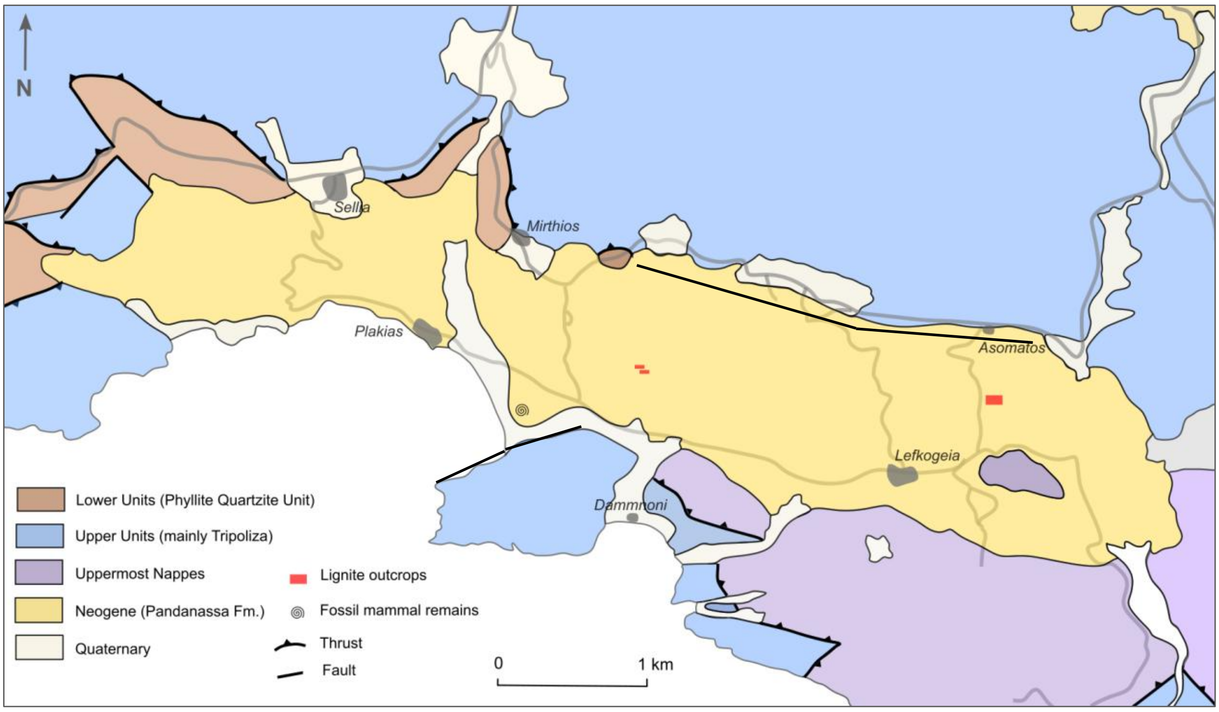


Schematic cross sections (1-7) showing progressive stretching of the brittle upper crust (upper tectonic units, not affected by late Oligocene/early Miocene HP-LT metamorphism) with evolution of half-graben structures. The upper units are separated by a low-angle detachment fault from the HP-LT metamorphic rocks of the Phyllite-Quartzite-Unit (PQ). Note tectonic erosion at the base of the upper units. The half grabens are filled with clastic sediments (CS). Stretching within the Phyllite-Quartzite Unit results in low- to moderate-angle normal faults. The scenario corresponds to a geometrical model of crustal stretching along spaced, discrete faults proposed by Le Pichon & Sibuet (1981) and to the shear-zone model for metamorphic core complexes proposed by Davis (1983). [Seidel M., 2003]

The lower footwall units were overprinted by high-pressure/low temperature metamorphism in the late Oligocene/early Miocene and were back in the upper crust by ca. 19 Ma. By contrast, the higher hanging wall units were not affected by Tertiary blueschist facies metamorphism.

The detachment fault indicates exhumation of the HP-LT metamorphic units by extension. The uplift of the high-pressure rocks was accompanied by structural disintegration of the hanging wall, leading to formation of sedimentary basins on top of the nappe pile in the lower to middle Miocene. The sedimentology of these supra-detachment basins reflects the tectonics of the Hellenic forearc at that time. The basins are half-graben structures filled by huge masses of clastic sediments (breccio-conglomerates). *[Seidel, 2003]*

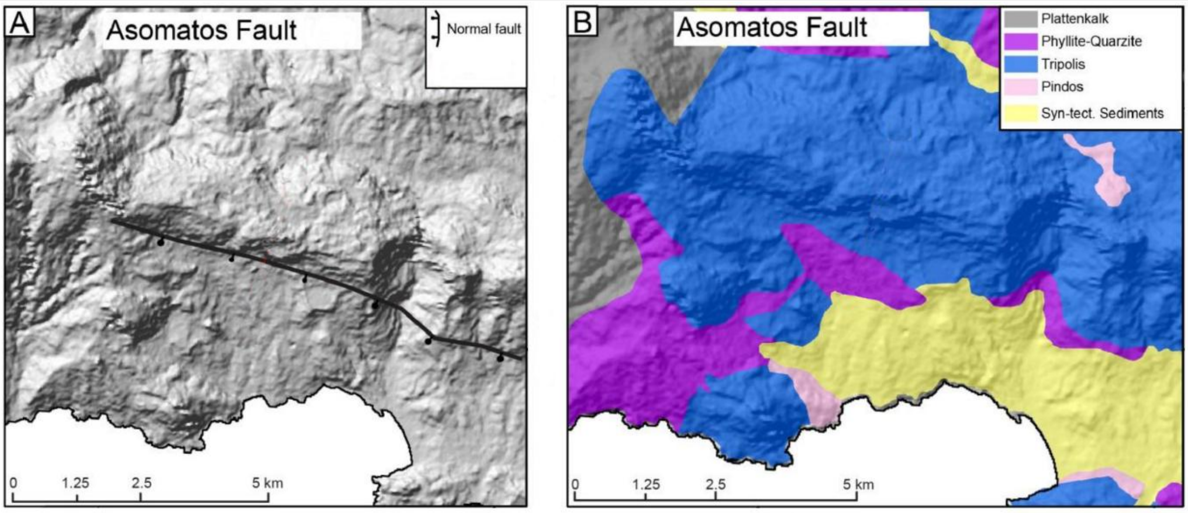
The Plakias Basin and its Neogene fill is predominantly underlain by high-pressure, low-temperature metamorphic rocks of the Phyllite–Quartzite unit. The Plakias Basin is filled with continental deposits characterized by sequences of silty clays, silts, (gravelly) sandstones, and conglomerates. Freshwater limestones are not present within the basin as opposed to other locations.



Geological map of the Plakias region, showing the Plakias Basin and the extent of Neogene sediments (Pandanassa Fm). Small-mammal fossil finds and lignite outcrops demonstrate that the Pandanassa Fm. is of continental origin. (Image based on the Geological map of Greece, Sheet Sellia. Athens: Institute of Geology and Mineral Exploration). [modified after Hans de Bruijn et al, 2012, and *Karageorgiou D., 2010]*

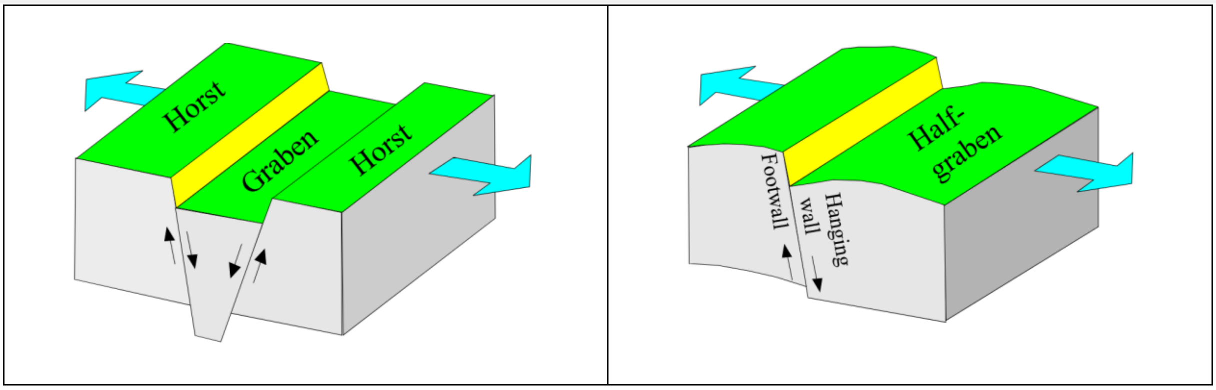
2.1 Lefkoghia Graben

During Late Serravallian to Late Tortonian times, the tectonic/sedimentary setting was one of a half graben, with most of the sediments being shed from a fault-bounded upland area to the north. An important feature of the basin is that it received coarse alluvial fan conglomerates from active faults or fault zones located mainly on its northern margin, and that the coarse alluvial facies interfinger with coastal plain facies (Drinia, 2001).



A) Topography of the Asomatos Fault based on the SPOT-DEM (Satellite Pour l'Observation de la Terre - Digital Elevation Model). B) Geological map of Crete (after Papanikolaou and Vassilakis, 2010) superimposed on the SPOT-DEM. [Rieger S., 2015]

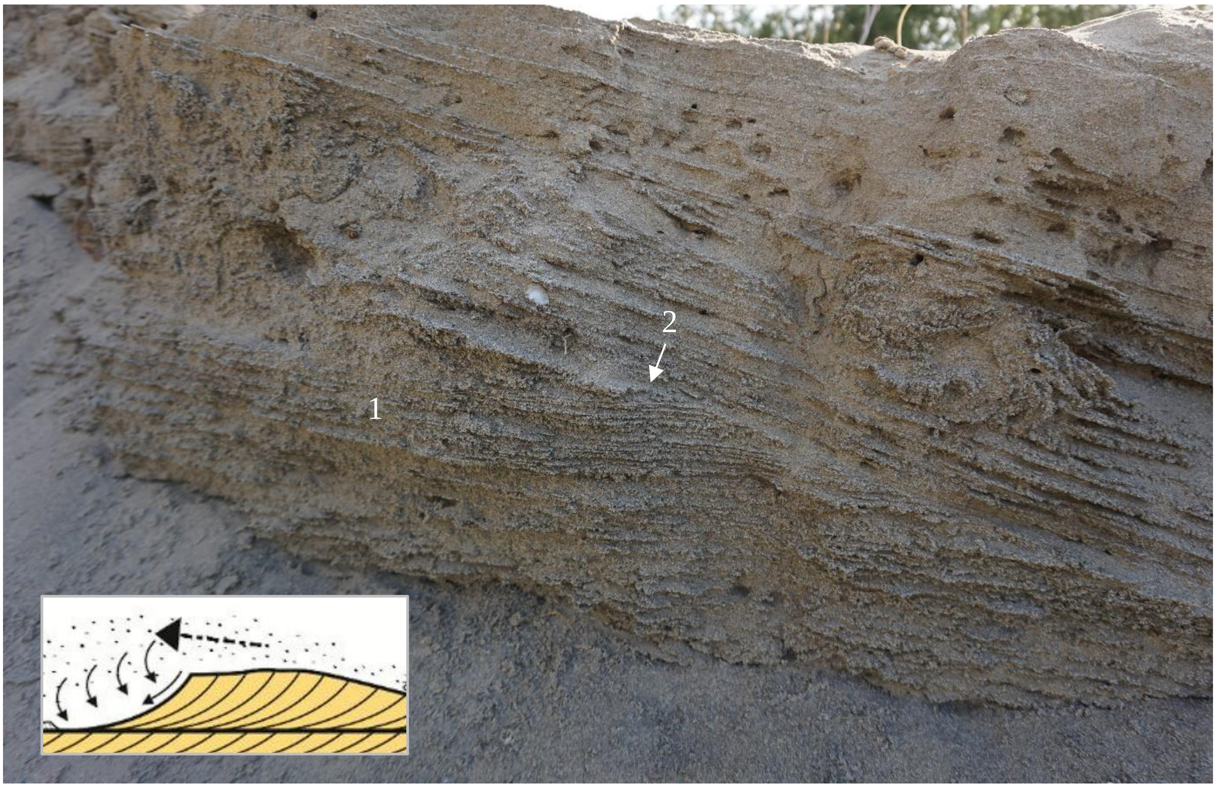
View of the Lefkoghia Half-graben looking eastwards. The fault at the Paligremnos Korifi (Plakias) is part of a system of east to west trending normal faults. Dashed lines are presumed North-South trending faults. Dotted line: presumed minor fault [Source of image: Google Maps]



Formation of graben structure due to extension. The Plakias basin/Lefkoghia Graben is a halfgraben, in which Neogene continental sediments have accumulated [Source of image Wikipedia, https://www.wikiwand.com/en/Half-graben

Overview of locations showing the eastern side of Plakias Bay and the Paligremnos fault. [Source of image: Google Maps]

I: Quaternary sand dunes at the edge of Plakias beach.

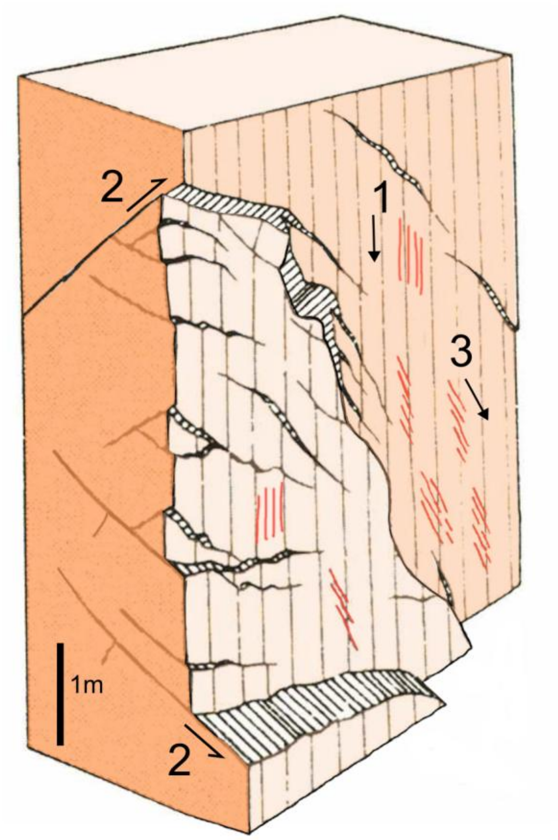


Outcrop II: Quaternary sand dune just behind Plakias Beach. 1: cross bedding, 2: change in wind direction causes truncation of lamina.

2.1.1 The Cliff at Paligremnos Korifi

Outcrop III: view of the normal fault at Paligremnos Korifi. The fault plane within Tripoliza limestone faces towards the NNW. 1: footwall, 2: hanging wall, 3: smaller normal fault plane indicating that there is an array of WSW-ENE trending faults.


Outcrop III: View of the normal fault looking WSW



Fault planes and fracture zones of the normal fault at Paligremnos Korifi near Plakias. The sequence of events is indicated by the numbers; 1 and 3 are the result of extensional movement; whereas 2 is the result of constriction. The constrictional movement may be divided into two different directions (Bonneau et at. 1977).

The Paligremnos normal fault (N 35° 10.86; E 24° 24, 10) is part of a complex fault system that runs along the southern edge of the Lefkoghia graben (Bonneau et al. 1977).
1: The almost vertical slickenside surface of 30-40m height is reported to be of Upper Pliocene age.
2: Second-order slickenlines interrupt the main near vertical slickenside pattern, due to constrictional movement.
3: Fine striations, recognizable only at some locations at close range, represent a third phase of diagonal movement. (Image modified after Bonneau et. al. 1977) [Kull, 2012].

Slickensides are a smoothly polished surface caused by frictional movement between rocks along a fault. This surface is typically striated with linear features, called slickenlines, in the direction of movement. A slickenside can occur as a single surface at a fault between two hard surfaces. Alternatively, the gouge between the fault surfaces may contain many anastamosing slip surfaces that host slickensides. These slip surfaces are on the order of 100 micrometers thick, and the size of the grains that constitute the surface are ultra-fine (0.01-1 micrometers in diameter). Slickensides can be used to determine the direction of movement along the fault. They are parallel to the direction of fault motion and serve as a kinematic indicator. *[Wikiwand]*

Outcrop III: Three directions of movement indicated by slickenlines. (1) and (3) are due to regional extension resulting in vertical movement along a normal fault plane whereas (2) is a result of constrictional stress [Bonneau et at. 1977]

Outcrop III: Close up of previous picture showing slickensides due to vertical movement (1)

Outcrop III: Close up of previous picture showing slickensides that indicate diagonal movement (3)

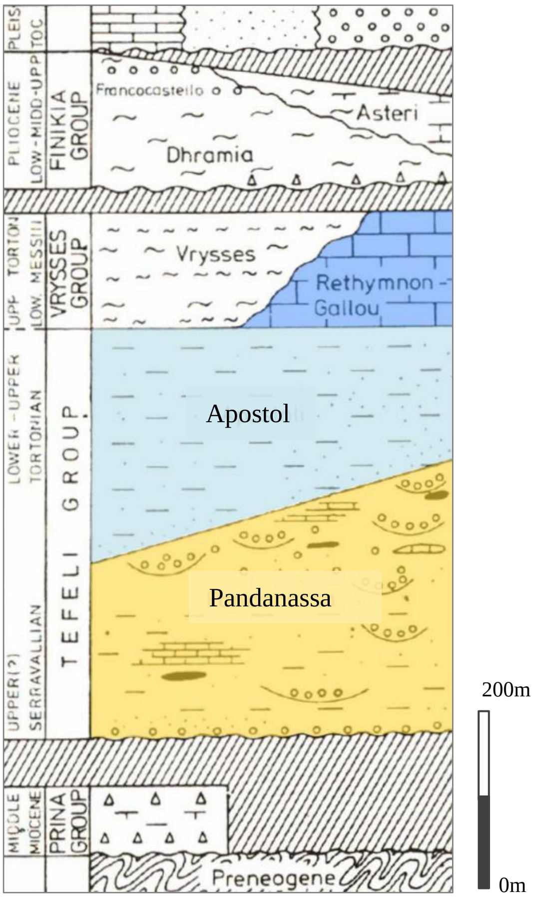
Outcrop III: Closeup of previous picture showing slickensides (3)

View of the fault array looking WSW from the beach. In the background: a further large normal fault projecting downwards into the sea. 1: Fault plane, 2: World War II coal loading bay.

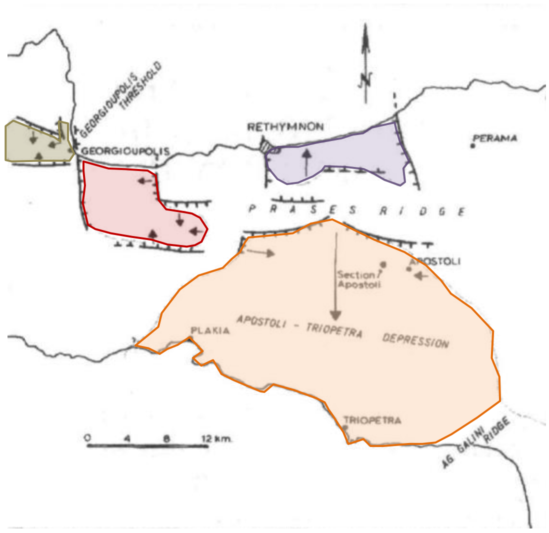
3 The Pandanassa Formation

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

The Pandanassa Formation is found in the central and southern basins of Crete. The northern boundaries of the outcrops are always marked by major faults. The southern boundaries of the Pandanassa sediments overlie Pre-Neogene rock (i.e. Tripoliza limestone and Phyllite Quartzite unit), but the contact is never clearly exposed. The Pandanassa Formation is commonly overlain by the Apostoli Formation, but not at the Plakias basin. Within the Plakias basin the thickness of the basin fill is indicated to be approx. 230 m at its northern margin owing to the dip and elevation of the bedding (Hans de Bruijn et al, 2012). Borings related to the exploration for lignite have revealed an average thickness of about 200m (Karageorgiou D., 2010).



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

Within the small town of Plakias continental Neogene sediments are exposed at many places especially where hillside construction has taken place and excavations are visible. The yellowish Neogene sediments stand out clearly from the grey Tripolitza limestone bedrock. The Pandanassa Formation within the Plakias basin consists of siltstones, clays, marls, individual conglomerate beds and layers of lignite. However, there are no limestone beds. The lithology represents an irregular succession of fluvial freshwater deposits (Meulenkamp J.E., 1969). The conglomerates vary from fine to coarse and they are more or less cemented. The pebbles are mostly well rounded and originate from Pre-Neogene rocks. In the lower part of the formation, the components may be less rounded, or partly angular. In the brownish or greyish sands, as well as in the mostly light-grey coloured sandy clays, gravel seams and scattered larger pebbles are common. At some locations lignite may be found between clay layers. Individual clay layers never exceed a thickness of about half a meter. The freshwater deposits occasionally contain Planorbidae, Melanoides (Melania), and Terebralia-like gastropods as well as plant remains (Meulenkamp J.E., 1969).

3.1 Neogene Freshwater Gastropods and Mammals

	*Planorbarius.mantelli, early middle Miocene (early Langhian). This example of the genus was found in a palaeolake in the Balkan Peninsula [Source: Neubauer T. A., 2017]*
	*Melanoides.tuberculata, freshwater snail of the family Thiaridae. [Source: https://www.wikiwand.com/en/articles/Red-rimmed_melania]*
	*Terebralia.lignitarum, specimen from the "Florianer Schichten" in St. Josef, Styria, Austria (Styrian basin), Miocene - Langhian, ca. 15 Ma). The recent species Terebalia.palustris lives in mangrove forests in the intertidal zone and is a herbivore.* *[Source: Franz Bernhard, https://www.thefossilforum.com/topic/90102-terebralia-horn-snails-from-fuggaberg-6-st-josef-austria-styria/*]

On a gentle slope about 200 m north of the Paligremnos cliff there is an outcrop of the Pandanassa Formation. At that location plant remains have been found within the marls. Based on the Pollen-spectrum, the age of the exposed sequence is reported to be Late Serravallian to Early Tortonian (approx. 11.6 Ma).

Gastropod and mammal remains have also been found in the vicinity, which based on their genus, indicate a connection to mainland Greece at that time (De Bruijn & Meulenkamp 1972,). *[Kull]*

Approximate location of excavations for fossil mammal remains – see white circle at top of picture (35°11.073'N–24°24.181'E). The location possibly no longer exists today due to construction. [Image from Google Maps]

The Plakias fossil mammal locality viewed from the west. The stippled line indicates the top of a paleosol (i.e. fossil soil horizon). Samples were taken from the grayish clay directly overlying the paleosol [image from Hans de Bruijn et al, 2012]

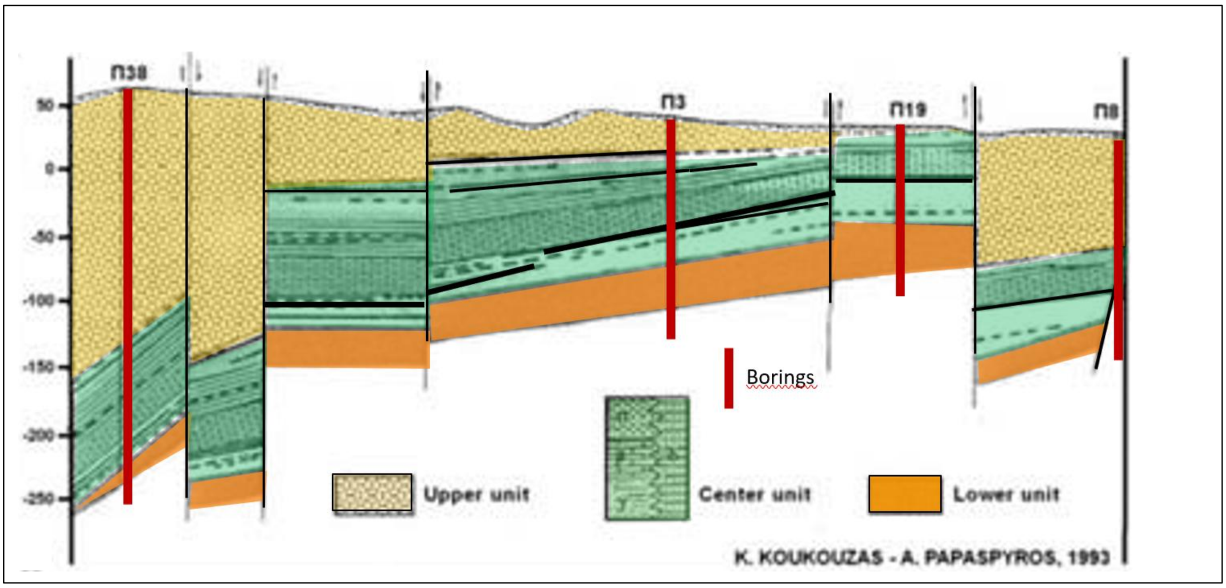
The site shown above has been investigated twice once in 1972 and again in 2011 (Hans de Bruijn et al, 2012). Although the old and the new collections of retrieved fossils both come from the same small outcrop, the composition of the two samples is quite different. The old collection contains abundant fish teeth, but these are rare in the new collection. Among the mammalian remains of the old collection were sciurids (squirrels). The dominating species in the new collection are eomyids (a family of extinct rodent similar to squirrels and rats) and insectivores. In particular, the new collection yielded a hitherto unknown genus of murid (a type of mouse). A total of three murids were discovered. The assemblage is estimated to be approx. 9.9 Ma (see Appendix: Description of relevant mammals and Stratigraphic scheme, showing the land mammal faunal succession of Crete). *[Hans de Bruijn et al, 2012]*

The small mammal remains consisting of 48 teeth were derived from a greyish clay bed overlying beige to brown colored clays with calcretes. The sampled clay interval also contained plant remains and sometimes whole specimens of fresh-water molluscs. Identified molluscs belong to the fresh-water gastropods *Planorbis* and *Brotia*. The underlying beige to brown-colored clays displaying calcretes represent a paleosol of ≥70 cm thickness. Silty clays and silts with a thin lignite layer that are presumably older than the paleosol are exposed about 50 m to the NE on the same slope. These and other fine-grained continental deposits in the Plakias Basin are interpreted as floodplain deposits with the conglomerates and gravelly sandstones representing river channel sediments.

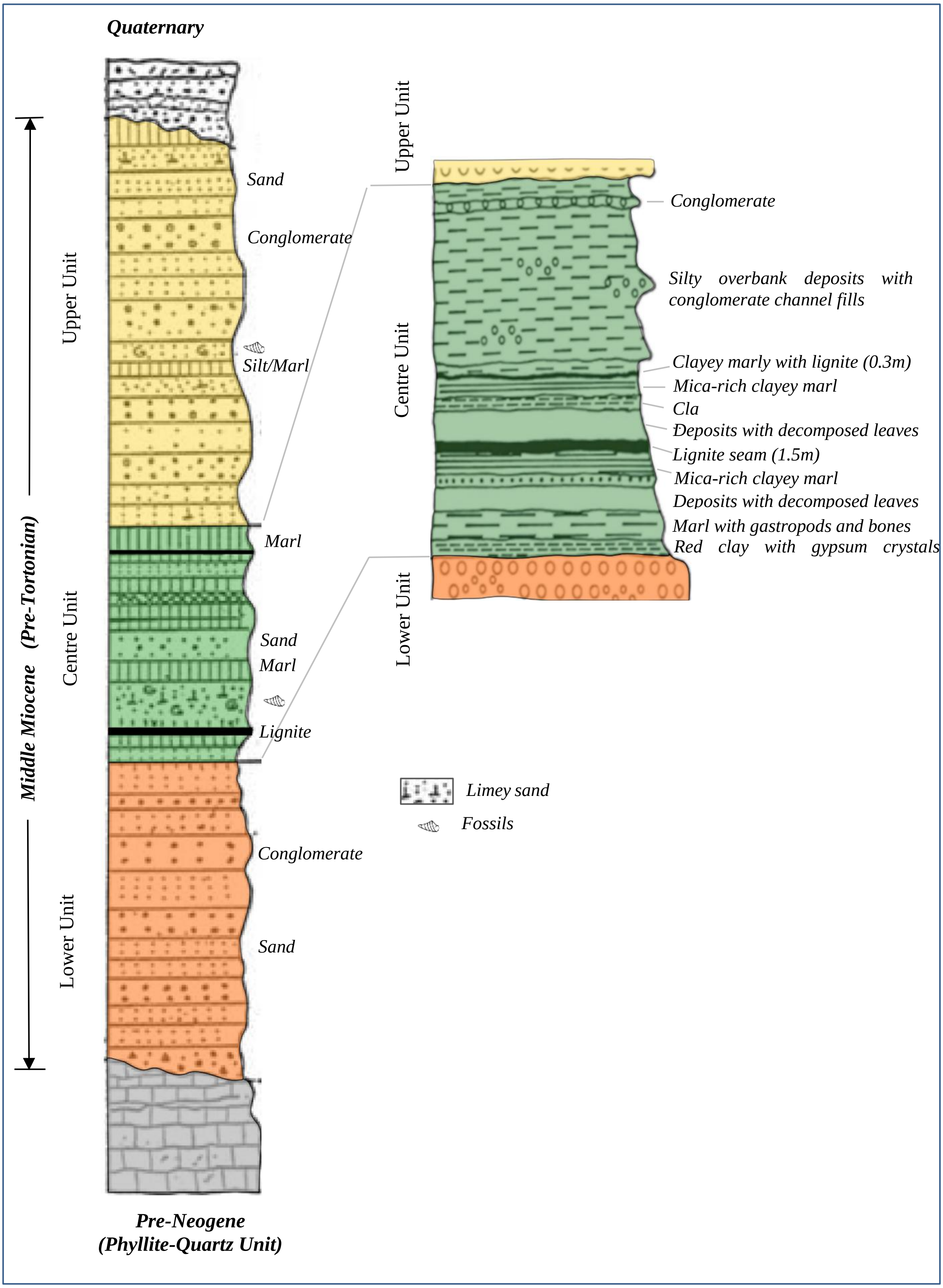
The Murinae are assumed to have originated in SE Asia after which they arrived in Anatolia at about 9.9 Ma. They are thought to have reached Crete at some time between 9.6 and 9.3 Ma indicating the existence of a land bridge. The first evidence for deep marine basins to the north of Crete dates back to 8.8 Ma (Zachariasse et al. 2011) and from that time onwards Crete was probably inaccessible for many mammals. *[Hans de Bruijn et al, 2012]*

3.2 Lignite

The Pandanassa Formation crops out in the Plakias basin over an area of approx. 6 km^2. A particularly conspicuous horizon that may be used for orientation is a lignite layer with a thickness of approx. 1.5 m (Miller W., 1977). Underground it extends over an area of approx. 10 km^2 and reportedly has reserves of approx. 2.3 million tons (Koukouzas and Papaspyros, 1993). In the recent past such as during World War II the coal seams were exploited on a small scale. About 450m NNW of Paligremnos cliff a short tunnel leads to a loading bay, which was used to load the lignite onto ships (Miller W., 1977).



Approximate North-South cross section of the Plakias basin showing boreholes associated with the exploration of lignite. The basin is vertically offset at several places by normal faults [Karageorgiou D., 2010, Koukouzas K. et al, 1993]

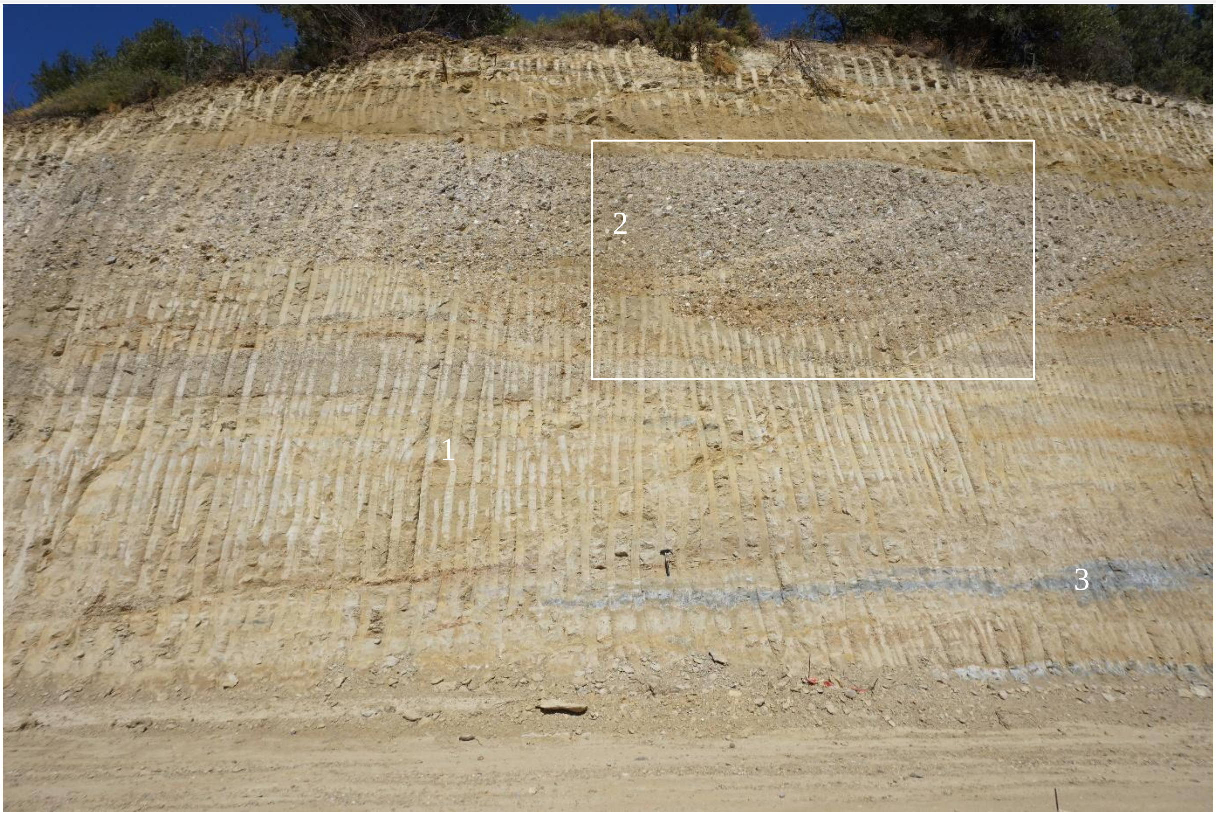


Stratigraphic section of the Pandanassa Fm. within the Plakias Basin after Karageorgiou D.E. et.al., 2010 and cross section of the "Centre Unit" containing the main lignite seam modified after Miller W., 1977

3.3 Fluviatile Sedimentation

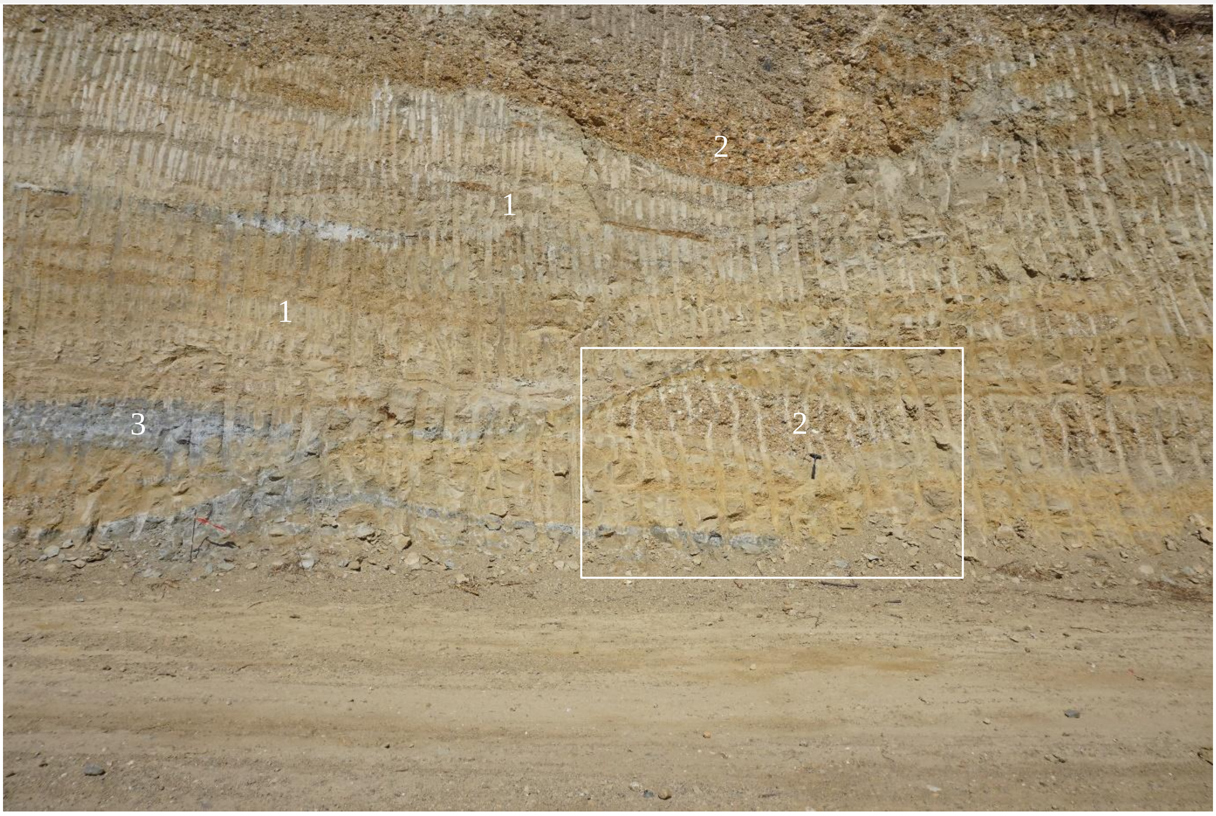
Location of outcrops within the Neogene continental sediments (upper centre of picture)


View of Plakias Bay and the village church as seen from outcrops I and II.



Outcrop I. Section of a continental fluvial depositional system. 1: Overbank deposits composed of fine sand and silt 2: River Channel sediments consisting of coarse material such as small pebbles, gravel and coarse sand. 3: Grey lagoonal clay and silt. (Scale: black hammer near the grey layer). The groves are from an excavator.

Outcrop I. Close up of previous picture displaying cross bedding within a river channel (dashed line). Crossbedding arises from transport of material within a medium, in this case by water.



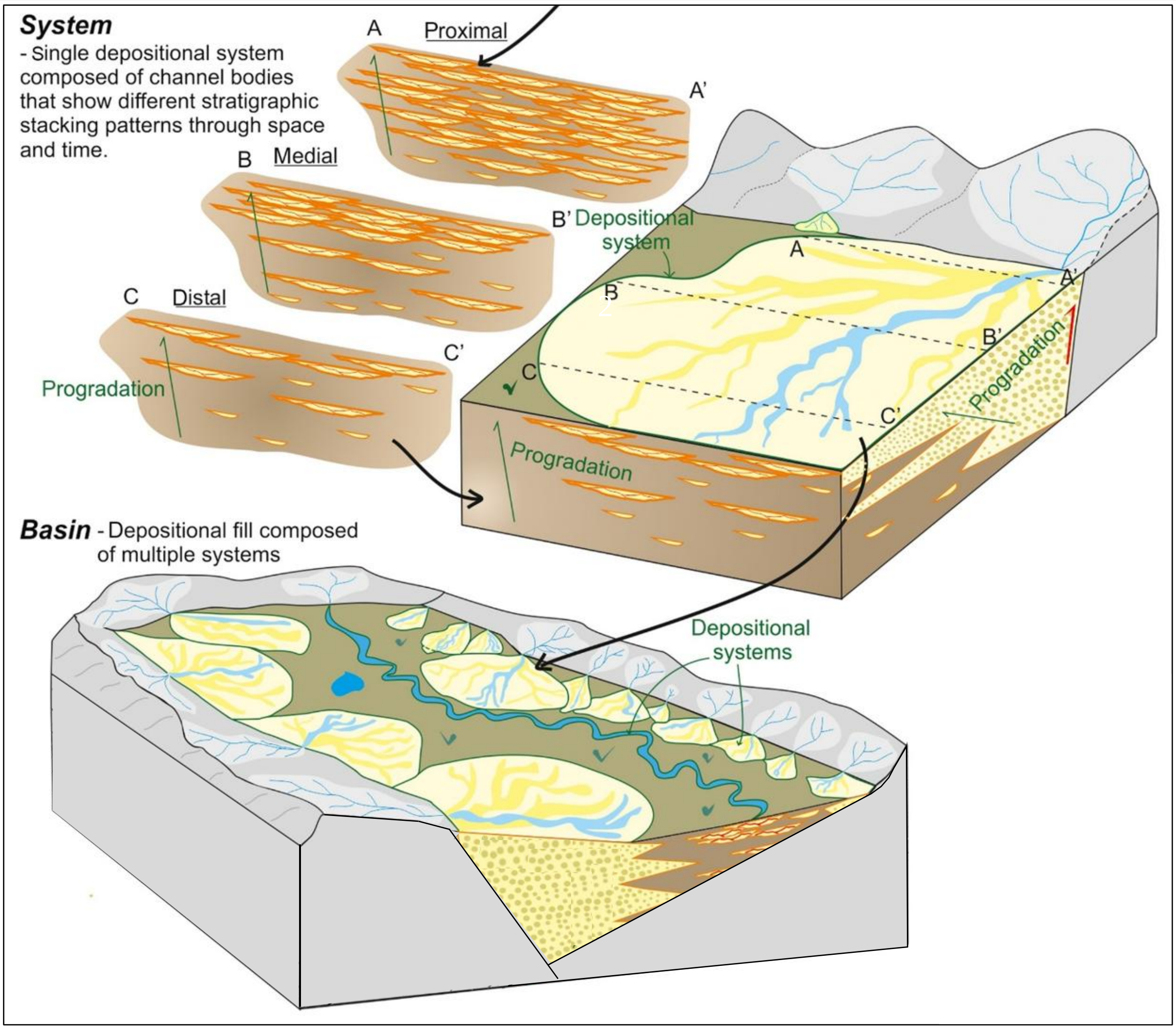
Overview of Outcrop II. 1: Overbank deposits, 2: River channel sediments, 3: Grey lagoonal deposits. (Scale: hammer near the lower figure two). The vertical succession of the three different sedimentary facies indicates the horizontal movement of small river beds over a flat plane with occasional flooding and deposition of fine overbank sediments (1). At some locations runoff accumulated causing the formation of ponds or small lagoons (3). Note that the section represents a system of alternating erosion and depositional processes.

Outcrop II. Closeup of previous picture. 2: River channel deposits consisting of poorly sorted pebbles gravel and sand.

Outcrop II. Closeup of the previous picture. The clasts are rounded to angular and poorly sorted (meaning of different sizes). There is also no noticeable stratification. Roundness is a function of travel distance as well hardness of the clasts. In this case the clasts are of different composition, which is a sign of the sediments originating from a wider catchment area. The matrix is clast supported.

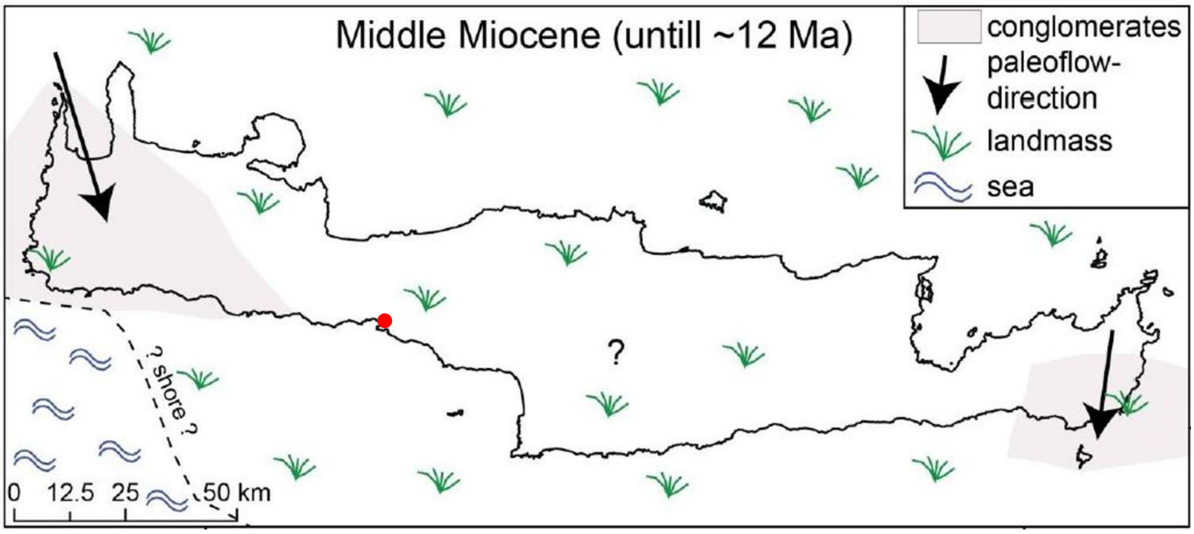
Outcrop II. 3: Grey lagoonal or lake deposits, 4: A piece of lignite that could have been a branch or root.

Outcrop II. Close up of previous picture. Arrows indicate lignite fragments. Lacustrine deposits are typically very well sorted with highly laminated beds of silts, clays, and occasionally carbonates. The very small particle size is a sign of low energy conditions, which enables minute particles to be deposited. The grey colour could reflect an increase in clay as opposed to carbonate.

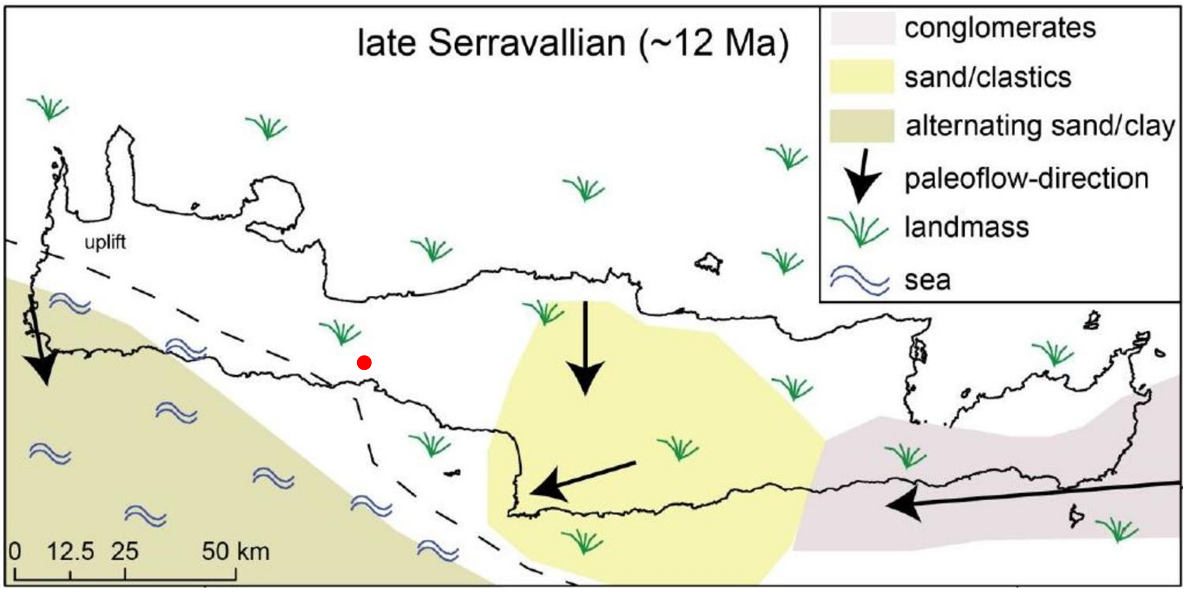


Source: Owen, A. et al., 2017, See Appendix

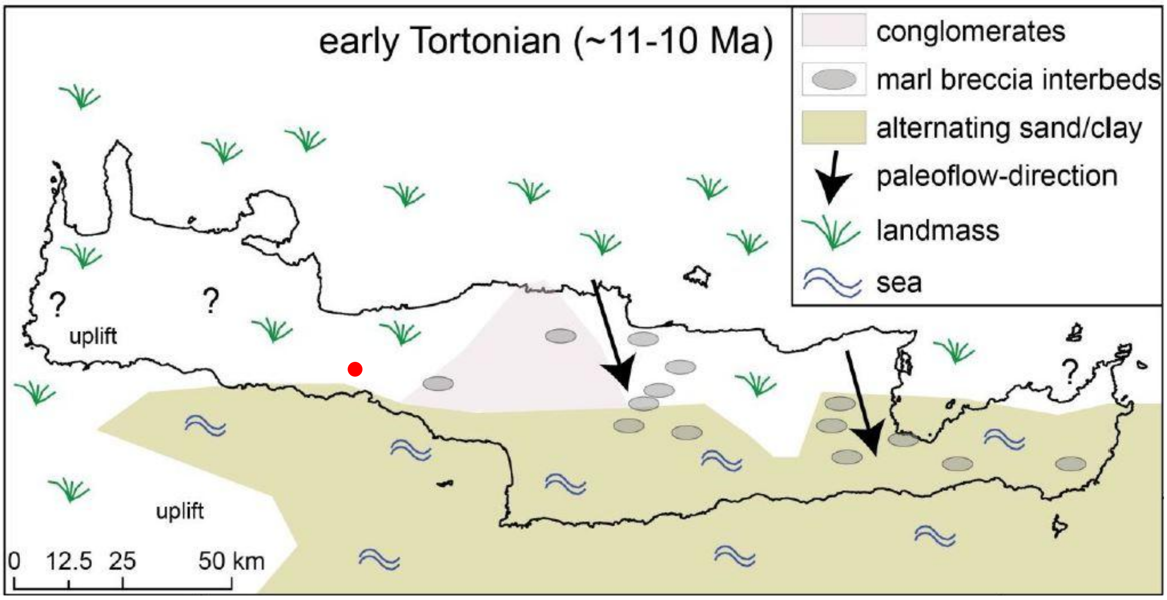
4 Paleogeography



Dispositional Environment of the Middle Miocene after van Hinsbergen et. al. 2006 [Rieger S., 2015]



Dispositional Environment of the late Serravalian after van Hinsbergen et. al. 2006 [Rieger S., 2015]



Dispositional Environment of the early Tortonian after van Hinsbergen et. al. 2006 [Rieger S., 2015]

5 References

Alexandra van der Geer1 & George Lyras, 2011: Field Trip Guidebook European Association of Vertebrate Palaeontologists, 9th Annual Meeting Heraklion, Crete, Greece 14-19 June, 2011

Alves, T. Cupkovic T., 2018: Footwall degradation styles and associated sedimentary facies distribution in SE Crete: Insights into tilt-block extensional basins on continental margins; 3D Seismic Lab, School of Earth and Ocean Sciences, Cardiff University, Cardiff, United Kingdom; Husky Energy, Atlantic Region, 351 Water St., Suite 105, St. John’s, Canada

Antoniolia F, 2005: A glacial isostatic adjustment origin for double MIS 5.5 and Holocene marine notches in the coastline of Italy Fabrizio Antoniolia, Luigi Ferrantib, Steve Kershawc,

Brack P., Meister P. H., Bernasconi S., 2013: Dolomite formation in the shallow seas of the Alpine Triassic, Article in Sedimentology · Feb. 2013, DOI: 10.1111/sed.12001]

Brandes C. et al., 2014: Fault-related folding: A review of kinematic models and their application, Institute for Geology, Leibniz Universität Hannover, Callinstr. 30, 30167 Hannover, Germany

Champod E. et al., 2010: Stampfli Field Course: Tectonostratigraphy and Plate Tectonics of Crete, Université de Lausanne, September 2010

Chatzaras, v., Xypolias, P. & Doutsos, T (2006): Exhumation of high-pressure rocks under continuous compression: a working hypothesis for the southern Hellenides (central Crete. Greece). - Geol. Mag. 143: 859-R76.

Evans J. E. et. al, 2018: Processes and facies relationships in a Lower (?) Devonian rocky shoreline depositional environment, East Lime Creek Conglomerate, south-western Colorado, USA

Evans J. E., Christopher S. Holm-Denoma, 25 February 2018; Graphics: shoreline [modified from Bourgeois & Leithold, 1984].

Fassoulas C., 2000: The tectonic development of a Neogene basin at the leading edge of the active European margin: the Heraklion basin, Crete, Greece, Natural History Museum of Crete, University of Crete, Heraklion 71409, Greece

Fassoulas C., Rahl J.M., 2004: Patterns and Conditions of Deformation in the Plattenkalk Nappe, Crete, Greece: A Preliminary Study, Natural History Museum of Crete, Yale University, New Haven, Connecticut

Granger D.E., 2007: Cosmogenic Nuclide Dating - Landscape Evolution, in Encyclopedia of Quaternary Science, Pages 445-452

Hans de Bruijn et al, 2012: New finds of rodents and insectivores from the Upper Miocene at Plakias (Crete, Greece), Swiss Journal of Palaeontology volume 131, pages 61–75
Jpd Tectonics, 2017: Thrust Systems

Karageorgiou D. E. et.al., 2010: Development of Lignite in Crete. Comparison of Basins, Possibilities of Exploration, Institute of Geology and Mineral Exploration, Olympic Village, Entrance C 136 77, Acharnae, Greece

Kull U., 2012: Kreta, Sammlung geologischer Führer

Langosch A. et al, 2000: Intrusive rocks in the ophiolitic melange of Crete ± Witnesses to a Late Cretaceous thermal event of enigmatic geological position, Institut für Mineralogie und Geochemie, Universität zu Köln.

McClay K.R.: Glossary of thrust tectonics terms, Department of Geology, Royal Holloway and Bedford New College, University of London, Egham, Surrey, England

Meulenkamp J.E., 1969: Stratigraphy of Neogene Deposits in the Rethymnon Province, Crete, with special Reference to the Phylogeny of Universal Uvigerina from the Mediterranean Region

Miller W., 1977: Geologie des Gebites Nördlich des Plakias-Bucht, Kreta, Freiburg im Breisgau, Diplomarbeit

Mountrakis D., Kilias A., Pavlaki A., Fassoulas C., Thomaidou E., Papazachos C., Papaioannou C., Roumelioti Z., et al., 2012: Neotectonic study of Western Crete and implications for seismic hazard assessment, Journal of the Virtual Explorer, Electronic Edition, ISSN 1441-8142, volume 42, paper 2 In: (Eds.) Emmanuel Skourtsos and Gordon S. Lister, The Geology of Greece, 2012.

Mourtzas N. et al., 2015: Vertical land movements and sea level changes along the coast of Crete (Greece) since Late Holocene, GAIAERGON Ltd, Athens, University of Peloponnese, Istituto Nazionale di Geofisica, Vulcanologia, Rome, Italy

Neubauer T. A. et. al., 2017: The discovery of Bulinus (Pulmonata: Planorbidae) in a Miocene palaeolake in the Balkan Peninsula, Department of Animal Ecology and Systematics, Justus Liebig University.

Owen, A. et al., 2017: Multi-scale classification of fluvial architecture: an example from the Palaeocene-Eocene Bighorn Basin, Wyoming. Sedimentology, 64(6), pp. 1572-1596.
Pirazzoli P.A., Thommeret J., Thommeret Y., Laborel J., and Montaggioni L.F., 1982: Tectonophysics 86, 27-43.

Pomoni F., Karakitsios V., 2016: Sedimentary facies analysis of a high-frequency, small-scale, peritidal carbonate sequence in the Lower Jurassic of the Tripolis carbonate unit (central western Crete, Greece): Long-lasting emergence and fossil laminar dolocretes horizons, Department of Geology and Geoenvironment, National and Kapodistrian University of Athens

Rahl J. M. et. al.: Exhumation of high-pressure metamorphic rocks within an active convergent margin, Crete, Greece: A field guide, Jeffrey M. Rahl, Charalampos, Fassoulas, and Mark T. Brandon, Department of Geology and Geophysics, Yale University, New Haven, Connecticut 06511, U.S.A. Natural History Museum of Crete, University of Crete, Heraklion 71409, Greece

Rieger S., 2015: Regional-Scale, Natural Persistent Scatterer Interferometry, Island of Crete (Greece), and Comparison to Vertical Surface Deformation on the Millennial-, and Million-Year Time-Scales; Phd.; Ludwig-Maximilians-Universität München

Seidel M., 2003: Tectono-sedimentary evolution of middle Miocene supra-detachment basins (western Crete, Greece), Ph.D. Dissertation, University of Köln.

Stampfli 2010: Stampfli Field Course, Tectonostratigraphy and Plate Tectonics of Crete, Université de Lausanne, France

Steiakakis E., 2017: Evaluation of Exploitable Groundwater Reserves in Karst Terrain: A Case Study from Crete; Greece Laboratory of Applied Geology, Technical University of Crete, 73100 Chania, Greece

Strasser T.F. et. al., 2011: Dating Palaeolithic sites in southwestern Crete, Greece, in Journal of Quaternary Science

Theye, T, Seidel, E. & Vidal, O. (1992): Carpholite, sudoite and chloritoid in low-grade high-pressure metapelites from Crete and the Peloponnese, Greece. - Europ, J. Mineral. 4 487-507.

Thomson S. N. et al., 1989: Apatite fission-track thermochronology of the uppermost tectonic unit of Crete, Implications for the post-Eocene tectonic evolution of the Hellenic Subduction System, Institut für Geologie, Ruhr-Universität Bochum

Thomson S. N., Stockert B., Brix M. R., 1999. Miocene high-pressure metamorphic rocks of Crete, Greece: rapid exhumation by buoyant escape. In: Ring, U., Brandon M. T., Lister G. S., Willetf S. D. (eds): Exhumation Processes: Normal Faulting, Ductile Flow and Erosion. Geological Society, London, Special Publications, 154, 87-107.

Thomson S. N., Stockhert, B. & Brix, M.R. (1998a): Thennochronology of the high-pressure metamorphic rocks of Crete, Greece: implications for the speed of tectonic processes. - Geology 26: 259-262.

Thrust faults: Some common terminology - Geological Digressions https://www.geological-digressions.com

Thu Anh Vu, 2020: Foraminiferal assemblages of Cretan beaches (Greece) – proxy for tsunami deposits? Faculty Georesource and Materials Engineering of the RWTH Aachen University

Tiberti M. M., Basili R. & Vannoli P., 2014: Ups and downs in western Crete (Hellenic subduction zone), Istituto Nazionale di Geofisica e Vulcanologia, Via di Vigna Murata 605, 00143 Rome, Italy

Tortorici L. et al., 2011: The Cretan ophiolite-bearing mélange (Greece): A remnant of Alpine accretionary wedge, Dipartimento di Scienze Geologiche, University of Catania, C.so Italia

van Hinsbergen D. J. J., Meulenkamp J. E., 2006: Neogene supradetachment basin development on Crete (Greece) during exhumation of the South Aegean core complex.

Vassilakis E. and Alexopoulos J., 2012: Recognition of Strike-slip Faulting on the Supradetachment Basin of Messara (Central Crete) with remote sensensing Image Interpretation Techniques; National and Kapodistrian University, Department of Dynamics, Tectonics and Applied Geology, Athens, Greece; National and Kapodistrian University, Department of Geophysics & Geothermics, Athens, Greece;

Wassmann S., 2012 Geländekurs Kreta

Zachariasse W., van Hinsbergen D., et al. 2011, Formation and Fragmentation of a late Miocene supradetachment basin in central Crete: implications for exhumation mechanisms of high-pressure rocks in the Aegean forearc, Stratigraphy and Paleontology group, Faculty of Geosciences, Utrecht University, Utrecht, The Netherlands; Physics of Geological Processes, University of Oslo

Zidianakis Ioannis, 2018: The floral study and the observed vegetational changes during Miocene regarding the palaeoenvironmental evolution of the Messara-Gavdos area in Crete (PhD); University of Patras

6 Appendix

Geological Time Scale

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
	Mesozoic	Cretaceous	Upper	Maastrichtian	72.1 ± 0.2
				Campanian	83.6 ± 0.2
				Santonian	86.3 ± 0.5
				Coniacian	89.8 ± 0.3
				Turonian	93.9
				Cenomanian	100.5
			Lower	Albian	~113
				Aptian	~125.0
				Barremian	~129.4
				Hauterivian	~132.9
				Valanginian	~139.8
				Berriasian	~145.0

[1] Millions of years ago

Neogene Mammals of Crete

Muridae

Source: Wikipedia, the free encyclopedia

Animal Murinae Leimacomyinae

Muridae

Temporal range: Early Miocene – Recent[1]

House mouse, *Mus musculus*

The Muridae, or murids, are the largest family of rodents and of mammals, containing approximately 1383 species including many species of mice, rats and gerbils found naturally throughout Eurasia, Africa, and Australia.

As with many other small mammals, the evolution of the murids is not well known, as few fossils survive. They probably evolved from hamster-like animals in tropical Asia sometime in the early Miocene, and have only subsequently produced species capable of surviving in cooler climates. They have become especially common worldwide during the current geological epoch, as a result of hitching a ride commensally with human migrations. Commensalism is a long-term biological interaction (symbiosis) in which members of one species gain benefits while those of the other species neither benefit nor are harmed.

Sciuridae (squirrel)

Source: Wikipedia, der freien Enzyklopädie

WIKIPEDIA
Die freie Enzyklopädie

 *Golden-mantled ground squirrel (Callospermophilus lateralis)*	 *The squirrel (Sciurus vulgaris) is the best-known species of squirrel.*

Squirrels (Sciuridae) are a family of rodents (Rodentia). This family includes the Eurasian squirrel, the chipmunk and the European ground squirrel, among others. Today, squirrels are divided into 51 genera with approximately 270 to 280 species, although the classification is still in flux. Squirrels are found all over the world except in Australia, New Guinea, Madagascar and Antarctica.

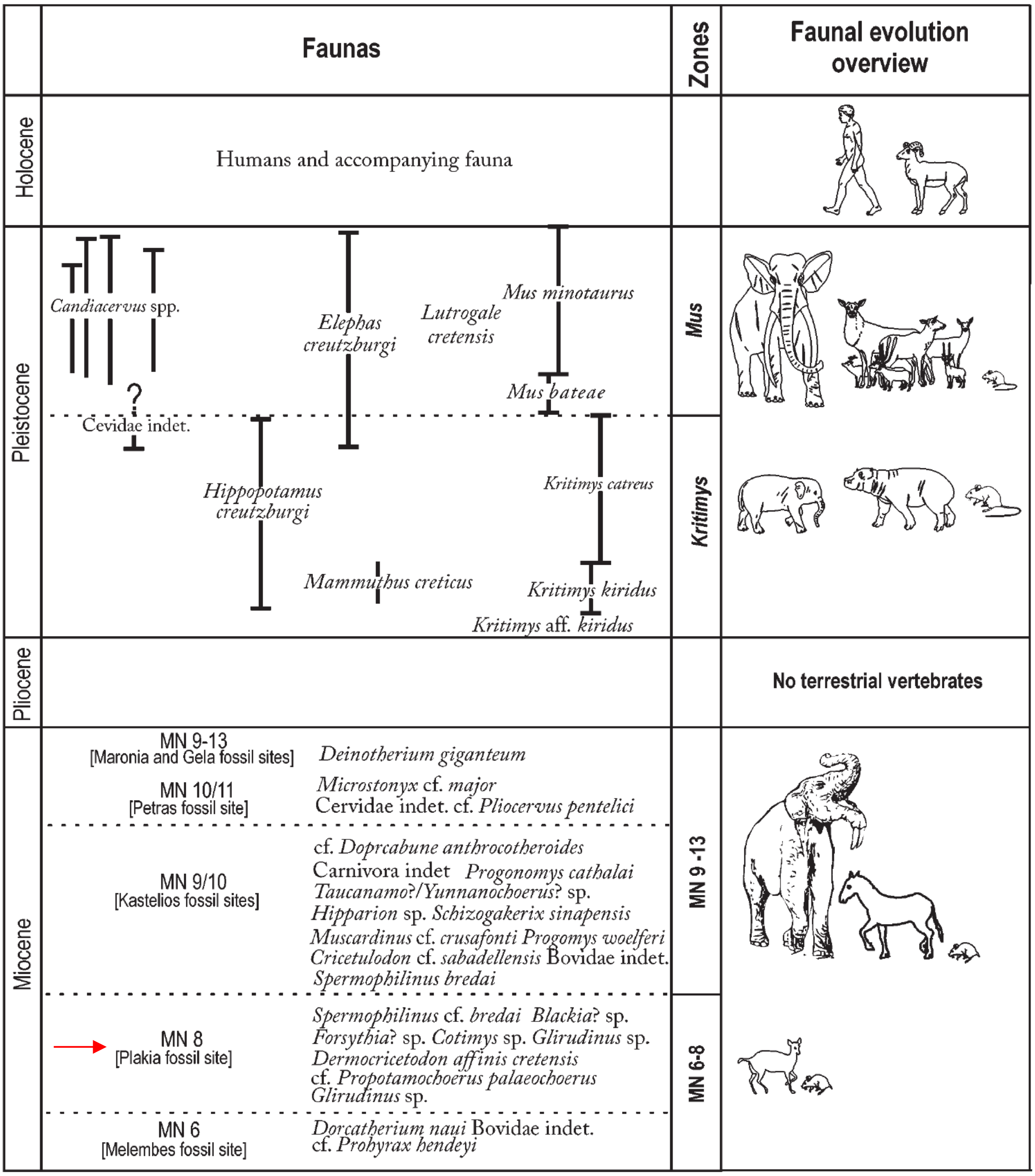
Unlike most rodents, squirrels are mostly diurnal and feed mainly on plant parts, fruits and seeds, as well as insects. The species vary greatly in size, with some species being very small, with a head-torso length of about seven centimetres and a body weight of about 15 grams, while other species reach head-torso lengths of up to 65 centimetres and a weight of up to 6.5 kilograms. The body is usually slender, especially in tree-dwelling species, with a long, bushy tail, while ground-dwelling species such as marmots are generally stockier and have shorter tails.

The fossil record of squirrels begins in the late Eocene. The oldest known fossils come from Chadronium in North America and are about 37 million years old. Squirrels probably originate from a common ancestor with the Aplodontiidae, whose only recent representative is the North American stub-tailed squirrel.

Eomyidae

Source: Wikipedia, der freien Enzyklopädie

Eomyidae is a family of extinct rodents from North America and Eurasia related to modern day pocket gophers and kangaroo rats. They are known from the Middle Eocene to the Late Miocene in North America and from the Late Eocene to the Pleistocene in Eurasia. Eomyids were generally small, but occasionally large, and tended to be squirrel-like in form and habits. The family includes the earliest known gliding rodent, Eomys quercyi.



Stratigraphic scheme, showing the land mammal faunal succession of Crete. Characteristic elements of the successive faunal units are shown to the right. The scheme of the Pleistocene mammals is based on de Vos (1996) with the modifications noted by van der Geer et al. (2010). The scheme for the pre- Pleistocene mammals is based on an overview by van der Made (1996) with the addition of the new findings reported by Athanassiou (2004) and Poulakakis et al. (2005). [Image source: Alexandra van der Geer1 et.al., 2011]

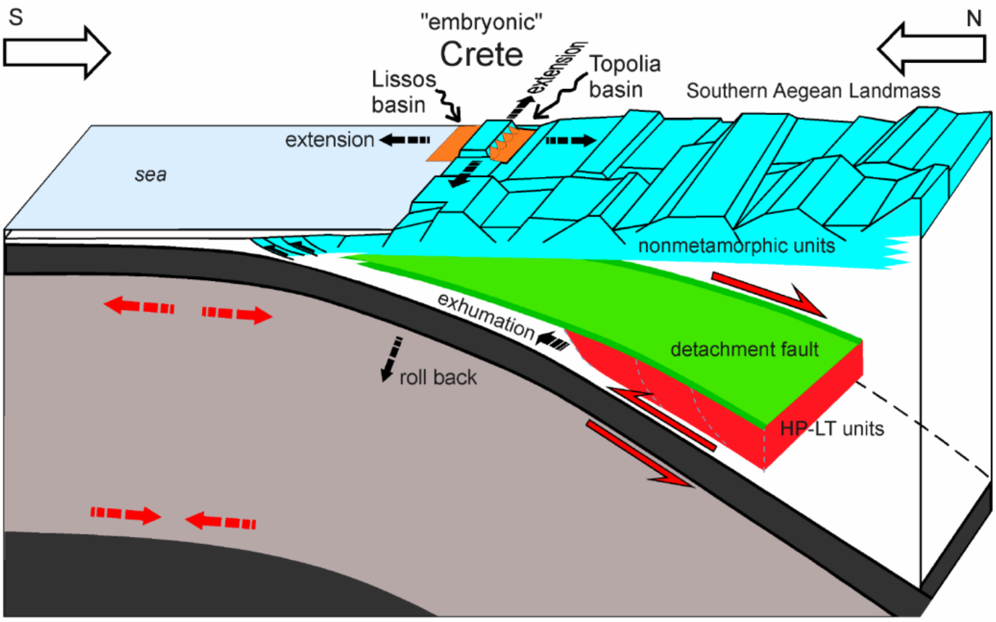
Various Extensional Plate Tectonic Models

Seidel, 2003: Tectono-sedimentary evolution of middle Miocene supra-detachment basins (western Crete, Greece), Ph.D. Dissertation, University of Köln.

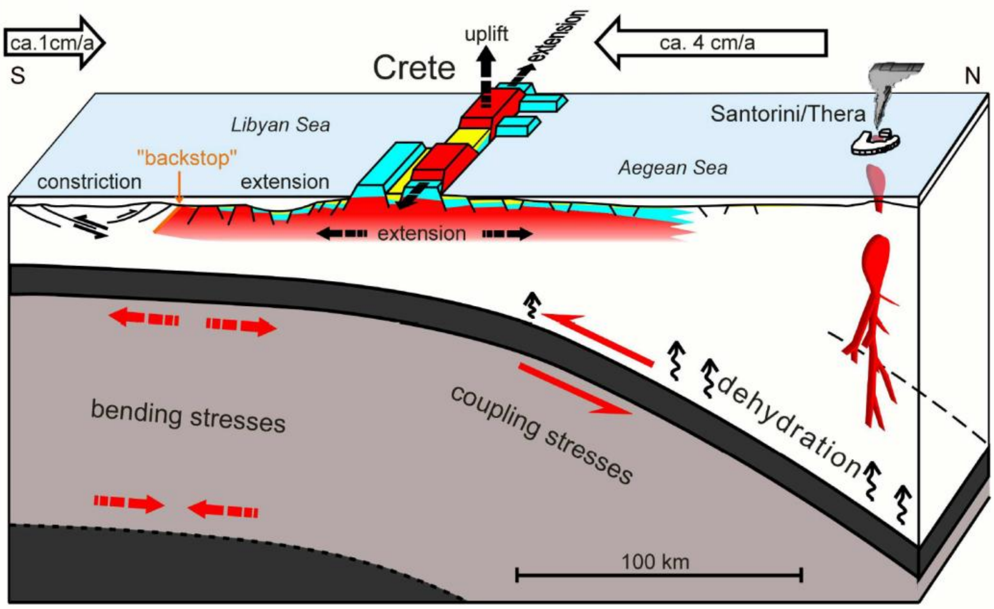
See also Section 1: Introduction

The exhumation of the high-pressure/low temperature metamorphic units during lower to middle Miocene times was accompanied by structural disintegration of the hanging wall, leading to formation of sedimentary basins on top of the nappe pile. The tectonosedimentary evolution of these supra-detachment basins provides information on the state of the Hellenic forearc at that time. The basins are half-graben structures filled by huge masses of clastic sediments exclusively derived from the tectonostratigraphic units atop the detachment fault which separates the HP-LT metamorphic units from the non-metamorphic units. This means that sedimentation of the breccio-conglomerates in western Crete took place before the exposure of the high pressure metamorphic units at the surface and their accessibility to erosion.

Facies analysis shows that the lower to middle Miocene basin fills of the half grabens vary from alluvial fan deposits in a terrestrial environment to turbiditic successions reflecting a marine environment. Predominant clastic components in the basin fills are limestones and dolomites with microfacies and fossil assemblages corresponding to members of the Tripolitza Unit. Limestones with chert, radiolarites, sandstones and calcarenites can easily be derived from the Pindos Unit, whereas the provenance of some pebbles to slabs of marbles remains enigmatic. Due to progressive extension, in places the western Cretan basin fills and the non-metamorphic units are now in tectonic contact along the detachment zone with the high-pressure/low-temperature metamorphic Phyllite-Quartzite Unit. Combining observations and information from field, laboratory and literature results Seidel, 2003 developed a simplified model for the tectonic evolution of western Crete during the Burdigalian to Langhian/Serravallian. The lower to middle Miocene basin fills of the half graben structures in western Crete document the history of continuous extension in the forearc of the roll back controlled Hellenic subduction zone and allow a reconstruction of the paleogeographic evolution for a period of time (20 to 15 Ma, Burdigalian – Langhian/Serravallian) otherwise not well recorded. Contrary to the lower to middle Miocene basin fills in western Crete, clastic sediments of similar facies and age in the Ierapetra region (eastern Crete) reflect block faulting during a compressional stage. *[Seidel, 2003]*

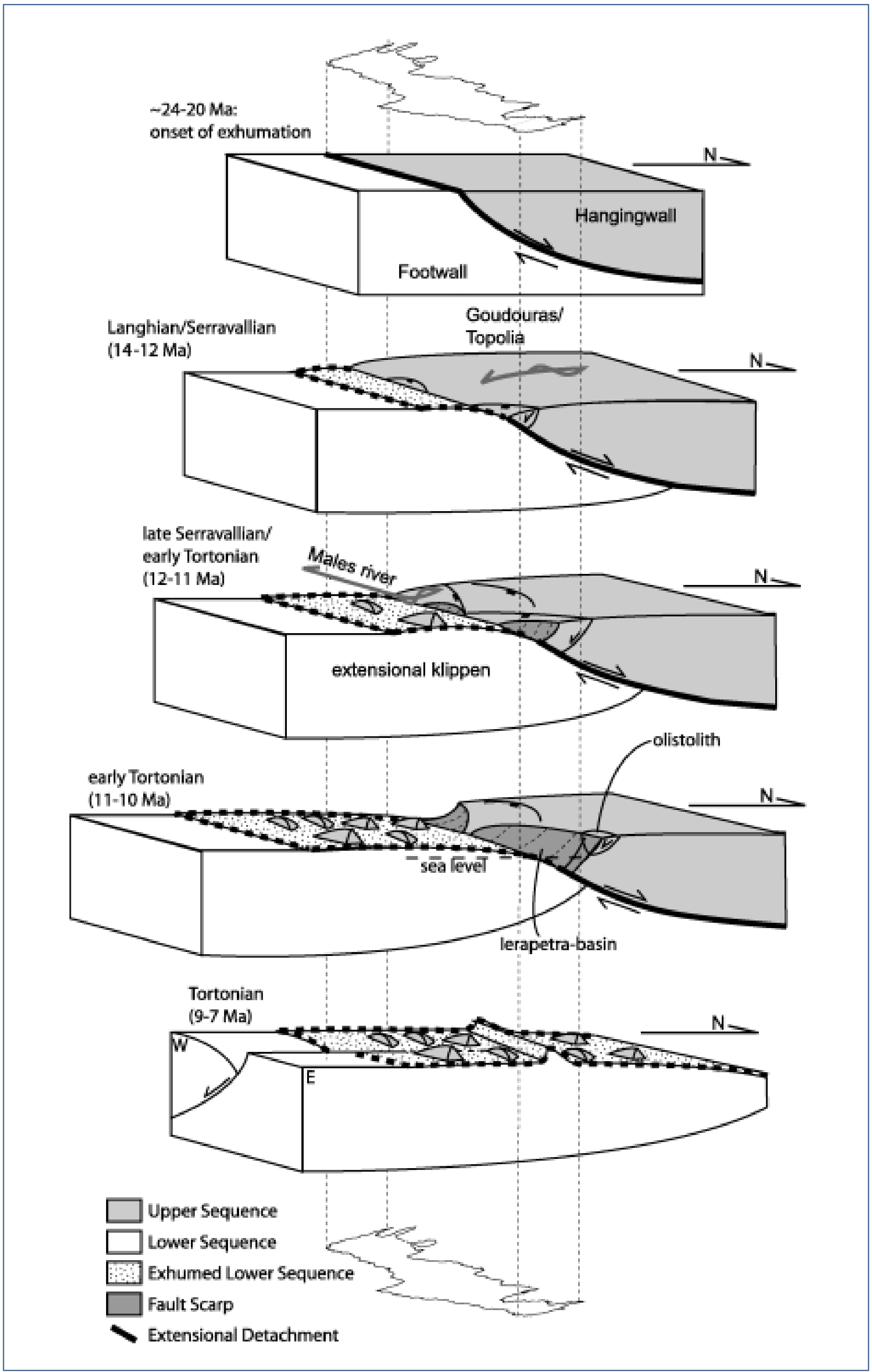


Schematic cross section of the Hellenic subduction zone and the southern Aegean region during lower to middle Miocene times. The supra-detachment basins are situated in the hanging wall of the detachment fault (green). The HP-LT units (red) are being exhumed due to extension tectonics caused by roll back. The clasts of the lower to middle Miocene basin fills (orange) in <u>*western Crete*</u> *are exclusively derived from the non-metamorphic units (blue). [Seidel*



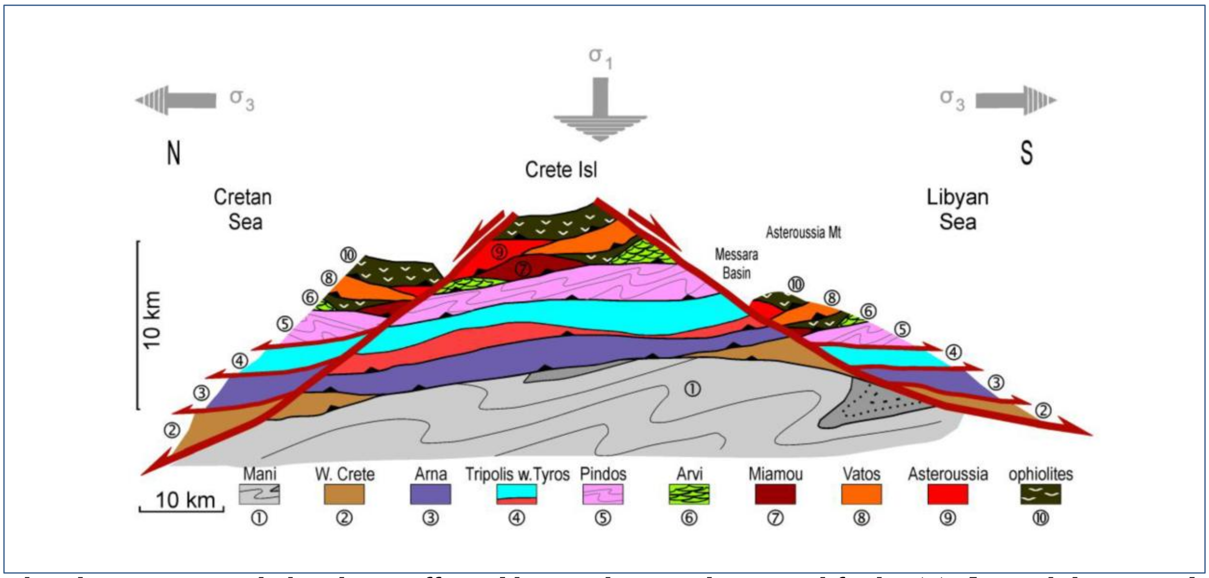
Schematic cross section of the Hellenic subduction zone and the geographic and tectonic setting of Crete in the central fore arc (modified after Papanikolaou & Stöckhert 1998). Seidel:

van Hinsbergen D. J. J., Meulenkamp J. E., 2006: Neogene supradetachment basin development on Crete (Greece) during exhumation of the South Aegean core complex.



Evolution of the Cretan Detachment Fault during the Neogene. Note that the position of Crete with respect to the outcrop of the detachment varied through time. The hanging wall to the Cretan detachment consisting mainly of the Tripolitza and Pindos units became fragmented from south to north, leading to the formation of extensional klippen. In between the klippen sedimentary *basins formed underlain by the footwall. The footwall consists of the lower nappes encompassing the metamorphic Plattenkalk and Phyllite-Quartzite units [van Hinsbergen D. J. J. et. al., 2006].*

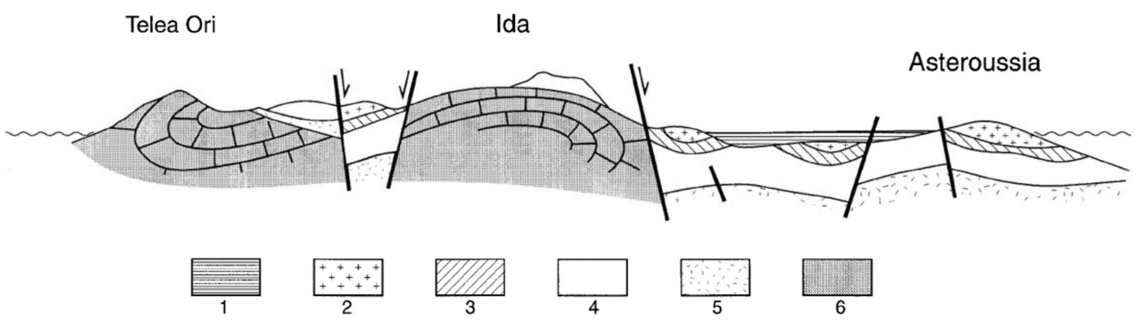
Vassilakis E. and Alexopoulos J., 2012: Recognition of Strike-slip Faulting on the Supradetachment Basin of Messara (Central Crete) with remote sensensing Image Interpretation Techniques



The alpine nappe pile has been affected by two low angle normal faults (2). [Vassilakis E. and Alexopoulos J., 2012]

Recent publications indicate that the Messara basin is a supra-detachment basin lying on top of the south Cretan extensional detachment (see figure above). The basin has all the characteristics of an active half graben as it is located at the active margin of the rapidly moving southwestwards Aegean micro-plate. The Messara basin is a similar structure, when on a much smaller scale, to the Cretan Sea half graben which lies on top of the north dipping Cretan low angle normal fault. This detachment's main activity was around and up to 15-17 Ma ago and various tectonic movements have disrupted the fault surface since then. In many cases the contact has been covered and sealed by post-alpine sediments. Indirect dating of the age, at which activity along the detachment ceased has been conducted *[Vassilakis E. and Alexopoulos J., 2012].*

J. H. ten Veen and G. Postma: Neogene tectonics and basin fill patterns in the Hellenic outer-arc (Crete, Greece)

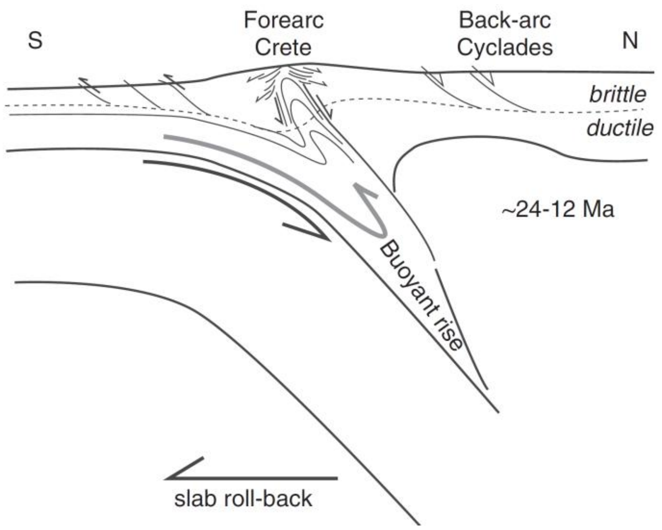


1=Neogene basin fill, 2=Ultra Mafic Series, 3=Pindos Series, 4=Tripolitza Series, 5=Phyllite–Quartzite Unit, 6=Plattenkalk Series.

N–S cross-section of central Crete redrawn from Bonneau et al. (1977) showing the most important fault and fold features, as well as the stacking of tectonic nappes. [Neogene tectonics and basin fill patterns in the Hellenic outer-arc (Crete, Greece), J. H. ten Veen and G. Postma; Faculty of Earth Sciences, Department of Geology, Utrecht University]

Zachariasse W., van Hinsbergen D., et al. 2011: Formation and Fragmentation of a late Miocene supradetachment basin in central Crete

Crustal extension, whether accommodated by symmetric (McKenzie, 1978) or asymmetric (e.g. Tirel et al., 2008, 2009) structures, is inevitably associated with basin subsidence. Zachariasse W., van Hinsbergen D. have shown that in the Cretan segment of the Aegean forearc, 'simple' crustal extension has been active for at least the last 10.8 Ma. However, the vast majority of exhumation of the LN now exposed on Crete, from depths of 30 km or more, to 2-3 km occurred before basin formation, between 24-21 Ma and 15-12 Ma (e.g. Jolivet et al., 1996; Thomson et al., 1998; Marsellos et al., 2010), and was associated with the strong reduction of the combined thickness of the UN. Based on the preserved combined thickness of the UN in western Greece of 25km (Jacobshagen, 1986; van Hinsbergen et al., 2005a), the reduction of the UN was considerable as on Crete the combined thickness is thought to be approx. 2 km (Bonneau, 1984).

	*Schematic cross-section illustrating the regional relationship between buoyancy-driven exhumation between 24-21 and 15-12Ma in the Aegean forearc (Crete) and back-arc (Cyclades) during early to middle Miocene exhumation of the south Aegean HP-LT metamorphic rocks. Figure modified from Jolivet et al. (2003). [Zachariasse W., van Hinsbergen D., et al. 2011]* *LN: Lower nappes* *UN: Upper nappes*

Early-middle Miocene exhumation of the LN is hence associated with extreme thinning and extension of the UN by a factor of 10 or more. If this was straightforward crustal extension, the present-day crustal thickness of Crete of approx. 30 km (Tirel et al., 2004) would restore to an original pre-Miocene thickness of 300 km, which is obviously impossible. In addition, such extreme thinning would inevitably lead to strong subsidence, and accumulation of deep marine sediments, of which there is no trace. Indeed, the only relics of pre-Viannos Fm sediments are nonmarine breccio-conglomerates (Kopp & Richter, 1983; Peters, 1985). Hence, the thinning of the UN, exhuming the LN, must have been compensated by a process that prevented the surface to subside. Previous workers have suggested a mechanism for exhumation of the LN by buoyancy- or extrusion driven upward flow of rock above the subducting African slab (Thomson etal.,1999; Jolivet etal., 2003; Chatzaras et al., 2006; Ring et al., 2010), a process that was numerically modelled by Beaumont et al. (2009). This process could be viewed as ‘intrusion’ of buoyantly rising HP-LT metamorphic rocks into a localized zone of extension. The fact that the relics of the Uppermost Unit are still present on Crete suggests that erosion had little influence during this process. Rather, the entire UN were tectonically thinned, and the growing evidence for coaxial deformation associated with the exhumation of the LN (e.g. Papanikolaou & Vassilakis, 2010) suggests that this process occurred symmetrically, similar to the modelling results of Beaumont et al. (2009). *[Zachariasse W., van Hinsbergen D., et al. 2011]*

Bandar Jissah, Christopher Sæbø Serck, et. al., 2020: Paleogene basin supradetachment to rift basin transition recorded in continental to marine deposition; NE Oman